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Economic Analysis of a Photovoltaic Hydrogen Refueling Station Based on Hydrogen Load

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Abstract: With the goal of achieving "carbon peak in 2030 and carbon neutrality in 2060", as clearly proposed by China, the transportation sector will face long–term pressure on carbon emissions, and the application of hydrogen fuel cell vehicles will usher in a rapid growth period. However, true "zero carbon" emissions cannot be separated from "green hydrogen". Therefore, it is of practical significance to explore the feasibility of renewable energy hydrogen production in the context of hydrogen refueling stations, especially photovoltaic hydrogen production, which is applied to hydrogen refueling stations (hereinafter referred to "photovoltaic hydrogen refueling stations"). This paper takes a hydrogen refueling station in Shanghai with a supply capacity of 500 kg/day as the research object. Based on a characteristic analysis of the hydrogen demand of the hydrogen refueling station throughout the day, this paper studies and analyzes the system configuration, operation strategy, environmental effects, and economics of the photovoltaic hydrogen refueling station. It is estimated that when the hydrogen price is no less than 6.23 USD, the photovoltaic hydrogen refueling station has good economic benefits. Additionally, compared with the conventional hydrogen refueling station, it can reduce carbon emissions by approximately 1237.28 tons per year, with good environmental benefits.

Keywords: hydrogen load; photovoltaic hydrogen refueling station; economic analysis

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1. Introduction

Carbon emissions in the transportation sector account for approximately one–quarter of the total global carbon emissions [1] and are closely related to human production and life, receiving significant attention from various countries. Carbon emissions in China's transportation sector account for approximately 10% of the total carbon emissions [2], with urban road transportation being the main source of carbon emissions. With the steady progress in China's economic development and the gradual improvement of people's living standards, the transportation sector will face carbon emission pressure in the long term. According to the data, the total carbon emissions in Shanghai's transportation sector (excluding long–distance aviation and air transportation) in 2019 were 20 million tons, with an average annual growth rate of approximately 2.0% [3]. In order to effectively promote the achievement of the "carbon peak by 2030 and carbon neutrality by 2060" goal in the transportation sector of Shanghai, the Shanghai Municipal Transportation Commission and the Shanghai Development and Reform Commission have issued the "Implementation Plan for Carbon Peak in the Transportation Sector of Shanghai" [4], which clearly proposes that by 2030, the proportion of new energy–powered motor vehicles added annually will not be less than 50%, and the carbon emission intensity per unit converted turnover of operating transportation tools will decrease by approximately 9.5% compared to 2020. With this goal, hydrogen fuel cell vehicles, the most common and mature application scenario for hydrogen applications, will inevitably experience a rapid growth period in the application of hydrogen energy as a source of "zero carbon" energy in the transportation field.

The construction of hydrogen refueling stations is a prerequisite for the widespread application of hydrogen fuel cell vehicles. It is also a key factor in achieving zero emissions in the transportation sector. A hydrogen refueling station is a gas station that pressurizes and stores hydrogen from different sources in a high–pressure tank inside the station through a compressor and then fills hydrogen fuel cell vehicles with hydrogen through a gas dispenser. It is an important infrastructure for the industrialization and commercialization of hydrogen fuel cells. According to different classification methods, there are different types of hydrogen refueling stations [5]. According to the different hydrogen refueling pressures, these can be divided into two types: 35 MPa and 70 MPa. According to the different hydrogen supply methods, these can be divided into external hydrogen supply stations and internal hydrogen production stations. Internal hydrogen production refueling stations supply hydrogen via the electrolysis of water in the station.

1.1. Application Status

The earliest hydrogen refueling stations can be traced back to the 1980s in Los Alamos in the United States. In terms of hydrogen refueling station construction, the United States mainly focuses on the layout of densely populated urban areas, such as San Francisco and Los Angeles, emphasizing the combination of hydrogen energy application scenarios for forming a unique hydrogen energy industry ecosystem in the local area. According to the data from the United States Department of Energy [6], as of November 2020, 46 commercial hydrogen refueling stations have been built in the United States, 45 of which are located in California. All the stations, except for the station in Newport Beach, are in normal operation. In addition, according to the US Hydrogen Economy Roadmap released by the Fuel Cell and Hydrogen Energy Association in November 2019, 580 hydrogen refueling stations will be built by 2025, and 5600 hydrogen refueling stations will be built by 2030 (as shown in Table 1).

Table 1. Development status and objectives of hydrogen stations in various countries.

Countries	Development Status	Development Goals
the United States	As of November 2020, 46 commercial hydrogen refueling stations have been built.	By 2025, 580 hydrogen refueling stations will be built. By 2030, 5600 hydrogen refueling stations will be built.
Korea	As of November 2020, 43 hydrogen refueling stations have been built.	By 2040, 1200 hydrogen refueling stations will be built.
Japan	As of November 2020, 146 commercial hydrogen refueling stations have been built.	By 2025, 320 hydrogen refueling stations will be built; By 2030, 900 hydrogen refueling stations will be built
China	As of 2023, more than 350 hydrogen refueling stations have been built.	By 2025, 1000 hydrogen refueling stations will be built; By 2035, 5000 hydrogen refueling stations will be built.

According to the data from H_2 Stations, as of November 2020, a total of 43 commercial and non–commercial hydrogen refueling stations have been built in South Korea, and 21 hydrogen refueling stations are under construction or planned, which are mainly distributed around the urban agglomerations of Seoul and Busan. According to a hydrogen economy roadmap announced in 2019 [7], South Korea plans to build 1200 hydrogen refueling stations by 2040 (as shown in Table 1).

Japan's fuel cell industry is at the forefront of global commerce, and they are a global leader in the construction of hydrogen refueling stations as infrastructure. According to data from the Japan Fuel Cell Utility Promotion Agreement, as of November 2020, Japan has built a total of 146 commercial hydrogen refueling stations, including 106 fixed stations and 40 skid–mounted stations, as well as 23 fixed hydrogen refueling stations under construction and planned. According to the Hydrogen Energy Utilization Schedule released by the Japanese government in 2019, the key goal of applying hydrogen energy in Japan is to build 320 hydrogen refueling stations by 2025 and increase them to 900 by

2030 (as shown in Table 1). In addition, by 2025, the construction and operation costs of hydrogen refueling stations should significantly decrease, with construction costs dropping to 200 million yen and operating costs dropping to 15 million yen per year.

China attaches great importance to the construction of hydrogen refueling stations. In 2006, China's first hydrogen refueling station was constructed in the New Energy Transportation Demonstration Park of the Yongfeng High–Tech Industrial Base in Zhongguancun, Beijing. In the same year, the first hydrogen refueling station in Shanghai, the Anting hydrogen refueling station, covers an area of 880 m^2 and has a maximum hydrogen capacity of 800 kg. It can provide continuous refueling services for 35 MPa fuel cell vehicles (20 sedans and 6 buses), with a maximum daily refueling capacity of approximately 400 kg/12 h. With the continuous maturity of the relevant technologies, the number of hydrogen refueling stations in China is steadily increasing. As of 2023 [8], more than 350 hydrogen refueling stations will be built nationwide, accounting for approximately 40% of the global total and ranking first in the world. According to the "Energy Conservation and New Energy Vehicle Technology Roadmap 2.0" [9], the construction goal of China's hydrogen refueling stations is to reach at least 1000 by 2025 and at least 5000 by 2035 (as shown in Table 1).

In summary, the number of hydrogen refueling stations around the world is increasing, which will accelerate the commercialization promotion of hydrogen fuel cell vehicles and provide an important guarantee for hydrogen energy applications.

1.2. Research Status

At present, research on hydrogen refueling stations mainly focuses on the layout of hydrogen refueling stations, the optimization of the hydrogen refueling station system, and the combined application of hydrogen refueling stations and renewable energy.

In terms of research on hydrogen refueling station layout, Ye et al. [10] designed and implemented a hydrogen refueling station site selection system considering multiple site selection factors. The system integrates data related to hydrogen refueling station site selection, supports modeling and analysis of site selection areas, analyzes the distribution of regional hydrogen refueling demand and the distribution of hydrogen refueling station candidate sites, and can be evaluated and compared horizontally in combination with other site selection goals. Huang et al. [11] carried out an in–depth analysis of the working mode of hydrogen production hydrogen refueling stations and built a hydrogen production hydrogen refueling station layout optimization model considering the coupling effect of distribution network and hydrogen fuel vehicles under the framework of transportation power network. Zhou et al. [12] conducted a study based on the composition of the hydrogen supply chain combined with the construction demand of the hydrogen energy highway; they aimed at minimizing the cost of hydrogen consumption and constructed a mathematical model for the location of hydrogen refueling station considering the optimal hydrogen supply chain by comprehensively considering the constraints, such as the distance between hydrogen refueling station, hydrogen source capacity, and geographical location, and taking the location of hydrogen refueling station and hydrogen transportation volume under different transportation modes as decision variables.

In terms of optimizing research on hydrogen refueling station systems, Zhao et al. [13] studied the optimization of a high–pressure hydrogen supply system of a hydrogen refueling station from the aspects of the configuration of hydrogen refueling machine, the configuration of compression and gas storage system, and design of high–pressure hydrogen precooler, aiming at the core of a hydrogen refueling station high–pressure hydrogen supply system consisting of compression, gas storage, precooling, and filling systems. Fan et al. [14] proposed the optimization process with a significant effect on protecting the 45 MPa hydrogen compressor, improving the effective hydrogen unloading capacity of long tube trailers and reducing the cost of hydrogen sales. It can provide a reference for actual production and operation. Liu et al. [15] obtained the change rule of key parameters by calculating the filling capacity of an example hydrogen refueling station and discussed the relationship between the changes in compressor power consumption and the filling sequence of each pressure level of the hydrogen storage container under the long tube trailer hydrogen supply method. These rules are helpful to understand and optimize the equipment configuration and operation mode of hydrogen refueling stations.

