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Potential Hydrogen Market: Value-Added Services Increase Economic Efficiency for Hydrogen Energy Suppliers

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Abstract: Hydrogen energy is a clean, zero-carbon, long-term storage, flexible and efficient secondary energy. Accelerating the development of the hydrogen energy industry is a strategic choice to cope with global climate change, achieve the goal of carbon neutrality, and realize high-quality economic and social development. This study aimed to analyze the economic impact of introducing value-added services to the hydrogen energy market on hydrogen energy suppliers. Considering the network effect of value-added services, this study used a two-stage game model to quantitatively analyze the revenue of hydrogen energy suppliers under different scenarios and provided the optimal decision. The results revealed that (1) the revenue of a hydrogen energy supplier increases only if the intrinsic value of value-added services exceeds a certain threshold; (2) the revenue of hydrogen energy suppliers is influenced by a combination of four key factors: the intrinsic value of value-added services, network effects, user scale, and the sales strategies of rivals; (3) the model developed in this paper can provide optimal decisions for hydrogen energy suppliers to improve their economic efficiency and bring more economic investment to hydrogen energy market in the future.

Keywords: hydrogen energy market; hydrogen value-added services; network effect; economic investment



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1. Introduction

In response to global climate change, dozens of countries and regions have proposed “zero-carbon” or “carbon neutral” climate goals and introduced related policies in recent years [1]. According to the forecast of the International Energy Agency, the total amount of hydrogen energy application in 2050 is expected to reach 20% of the total energy consumption, which is equivalent to replacing fossil fuels with a calorific value of 78EJ per year, corresponding to a reduction of 6 Gt of CO₂ emissions per year, equivalent to 18% of global emissions in 2019 [2]. It shows that the development of hydrogen energy is one of the effective ways to deal with climate problems and achieve “carbon peaking and carbon neutrality” [3].

As a kind of secondary energy, hydrogen energy has three main sources: fossil energy such as coal and natural gas, industrial by-product gas such as coke oven gas and Chlor-alkali tail gas, and electrolysis of water [4]. In addition, hydrogen energy can be produced by biomass energy, solar photocatalytic water splitting, and nuclear energy. Hydrogen produced by using renewable energy to power the electrolysis is also called green hydrogen, which is more environmentally sustainable. The global hydrogen market was valued at USD 187,517.3 Million in 2020, while the global hydrogen demand was around 90 Mt H₂ [5]. According to a comprehensive research report by Business Wire, green hydrogen

market was valued at USD 0.58 billion in 2020 and is projected to be worth USD 2.94 billion by 2025. Europe is the largest segment for green hydrogen market in terms of region and Asia-Pacific is the largest growing region [6]. With an installed global electrolyzer capacity of 290 MW, more than 40% is based in Europe with the next-largest capacity shares in Canada (9%) and China (8%). However, the market price of green hydrogen in the EU is now uncompetitive and stands at EUR