In terms of research on the combined application of hydrogen refueling stations and renewable energy, especially in the combination of hydrogen refueling station and photovoltaic (PV) hydrogen production, El Manaa et al. [16] considered a transport company in Tunis Tunisia as an example; a detailed economic assessment and evaluation of the Levelized Hydrogen Cost (LHC) and the Net Profit(NP) of a photovoltaic hydrogen refueling station were presented and discussed. Barhoumi et al. [17] discussed the feasibility of hydrogen production in grid–connected photovoltaic power stations and the economic efficiency and optimization of the PV grid–connected system for the production of hydrogen. Marcos et al. [18] proposed a novel stochastic–interval model for the optimal scheduling of photovoltaic–assisted refueling stations, and the vehicle demand was modelled using a more suitable approach based on scenarios. The results revealed the importance of selling energy to the grid in order to complement the revenues obtained from refueling. Li et al. [19] selected five representative cities with different situations in China as the background, carried out a conceptual design for a photovoltaic electrolysed water hydrogen production hydrogen refueling station, and analyzed its cost. The results showed that the hydrogen production cost of an electrolysed water hydrogen refueling station powered by a grid–connected photovoltaic power generation system is close to that of an electrolysed water hydrogen refueling station powered by a traditional grid.

In summary, most of the existing studies on hydrogen refueling stations focus on the spatial location layout as transportation infrastructure, and the system equipment configuration and operation optimization, while most of the studies on photovoltaic hydrogen refueling stations focus on the system configuration. However, there are fewer studies on the operation strategy of photovoltaic hydrogen refueling stations based on hydrogen demand and its economic and environmental application feasibility.

In order to make full use of regional renewable energy resources and promote the application of hydrogen fuel cell vehicles to truly achieve "zero carbon" emissions in the transportation field, this paper takes a 500 kg/day hydrogen refueling station in Shanghai as the research object to analyze the feasibility of the photovoltaic hydrogen production applied to hydrogen refueling station (hereinafter referred to as "photovoltaic hydrogen refueling stations").

2. Analysis of Hydrogen Load Characteristics at Hydrogen Refueling Stations

The hydrogen demand characteristics of hydrogen refueling stations are the basis for determining the equipment configuration and the operation strategy of photovoltaic hydrogen refueling stations.

2.1. Analysis of Hydrogen Demand for Different Types of Hydrogen Fuel Cell Vehicles

At present, hydrogen fuel cell vehicles mainly involve heavy trucks, logistics vehicles, buses, medium–capacity buses, passenger cars, and other vehicles:

- Heavy trucks mainly include various specialized vehicles (sprinkler trucks, fire trucks, road cleaning vehicles, oil tank trucks, mixer trucks, etc.), dump trucks (bulldozers, all with elevators), trucks (transporting goods, including livestock, etc.), and some rare off–road vehicles (mostly military).
- Logistics vehicles refer to a unit of mobile container equipment equipped with four casters for transporting and storing materials, commonly used for logistics distribution in large supermarkets or logistics turnover between factory processes.
- Buses refer to specialized motor vehicles that usually follow a fixed route and have a dedicated road number to carry passengers for travel. In urban areas, its speed is generally between 25–50 km/h, and in suburban areas, it can reach up to 80 km/h.
- Medium–capacity public transportation refers to buses operating on the bus rapid transit routes, with dedicated boarding and alighting platforms and dedicated driving

lanes. Its passenger capacity is between that of high–volume rail transit and low–volume conventional transportation, and its departure interval is significantly shorter than that of regular public transportation, which is close to rail transit.

- Passenger cars refer to cars that are primarily and technically designed to carry passengers and their accompanying luggage or temporary items, with a maximum of nine seats (including the driver's seat).

2.1.1. Analysis of Hydrogen Demand for Different Types of Hydrogen Fuel Cell Vehicles

According to the different functions of different types of hydrogen fuel cell vehicles, traffic regulations, and working time constraints of hydrogen refueling stations, their travel characteristics and refueling behavior vary (as shown in Table 2).

Table 2. Analysis of travel characteristics and hydrogen refueling behavior of various types of hydrogen fuel cell vehicles [20–27].

Different Types of Vehicles	Driving Mileage [1] (km)	Daily Mileage [2] (km)	Single Trip Duration [2] (h)	Daily Working Hours [2]	Operating Time [3]	Analysis of Hydrogen Refueling Behavior
Heavy truck	700	50–100, >300	0.5–1	>8	Suburban: 8:00~17:00 Urban area: 20:00–7:00 the next day	Due to traffic regulations, restrictions on working hours at hydrogen refueling stations, and their commercial attributes, the refueling time is generally during the rest time during its operating period or nearby refueling
Logistics vehicle	260	90–185	0.5–1	3–4.5	24 h a day	Restricted by working hours of hydrogen refueling stations
Bus	350	70–230	1–1.5	5.5–7, 8.5–9.5	6:50–18:15	Due to the limitations of the working hours of hydrogen refueling stations and their passenger transportation functions, the refueling time is generally during the rotation period during their operating hours
Medium volume traffic	150	70–230	1–1.5	5.5–7, 8.5–9.5	6:00–22:30	restricted by working hours of hydrogen refueling stations
Passenger cars	440	20–80	0–1.5	0.5–3	24 h a day, there are two peak hours from 8:00 to 9:00 and from 18:00 to 20:00	Due to traffic regulations, restrictions on the working hours of hydrogen refueling stations, and their commercial attributes, the refueling time is generally around 8 a.m. and 8 p.m.

[1] Driving mileage refers to the distance that a hydrogen vehicle can travel after a single refueling of hydrogen, and it is one of the important criteria for judging the performance of a car. [2] Daily mileage, single trip duration, and daily working hours refer to the possible daily mileage, single trip duration, and daily operating duration of each hydrogen vehicle, which can be used to analyze the refueling frequency of different hydrogen–powered vehicles. [3] The operating time is limited by the functional positioning of different vehicles and the traffic control in different cities (this table is based on Shanghai).

2.1.2. Hydrogen Demand Analysis

The hydrogen demand for hydrogen fuel cell vehicles is the basis for accurately predicting the hydrogen load required for hydrogen fuel cell vehicles. Based on the principle of vehicle longitudinal dynamics, the energy consumption per trip of the vehicle is estimated, and the average speed, distance traveled, and variance of the average speed of the trip feature data are selected to describe energy consumption during the vehicle's driving process. Considering the wind resistance, rolling resistance, motor efficiency, and transmission efficiency of the vehicle during driving, the following formula is used to estimate the energy consumption of the vehicle [28]:

$$C_e^{100} \approx \frac{2.8 \times 10^{-2}\left(f_a\left(\overline{v}^2 + 3\sigma\right) + f_r\right)}{\eta_t \eta_m} \tag{1}$$

$$f_a = \frac{1}{2}\rho C_d A \tag{2}$$

$$f_r = m_v g F_0 \tag{3}$$

Among them, C_e^{100} is the energy consumption per 100 km of the vehicle, kWh/100 km; ρ is the density of air, kg/m^3; C_d is the air resistance coefficient; A is the windward area of the vehicle, m^2; m_v is the equivalent mass of the vehicle, considering the rotating parts of the vehicle and the mass of passengers, kg; g is gravity acceleration, m/s^2; F_0 is the rolling resistance coefficient; η_t is the efficiency of vehicle transmission, %; η_m is vehicle motor efficiency, %; $\overline{v}$ is the average speed within the travel segment, m/s; σ is the standard deviation of the average speed of vehicles within the travel segment.

The formula for hydrogen consumption per 100 km of hydrogen fuel cell vehicles is as follows:

$$m_{H_2} \approx \frac{C_e^{100}}{W_{H_2} \times \eta_{to}} \tag{4}$$

Among them, m_{H_2} is the hydrogen consumption per 100 km of hydrogen fuel cell vehicles, kg/100 km; W_{H_2} is the mass–energy density of hydrogen, and the calorific value of water vapor generated by the complete combustion of 1 kg hydrogen under standard conditions is approximately 33.26 kWh/kg; η_{to} is the overall power generation efficiency of hydrogen fuel cell systems, which is generally between 40% and 60%.

Based on the current research and application level of key technologies for hydrogen fuel cell vehicles, the hydrogen consumption per 100 km is shown in Table 3.

Table 3. Hydrogen consumption per 100 km for various types of hydrogen fuel cell vehicles [20–27].

Parameter	Hydrogen Consumption per 100 km (kg/100 km)
Heavy truck	7.5–14
Logistics vehicle	3
Bus	4.1–4.5
Medium volume traffic	14.4–21.6
Passenger cars	0.65–0.75

2.2. Hydrogen Load Analysis of Hydrogen Refueling Station

As an infrastructure for providing hydrogen to fuel cell vehicles, hydrogen refueling stations have similar functionality to gas stations as an infrastructure for providing fuel oil to fuel cell vehicles. In addition, hydrogen refueling stations and gas stations also have regional exclusivity characteristics, and the best path for hydrogen refueling station construction at present is to prioritize selecting sites around the original gas station location and explore joint construction stations if conditions permit. Based on the multiple similarities between hydrogen refueling stations and gas stations, as well as the limited research on hydrogen loading at refueling stations, this paper analyzes the characteristics of hydrogen refueling demand curves of hydrogen refueling stations by analyzing the refueling demand curve of gas stations.

The research report "Analysis Model of H2A Transportation Facilities and Analysis Results of Conventional Transportation Methods" [13] conducted a survey on the temporal distribution characteristics of the refueling volume at Chevron gas stations. The results showed that the refueling demand in summer was the highest, about 1.1 times the average demand during the year. During the week, the refueling demand on Friday was significantly higher than the other days, approximately 1.08 times the weekly average demand. In this report, the refueling station was designed using the Chevron refueling demand curve for summer and Friday (as shown in Figure 1, which is a single–peak demand curve).

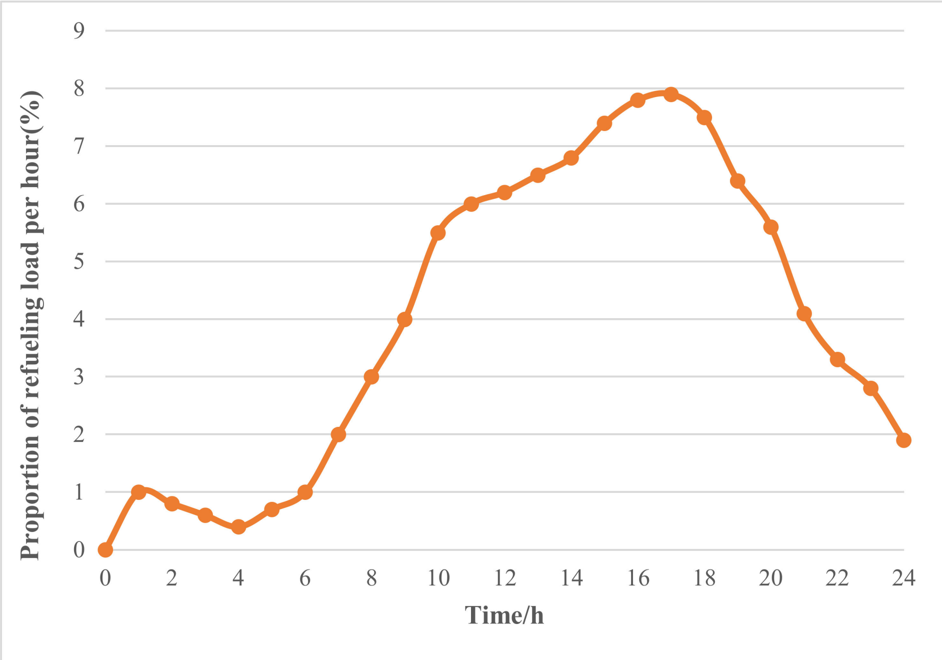

Figure 1. Friday hourly variation in refueling station demand; elaboration based on data from [13].

Dalian University of Technology [29] conducted cluster analysis on the daily oil sales curve of No. 92 gasoline for 120 days at a gas station in Dalian and found that the main oil sales models at the station can be divided into the following three types (as shown in Figure 2): between 7:00 and 16:00, sales model A shows a significant downward trend; sales mode B maintains a high sales volume every hour; sales model C exhibits obvious multi–peak characteristics. According to the three sales model curves, it can be seen that the fuel demand curve of gas stations in Dalian, China, is mainly composed of multi–peak demand curves, such as double peak and three peak.

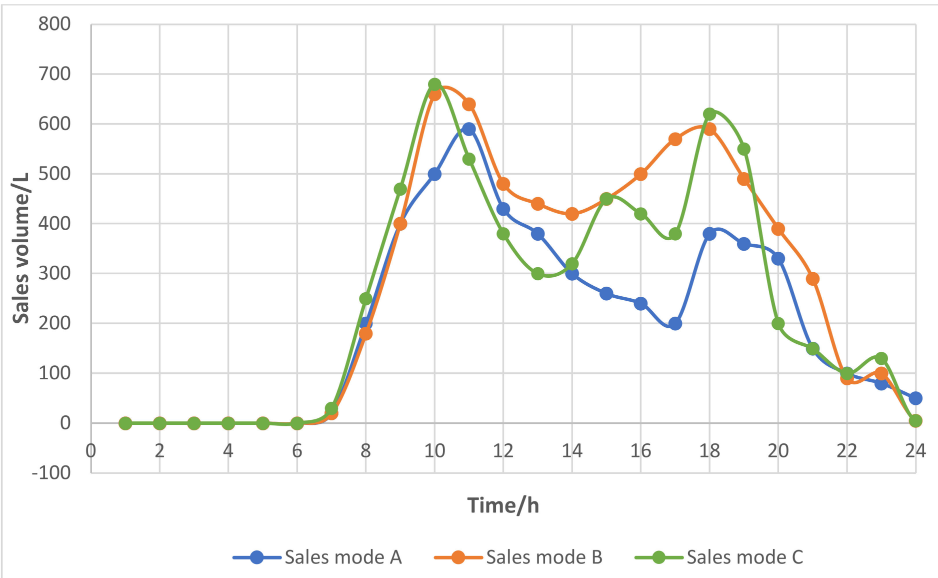

Figure 2. The clustering results of the daily sales curves of No.92 petrol products in a gas station; elaboration based on data from [29].

Shanghai Shunhua New Energy System Co., Ltd. (Shanghai, China) [15] analyzed the distribution of domestic and international hydrogen refueling demand throughout the day (i.e., the proportion of hydrogen refueling demand for fuel cell vehicles per hour of operation to the total hydrogen refueling demand throughout the day) curve(as shown in Figure 3). Among them, via statistical analysis of the annual average hydrogen refueling demand data of 33 hydrogen refueling stations in California, the United States, in 2016, it was found that the distribution curve of hydrogen refueling demand in foreign countries is mainly a single peak distribution, which is basically the same as the distribution curve of refueling demand of the gas stations in foreign countries. Via statistical analysis of the hydrogen refueling demand data of the Anting hydrogen refueling station in Shanghai, China in 2017, it was found that the distribution curve of China's full–day hydrogen refueling demand showed a three–peak distribution. There is a significant difference in the distribution pattern between the three–peak demand curve and the single–peak demand curve; that is, there are multiple peak refueling demand peaks during the full day of operation.

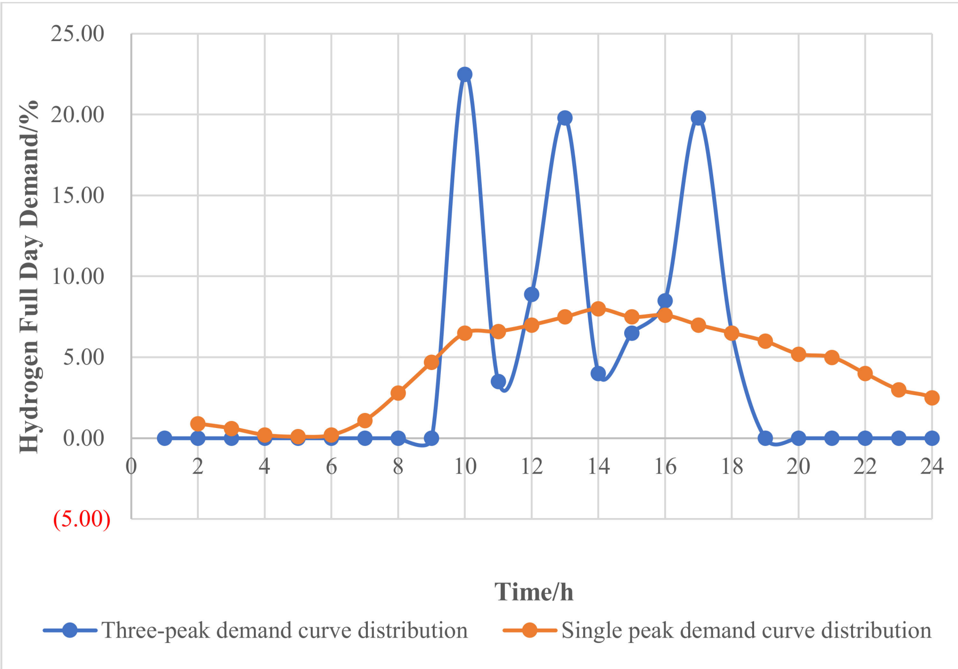

Figure 3. Distribution of hydrogen demand for refueling stations throughout the day; elaboration based on data from [15].

In summary, the full–day refueling demand curve of foreign hydrogen refueling stations is the same as that of gas stations, which is a single peak demand curve. The full–day refueling demand curve of domestic hydrogen refueling stations is the same as that of gas stations, which is a multi–peak demand curve. Considering that China's fuel cell vehicle development strategy prioritizes its application in the commercial vehicle field, the main service targets of domestic hydrogen refueling stations will be commercial vehicles operating on fixed routes, such as logistics, public transportation, and buses, for a long time in the future, with a multi–peak demand distribution.

3. System Descriptions and Modeling

The photovoltaic hydrogen refueling station mainly consists [15] of a photovoltaic power generation system, hydrogen production electrolysis tank, compressor, hydrogen storage tank, hydrogen refueling station, etc (as shown in Figure 4). The hydrogen production electrolysis cell is connected to a photovoltaic power generation system through a step–down converter with a current controller. Hydrogen is generated at constant pressure and different temperatures, and the generated hydrogen is compressed by a compressor under high pressure and stored in a hydrogen storage tank for use at the hydrogen refueling station. The hydrogen in the hydrogen refueling station is mainly supplied to various types of hydrogen fuel cell vehicles. The purpose of this paper is to study the feasibility of photovoltaic hydrogen production for hydrogen refueling stations. Therefore, except for the photovoltaic hydrogen production equipment, the other equipment is the same as that of the conventional hydrogen refueling station.

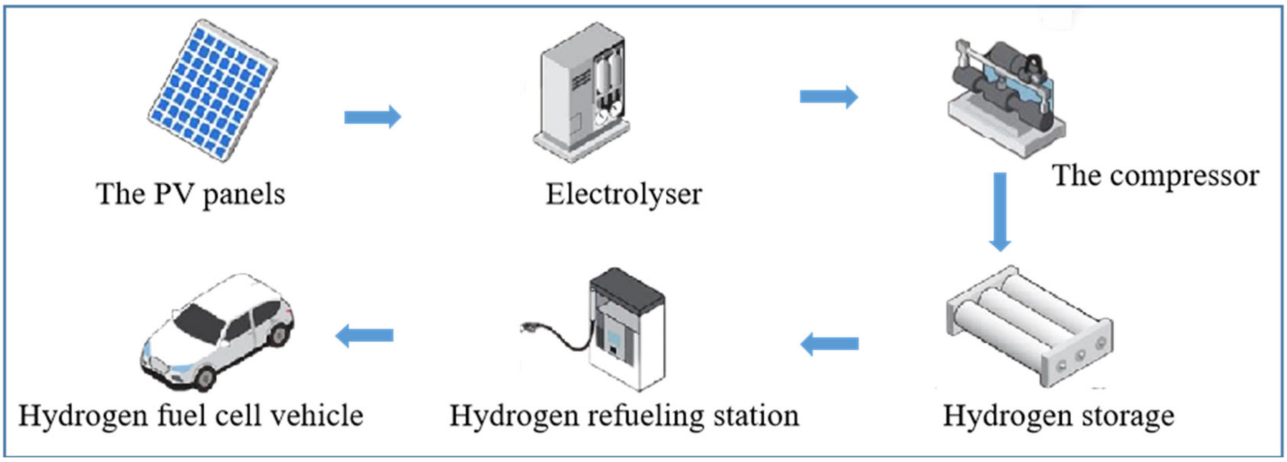

Figure 4. Composition of a photovoltaic hydrogen refueling station.

3.1. Electrolytic Cell

The electrolytic cell is the core device of the hydrogen production system by electrolysis of water, and its main function is to use electricity to drive the oxidation–reduction reaction to decompose chemical substances. Currently, the main electrolytic cells on the market include proton exchange membrane (PEM), alkaline electrolytic cell (AE), solid oxide electrolytic cell (SOE), etc. Due to the uncertainty and volatility of renewable energy, the electrolysis equipment in the wind/light/water waste hydrogen production system should have the ability to safely produce hydrogen under unstable conditions. AE can operate stably under low voltage, high current density, and intermittent power conditions, making them suitable for renewable energy hydrogen production.

The working principle of an alkaline electrolytic cell is as follows [30–32]:

$$2\mathrm{H_2O} \leftrightarrow 2\mathrm{H_2} + \mathrm{O_2}$$

Anode: OH^- ions are oxidized under the action of current, producing O^2 and H_2O and releasing electrons, which pass through an external circuit to the cathode. The reaction equation is as follows:

$$2\mathrm{OH^-} \rightarrow \frac{1}{2}\mathrm{O^2} + \mathrm{H_2O} + 2\mathrm{e^-}$$

Cathode: Electrons cannot reduce K^+ ions in the solution, so what happens on the cathode is a reduction reaction of water itself. The reaction equation is as follows:

$$\mathrm{H_2O} + 2\mathrm{e^-} = \mathrm{H^2} + 2\mathrm{OH^-}$$

The voltage and current equations of the electrolytic cell are as follows [33]:

$$U_{el} = N_{el}\left(U_{re} + \frac{r_1 + r_2 T_{el}}{A_{el}} I_{el} + \left(s_1 + s_2 T_{el} + s_3 T_{el}^2\right)\log\left(\frac{t_1 + \frac{t_2}{T_{el}} + \frac{t_3}{T_{el}^2}}{A_{el}} + 1\right)\right) \quad (5)$$

Among them, U_{el} is the voltage of the electrolytic cell, V; N_{el} is the number of batteries connected in series in the electrolytic cell; U_{re} is the reversible battery voltage, V; I_{el} is the current of the electrolytic cell, A; r_1,r_2 is the ohmic parameter of the electrolyte; A_{el} is the reaction area of the battery, m^2; T_{el} is the electrolyte temperature, K; $s_1, s_2, s_3, t_1, t_2, t_3$ are the electrode overvoltage parameters.

According to Faraday's law, the hydrogen production flow rate of an electrolytic cell is proportional to the external circuit current:

$$V_{H_2} = \eta(T, J)\frac{N_{el}}{2F} \tag{6}$$

Among them, V_{H_2} is the hydrogen production rate, Nm^3/h; T is the ambient temperature, K; J is the current density during the reaction, A/m^2; F is the Faraday constant; η is the relationship function between T and J:

$$\eta = a_1 exp\left(\frac{a_2 + a_3 T_{el}}{\frac{I_{el}}{A_{el}}} + \frac{a_4 + a_5 T_{el}}{\left(\frac{I_{el}}{A_{el}}\right)^2}\right) \tag{7}$$

In the formula, a_i is the relative coefficient of Faraday efficiency (i = 1,2,3,4,5).

3.2. Compressor

The hydrogen generated via the electrolytic cell is at ordinary temperature and pressure, which usually cannot meet the pressure requirements of the system and requires compression treatment. The hydrogen storage requirements for hydrogen refueling stations are usually 20 MPa, 35 MPa, and 70 MPa [34]. According to the requirements for compressing hydrogen gas pressure, different stages of compression are selected, usually consisting of three stages. The equation for the compression system is as follows [35]:

$$E_{co} = m_{H_2} \times \frac{n}{n-1} \times R \times T\left(\left(\frac{P_{co}}{P_{in}}\right)^{\frac{n-1}{n}} - 1\right) \tag{8}$$

In the equation, E_{co} is the power consumption of the compressor, J; m_{H_2} is the mass flow rate of hydrogen gas, kg; n is the heat capacity ratio, and the value is 1.4; R is the gas constant of hydrogen, which is 4124 J/(kg·K); T is the temperature of the compressed gas, K; P_{co} is the gas compression pressure, Pa; P_{in} is the compressor inlet pressure, Pa.

3.3. Photovoltaic Power Generation System

The composition of the photovoltaic power generation system is shown in Figure 5, where the photovoltaic array has a large number of photovoltaic cells in series and parallel. It utilizes the principle that semiconductor materials generate voltage at both ends after being illuminated, converting light energy into electrical energy. The current generated by the photovoltaic array is direct current, which needs to be converted into alternating current via an inverter, and then boosted by a transformer before being connected to the power grid.

The photovoltaic current equation based on the influence of solar radiant intensity and actual temperature is as follows [36,37]:

$$I = N_P^{PV} I_{sc} \cdot \left\{1 - C_1\left[exp\left(\frac{U - dU}{C_2 N_S^{PV} U_{oc}}\right) - 1\right]\right\} + dI \tag{9}$$

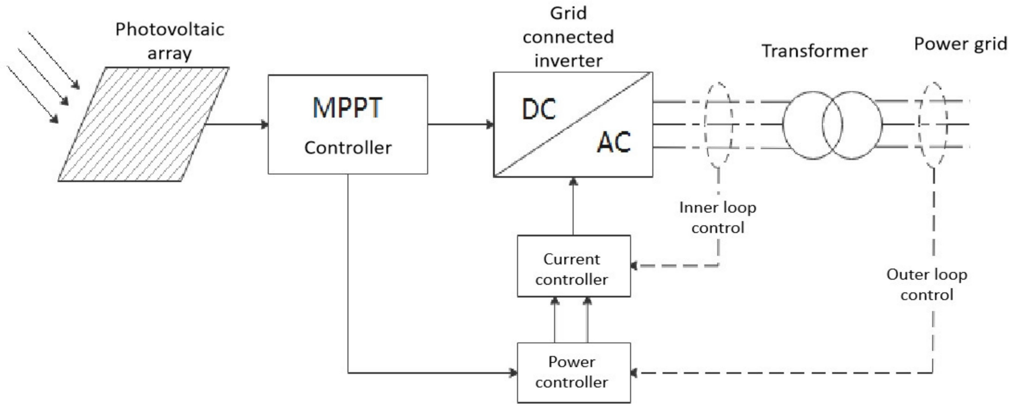

Figure 5. Schematic diagram of photovoltaic power generation system group.

The calculation formula for the parameters in the equation is as follows [38,39]:

$$\begin{cases} C_1 = \left(1 - \frac{I_m}{I_{sc}}\right) \cdot exp\left(-\frac{U_m}{C_2 U_{oc}}\right) \\ C_2 = \frac{\frac{U_m}{U_{oc}} - 1}{ln\left(1 - \frac{I_m}{I_{sc}}\right)} \\ dI = -a\frac{G}{G_{ref}}\left(T_c - T_{ref}\right) + \left(\frac{G}{G_{ref}} - 1\right) \cdot N_P^{PV} I_{sc} \\ dU = bdT - R_s dI \\ T_c = T_a + t_c G \end{cases} \tag{10}$$

Among them, U_{oc} is the open circuit voltage, V; I_{sc} is the short circuit current, A; U_m is the voltage value at the maximum power point, V; I_m is the current value at the maximum power point, A; a and b are the current and voltage temperature change coefficients under the reference radiant intensity, respectively; T_a is the ambient temperature, K; t_c is the temperature change coefficient of the photovoltaic module; T_c is the temperature of the photovoltaic panel, K; G is the radiant intensity of the sun, W/m^2; R_s is the series resistance of the photovoltaic cell, Ω; N_s^{PV} is the serial number of photovoltaic array components; N_P^{PV} is the parallel number of photovoltaic array components.

Under the conditions of known light intensity and environmental temperature, the photovoltaic output can be calculated using the following formula (11) [40]:

$$P_{PV} = \alpha_F U_{PV} I_{PV} \tag{11}$$

The calculation formula for the parameters in the equation is as follows:

$$\begin{cases} I_{PV} = G[I_{sc} + \alpha(T_c - 25)] \\ U_{PV} = U_{oc} - \beta T_c \\ \alpha_F = \frac{U_m I_m}{U_{oc} I_{sc}} \end{cases} \tag{12}$$

Among them, P_{PV} is the active power of the photovoltaic cell, W; α_F is the fill factor.

A large number of statistical data show that the solar illumination intensity conforms to the beta distribution. Similarly, when the PV installed capacity is unchanged, the annual utilization hours of PV can also be fitted by the beta distribution, and its probability density function can be expressed as:

$$f_{PV}(h_{PV}) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \left(\frac{h_{PV}}{8760}\right)^{\alpha - 1} \left(1 - \frac{h_{PV}}{8760}\right)^{\beta - 1} \tag{13}$$

where α and β are distribution parameters of the beta function; h_{PV} is the annual utilization hours of photovoltaic; $\Gamma(\ )$ is a gamma function.

3.4. Hydrogen Storage

There are three key technologies for hydrogen storage: high–pressure gas hydrogen technology, low–temperature liquid hydrogen technology, and solid hydrogen storage technology (as shown in Table 4). Among them, high–pressure hydrogen storage technology refers to the storage of gaseous hydrogen in gas tanks through high–pressure compression above the critical temperature of hydrogen. It has the characteristics of low cost, low energy consumption, easy dehydrogenation, and wide working conditions, and is the most mature, engineering–oriented, and commonly used hydrogen storage technology.

Table 4. Comparison of hydrogen storage technologies [41].

Hydrogen Storage Technology	Volume Specific Capacity	The Cost	Security	Technical Maturity
High–pressure gas hydrogen storage	small	lower	poor	mature
Liquid hydrogen storage	large	high	poor	not very mature
Solid hydrogen storage	large	high	security	immature, in the laboratory stage

The hydrogen storage model is shown in Equation (14) [42]:

$$p_s - p_{si} = z\frac{v_{H_2}RT_s}{M_{H_2}V_s} \tag{14}$$

In the formula, p_s and p_{si} are the pressure and initial pressure of the storage tank, Pa; M_{H_2} is the molar mass of hydrogen, kg/kmol; v_{H_2} is the rate of hydrogen gas generated by the electrolytic cell and transported to the storage tank, mol/s; T_s is the working temperature of the hydrogen storage tank, K; V_s is the volume of the storage tank, m^3; z is the compressibility factor.

3.5. Economic Analysis Model

3.5.1. Annual Total Cost Model of Energy System

The annual total cost (C_{AT}) of the energy system proposed in this paper includes the annual investment cost (C_{AI}), annual maintenance cost (C_{AM}), annual operating cost (C_{AO}), and annual carbon emission transaction cost (C_{ACET}) of each equipment in the system, as shown in Formula (15) [43].

$$C_{AT} = C_{AI} + C_{AM} + C_{AO} + C_{ACET} \tag{15}$$

C_{AI} and C_{AM} refer to the average amortization of the total investment cost and maintenance cost of equipment in the whole life cycle of the system. The calculation formulas are (16) and (17).

$$C_{AI} = CRF \cdot \sum_{n=1}^{N} NC_n \cdot C_n \tag{16}$$

$$C_{AM} = \beta \cdot \sum_{n=1}^{N} NC_n \cdot C_n \tag{17}$$

where, NC_n is the nominal capacity of the nth equipment in the system, kW; C_n is the initial capital investment cost of the nth equipment, USD; β is the proportion between annual maintenance cost and initial investment cost of each equipment in the system, %; CRF is the capital recovery factor. The calculation method is as follows:

$$CRF = \frac{r(1+r)^y}{(1+r)^y - 1} \tag{18}$$

where r is the interest rate, and the value is 6%; y is the service life (years) of each equipment in the system.

C_{AO} refers to the cost of fuel consumed by system equipment, such as hydrogen consumed by hydrogen fuel cells, and the cost of purchasing electricity from external power grids. The calculation equation is as follows:

$$C_{AO} = \sum_{t=1}^{8760} \left(E_{grid}^{t} EC_{e}^{t} + F_{H_2}^{t} EC_{H_2}^{t} \right) \tag{19}$$

where, E_{grid}^{t} is the electricity purchased in t hours, kWh; $F_{H_2}^{t}$ is the amount of hydrogen consumed in t hours, kWh; EC_{e}^{t} and $EC_{H_2}^{t}$ are the energy price of electricity and hydrogen in t hours, USD/kWh.

C_{ACET} refers to the cost of carbon emissions generated by the energy supply of the energy system every year. The trading price of carbon (p_{ct}) is the price paid by users through the purchase and sale of carbon emission rights. It takes carbon emission rights as a commodity and forms carbon emission rights trading, referred to as carbon trading. This is an effective way to reduce carbon emissions and a cost–effective way to guide the economy towards a greener future. The calculation equation is as follows:

$$C_{ACET} = CE \times p_{ct} \tag{20}$$

Among them, C_{ACET} is the carbon emission cost, USD; CE is carbon emissions (ton); p_{ct} is the carbon trading price, USD/ton, where buying is positive and selling is negative.

3.5.2. Cost–Benefit Analysis Model of Energy System

The economic evaluation indicators for energy system projects are based on the project plan and external data, including detailed statistics of external energy demand, reasonable and comprehensive calculation of various investment costs, calculation of fuel costs, electricity price income, and heat (cold) sales income based on actual prices. On this basis, appropriate evaluation indicators are selected to calculate the profitability of the project. Evaluate the investment return of the project through a 'Cost–Benefit Analysis' of the energy system.

(1) Investment payback period [44,45]

The investment payback period can be divided into a static investment payback period and a dynamic investment payback period.

The static investment payback period is the time required to recover all investments from the project's net income without considering the time value of funds. The main objects of static analysis are the project's investment profitability, capital profitability, static payback period, etc.

$$\sum\nolimits_{t=0}^{T_s} (B_t - C_t) = 0 \tag{21}$$

Among them, t is the number of years after the project investment; T_s is static investment payback period; B_t is cash inflow of energy system projects in year t; C_t is the cash outflow from energy system projects in year t.

The dynamic analysis method is used to calculate the economic benefits of the project; that is, the reciprocal (discount) of compound interest is used to convert the benefits and costs within the project life cycle into the present value, and compare the present value of benefits and costs. The economic evaluation indicators used include a dynamic investment payback period (T_p), financial net present value (NPV), and internal rate of return (IRR).

The calculation formula for the dynamic investment payback period (T_p):

$$\sum_{t=0}^{T_p} \frac{B_t - C_t}{(1 + i_c)^t} = 0 \tag{22}$$

Among them, T_p is the dynamic investment payback period; i_c is the industry's benchmark discount rate.

(2) Net present value (*NPV*)

Net present value (*NPV*) [46,47] is the most commonly used dynamic economic evaluation indicator. The calculation method is to discount the net cash flow of each year at a certain interest rate to the sum of the present value at the same time (usually at the beginning). The calculation formula for net present value is as follows:

$$NPV = \sum\nolimits_{t=0}^{T} \frac{B_t - C_t}{(1 + i_c)^t} \tag{23}$$

Among them, T is the number of years of project life.

When using the net present value calculation method to measure the project value, there are three situations as follows:

When the $NPV > 0$, it indicates that the income from the development of the project is greater than the cost. Not only can the loan be repaid but profit can also be obtained. It indicates that there is no risk and the project can be launched.

When the $NPV = 0$, it indicates that the development of the project just achieves the benefits of the expected rate of return on investment. The income and expenditure are balanced, and only the interest can be paid, but there is no profit, which is worth investigating further.

When the $NPV < 0$, it indicates that the project cannot reach the interest rate of the expected rate of return on investment, there is no profit, there is risk, and the project cannot be launched.

(3) Internal rate of return (*IRR*)

Internal rate of return (*IRR*) [47] refers to the corresponding discount rate when the net present value is zero. The financial internal rate of return is the discount rate when the sum of the present values of the financial net cash flows of each year in the whole calculation period of the project is equal to zero. From an economic point of view, at the end of the life of the project, the discount rate at which the investment is fully recovered is the internal rate of return. In other words, before the end of the project's lifespan, if the interest rate $i = IRR$ is calculated, there will always be uncollected investments in the project, and at the end of the lifespan, all investments will be recovered. The mathematical formula is as follows:

$$\sum_{i=1}^{t} \frac{B_t - C_t}{(1 + IRR)^t} = 0 \tag{24}$$

The calculation result of the internal rate of return (*IRR*) has three situations:

When *IRR* = opportunity cost of funds (a standard investment return rate determined in advance, such as 12%, etc.), it indicates that the profitability of the project is equal to the level of investment profitability determined by us, and the project is acceptable.

When *IRR* > opportunity cost of funds, it indicates that the profitability of the project is relatively high, that is, higher than the standard return on investment (12%) level specified by us, and the project is desirable.

When *IRR* < opportunity cost of funds, it indicates that the profitability of this project cannot reach the profitability level specified by us, and this project is not advisable.

4. Case Study

4.1. Research Subjects

This paper takes a hydrogen refueling station in Shanghai as an example to study the economy and feasibility of a photovoltaic hydrogen refueling station. The hydrogen refueling capacity of this refueling station is 500 kg/day, which can meet the hydrogen demand of four heavy–duty trucks, five logistics vehicles, eight buses, two medium–capacity buses, and two passenger cars. The hydrogen gas in the hydrogen refueling station mainly comes from a hydrogen source point 100 km away and is transported by a long tube trailer, the hydrogen refueling process is shown in Figure 6.

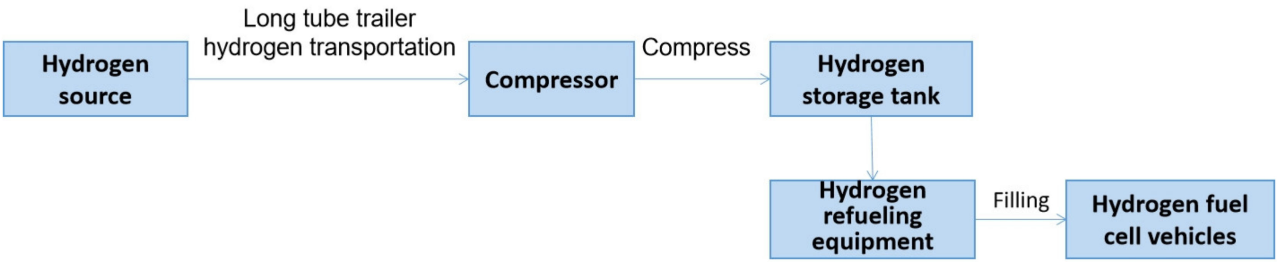

Figure 6. Hydrogen refueling process of hydrogen refueling station.

At present, in order to improve the economic and social benefits of the hydrogen refueling station, a deep green transformation is carried out. Due to the limitation of the available area of the hydrogen refueling station, a portion of the hydrogen in the transformed station still comes from long–distance trailer transportation, and a portion comes from photovoltaic and municipal electricity hydrogen production (as shown in Figure 7), which is a combination of photovoltaic hydrogen production and external hydrogen supply [14].

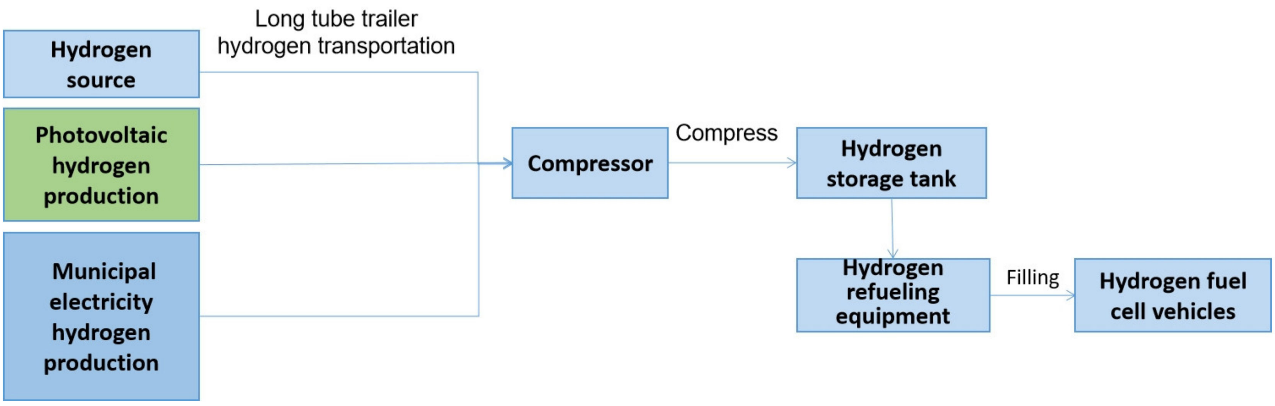

Figure 7. Hydrogen refueling process of photovoltaic hydrogen refueling station.

4.2. Hydrogen Load Analysis

Based on the gas carrying capacity of long tube trailers and the available area of hydrogen refueling stations, the daily hydrogen source of 500 kg is divided into 350 kg/day for long tube trailer transportation and 150 kg/day for photovoltaic and municipal electricity hydrogen production. Based on the analysis in Section 2.2, this paper takes the full–day hydrogen refueling demand curve of the Anting hydrogen refueling station in Shanghai as a reference, so the hydrogen demand curve is shown in Figure 8.

4.3. Equipment Composition

The photovoltaic hydrogen refueling station includes a hydrogen refueling station system, a long tube trailer, a photovoltaic power generation system, an electrolytic cell system, etc. The parameters of each equipment are shown in Tables 5–8:

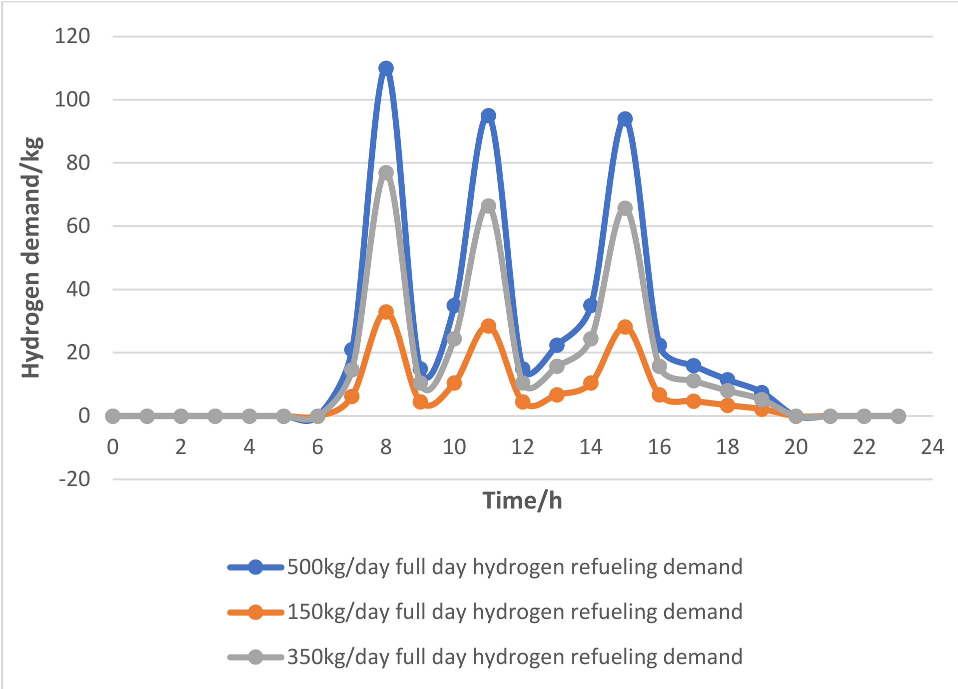

Figure 8. Hydrogen demand curve for a full day.

Table 5. Hydrogen refueling station system parameters.

Parameter	Value
Daily hydrogen refueling capacity	500 kg
Filling pressure	35 MPa
Full–year operation	365 days
Rated heating power	700 kW
Equipment procurement and installation costs	USD 1,660,000
Land and civil engineering costs	USD 420,000
Equipment depreciation	15 years
Land and housing	30 years
Annual management maintenance and labor costs	USD 280,000

Table 6. Long tube trailer parameters.

Parameter	Value
Full load hydrogen mass	350 kg
Residual rate of hydrogen gas in the tube bundle	20%
Average trailer speed per hour	50 km/h
Fuel consumption per 100 km	25 L
Trailer hydrogen charging and unloading time	5 h
Annual maintenance costs	USD 58,000
Equipment depreciation	15 years

Table 7. Photovoltaic power generation system parameters.

Parameter	Value
Installed capacity	1070 kW
Unit cost of equipment	0.388 USD/W
Civil and installation costs	USD 210,000
Equipment depreciation period	25 years
Depreciation period for civil engineering and installation	30 years
Annual maintenance costs	USD 42,000

Table 8. Electrolytic cell system parameters.

Parameter	Value
Electrolytic cell cost	USD 630,000
Civil engineering and equipment installation	USD 210,000
Equipment depreciation period	10 years
Depreciation period for civil engineering and installation	20 years
Annual labor and maintenance costs	USD 56,000

4.4. Economic Parameters

The commonly used economic parameters involved in this paper include electricity prices, water prices, and hydrogen prices (as shown in Table 9). Among them, the price for buying hydrogen mainly comes from industrial by–product hydrogen.

Table 9. Economic parameters [48–53].

Hydrogen price (USD/kg)	Prices for buying hydrogen	1.88
	Prices for selling hydrogen	8.7
Electricity price (USD/kWh)	Valley time	0.04
	Normal time	0.082
	Peak time	0.14
Water Price (USD/ton)		0.725
Carbon trading price (USD/ton)		8.2

5. Results and Discussion

5.1. Operation Strategy Analysis

The seasonal variation of solar energy resources in Shanghai is very obvious, as shown in Figure 9. The solar irradiance is the highest in the summer from May to August, and lowest in the winter in January, November, and December. Therefore, this paper selects three typical days from the summer, winter, spring, and autumn seasons to analyze and study the photovoltaic system's power generation. Due to the limitation of available area, the installed capacity of the photovoltaic system of the hydrogen refueling station is approximately 1070 kW, and the power generation curve is shown in Figure 10. The panels with a rated power of 585 Wp are proposed in this project. Then, to produce the required amount of electrical power, 1828 PV panels are required to be installed.

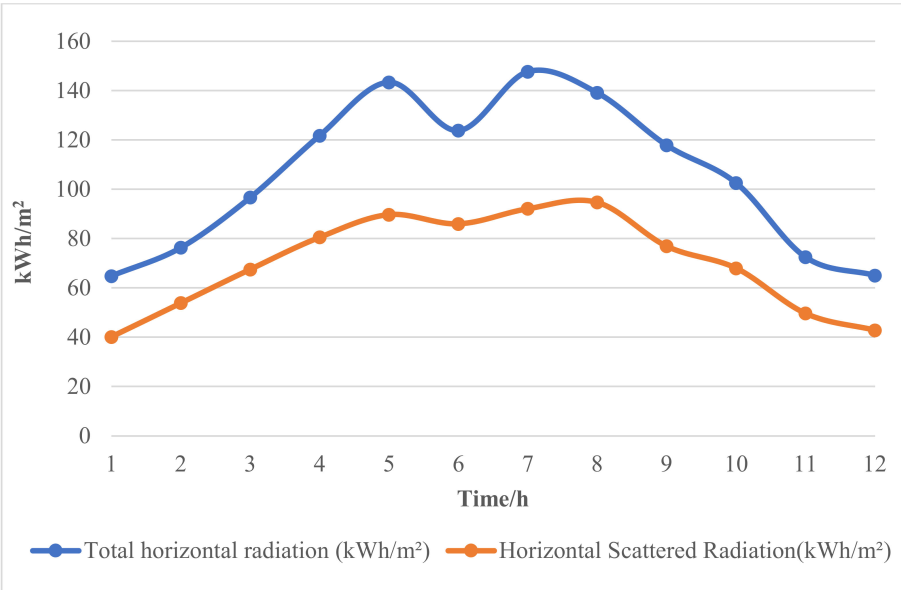

Figure 9. Monthly distribution of solar radiant intensity in Shanghai.

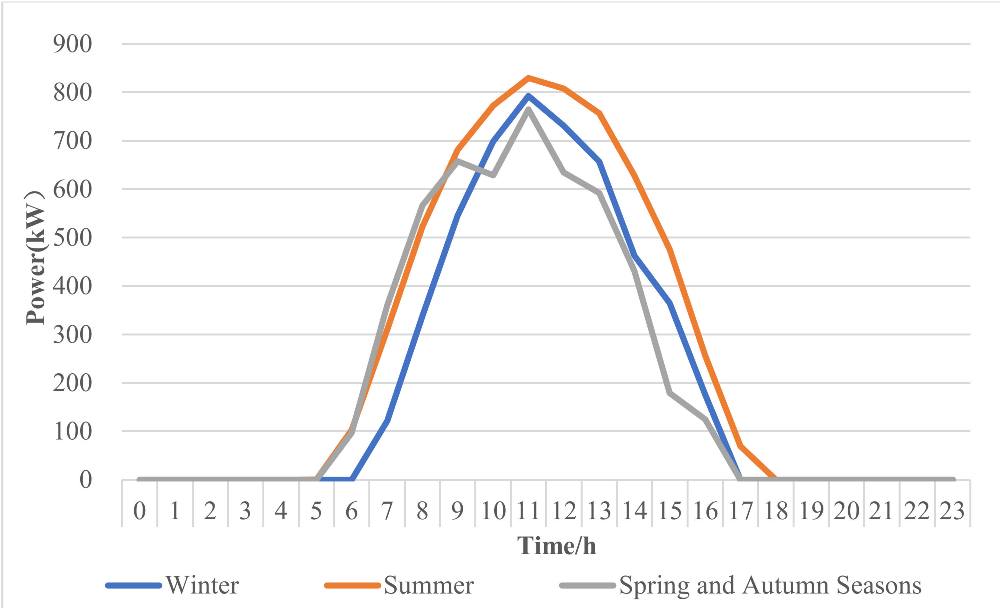

Figure 10. Typical solar volt system power generation curve.

Based on the principle of transporting hydrogen from hydrogen sources, supplementing and prioritizing the use of electrolytic hydrogen production, during summer, due to strong sunlight, the hydrogen production capacity through photovoltaic power generation can already cover the hydrogen demand, so there is no demand for municipal electricity hydrogen production (as shown in Figure 11). In winter, spring, and autumn, due to the weak sunlight intensity, some hydrogen demand needs to be met via the production of hydrogen from municipal electricity. Considering the economy and working hours, valley time electricity prices can be used to produce hydrogen at 6 a.m (as shown in Figures 12 and 13).

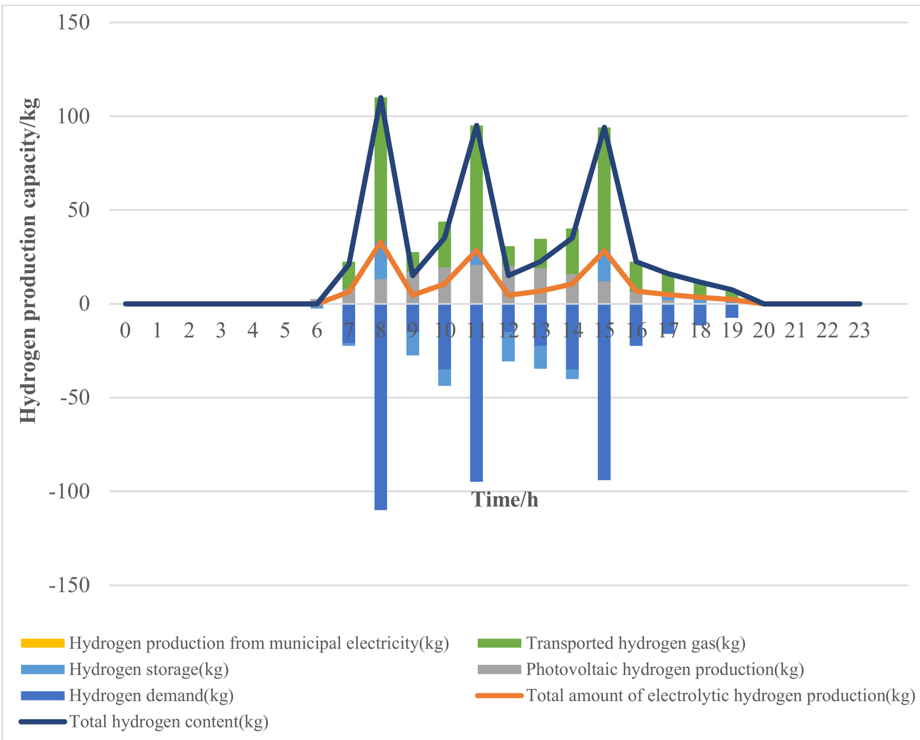

Figure 11. Typical daily hydrogen production operation curve of the photovoltaic hydrogen refueling station in summer.

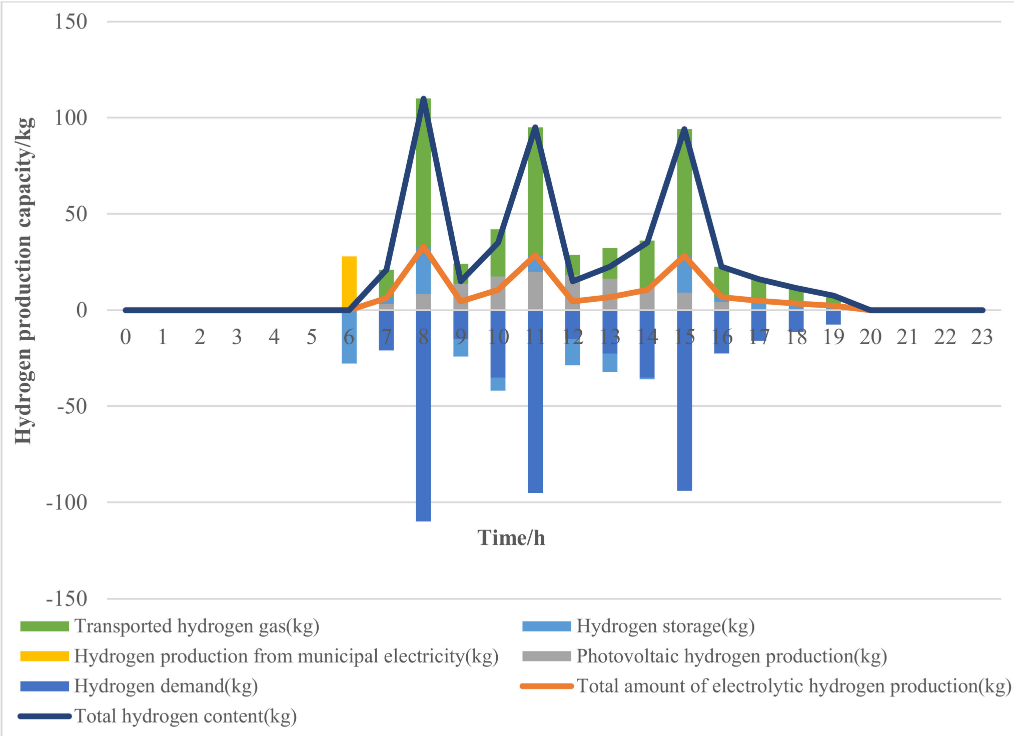

Figure 12. Typical daily hydrogen production operation curve of the photovoltaic hydrogen refueling station in winter.

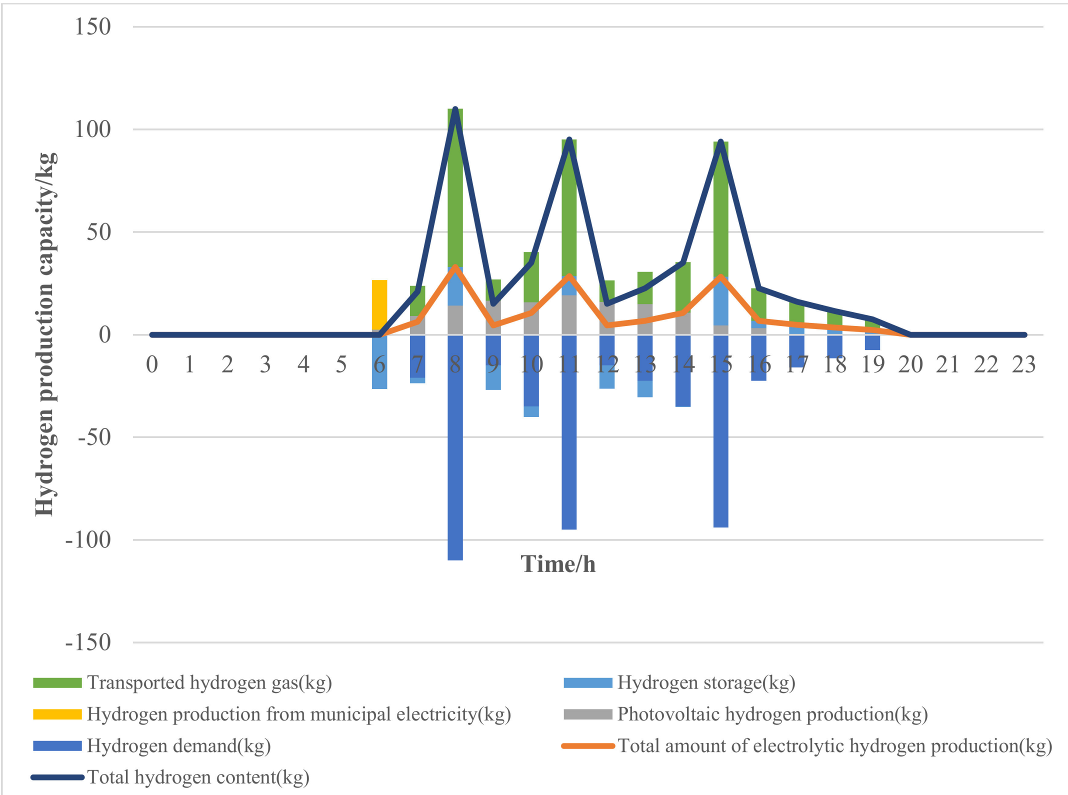

Figure 13. Typical daily hydrogen production operation curve of the photovoltaic hydrogen refueling station in spring and autumn.

5.2. Economic Analysis

The total annual costs and cost components of the hydrogen refueling station and the photovoltaic hydrogen refueling station are shown in Table 10. It can be seen that even though the annual investment cost of the photovoltaic hydrogen refueling station is higher than that of the hydrogen refueling station, the total annual cost of the photovoltaic hydrogen refueling station is lower than that of hydrogen refueling stations because the hydrogen generated is green hydrogen with no carbon emissions and carbon emission benefits.

Table 10. The annual costs of the hydrogen refueling station and the photovoltaic hydrogen refueling station.

Type of Hydrogen Refueling Station	Annual Investment Cost (USD)	Annual Operating Cost (USD)	Annual Maintenance Cost (USD)	Annual Carbon Benefits Cost (USD)	Annual Total Cost (USD)
The hydrogen refueling station	130,434.78	664,511.59	2608.6957	0	797,555.07
The photovoltaic hydrogen refueling station	230,391.88	439,340.97	4607.84	10,145.67	664,195.01

To analyze the economics of the two kinds of hydrogen refueling stations, this paper calculates the investment payback period, *NPV*, and *IRR* based on the different sale prices of hydrogen, as shown in Table 11, Figures 14 and 15.

Table 11. Cost–benefit analysis results.

Hydrogen Price (USD)	The Hydrogen Refueling Station			The Photovoltaic Hydrogen Refueling Station		
	Investment Payback Period (Year)	*NPV*	*IRR*	Investment Payback Period (Year)	*NPV*	*IRR*
1.45	/	/	/	/	/	/
2.90	/	/	/	/	/	/
4.64	44.53	−1.35	/	20.90	−0.96	3%
5.07	16.96	−0.42	4%	14.56	−0.03	6%
5.80	8.35	1.13	11%	9.67	1.51	10%
5.91	7.72	1.38	12%	9.17	1.76	10%
6.23	6.40	2.06	15%	8.05	2.44	12%
7.25	4.14	4.22	23%	5.78	4.61	17%
8.70	2.75	7.32	35%	4.13	7.70	24%
10.14	2.06	10.41	46%	3.21	10.80	30%

In terms of the investment payback period, when the selling price of hydrogen is less than USD 4.37, the hydrogen refueling station is in a loss state, and the investment payback period is negative or infinite years. When the selling price of hydrogen is less than USD 3.64, the photovoltaic hydrogen refueling station is in a loss state, and the investment payback period is negative or infinite years. When the selling price of hydrogen is higher than USD 5.07, the investment payback period of the hydrogen refueling station is within a reasonable range, but its *NPV* value is less than 0, so there is a risk in the project.

In terms of *NPV* and *IRR*, the *NPV* value of the photovoltaic hydrogen refueling station is always higher than the *NPV* value of the refueling station. When the hydrogen price is equal to or higher than USD 5.91, the *NPV* of the hydrogen refueling station project is > 0, and the *IRR* is $\geq$ 12%, and then the project has economic benefits and is feasible.

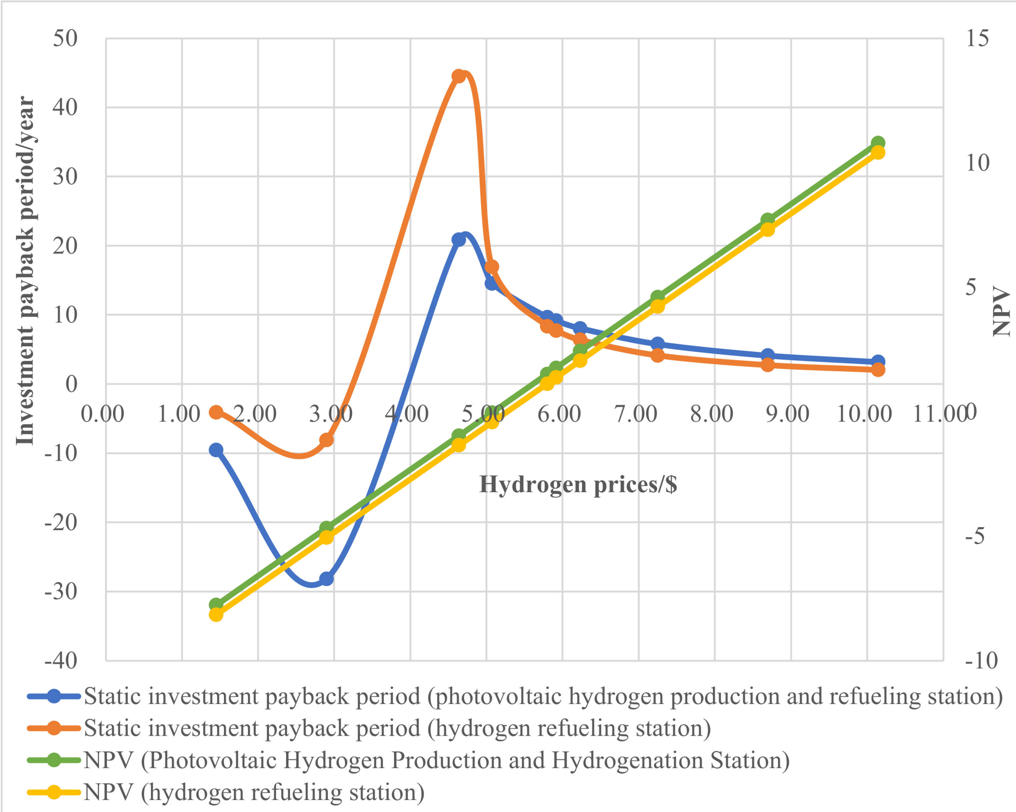

Figure 14. Comparison of static investment payback period and *NPV* between the photovoltaic hydrogen refueling station and the hydrogen refueling stations under different hydrogen prices.

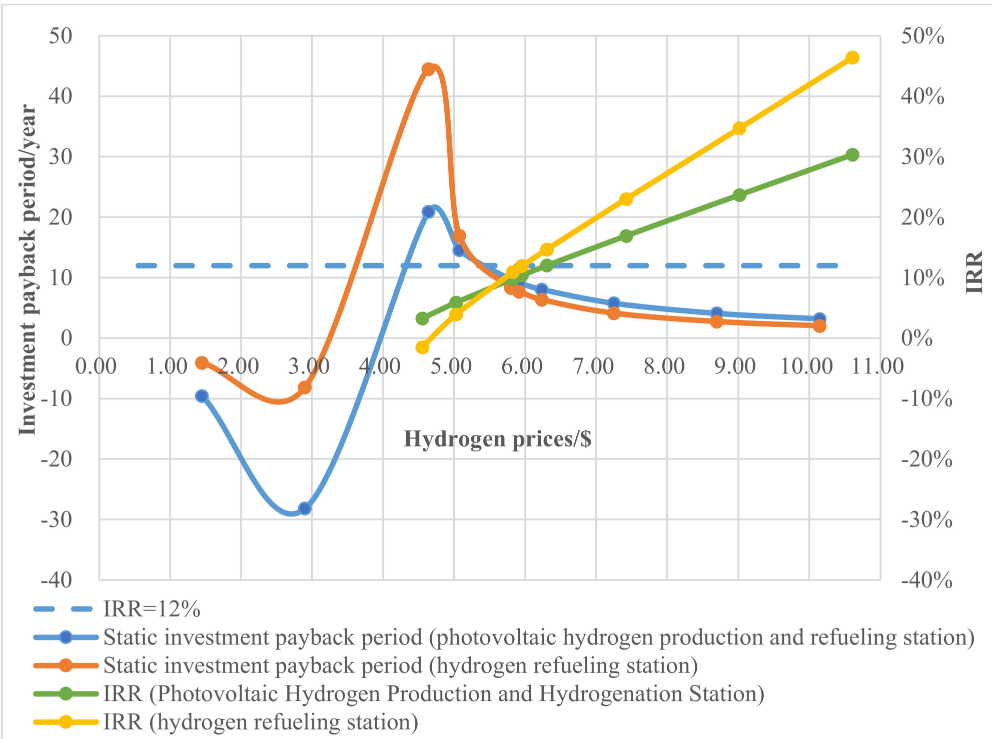

Figure 15. Comparison of static investment payback period and *IRR* between the photovoltaic hydrogen refueling station and the hydrogen refueling station under different hydrogen prices.

In terms of energy conservation and emission reduction in environmental effects, under ideal conditions, hydrogen fuel cell vehicles fueled by the hydrogen refueling station can reduce carbon emissions by approximately 2737.5 tons/year compared to traditional fuel vehicles. At the same time, based on the 1070 kW photovoltaic system configured in this paper, the annual power generation is approximately 1241 MWh, which can reduce carbon emissions by approximately 1237.28 tons/year compared to municipal electricity hydrogen production or industrial by–product hydrogen. From this, the photovoltaic hydrogen refueling station will effectively support the transformation of the transportation sector towards green and low–carbon.

6. Summary

This paper takes a hydrogen refueling station in Shanghai as the research object to study the feasibility of photovoltaic hydrogen production applied to a hydrogen refueling station. Limited by the available area and regional solar energy resources, the hydrogen source of the hydrogen refueling station in this paper is partly from long–distance trailer transportation, and partly from photovoltaic and municipal electricity hydrogen production. Compared with the hydrogen refueling station, in terms of economy, the *NPV* of the photovoltaic hydrogen refueling station is always higher than that of the hydrogen refueling station, that is, the scheme and the investment benefit of the photovoltaic hydrogen refueling station project are better. And when the hydrogen price is no less than 6.23 USD, the photovoltaic hydrogen refueling station project has economic benefits. In terms of the environment, the photovoltaic hydrogen refueling station can reduce carbon emissions by approximately 1237.28 tons per year. Therefore, the photovoltaic hydrogen refueling station will have a good application effect and prospect at an appropriate hydrogen sales price.

This paper is expected to provide a theoretical reference for the promotion and application of photovoltaic hydrogen production in hydrogen refueling stations, accelerate the promotion and application of hydrogen energy in the field of transportation, and help achieve low carbon.

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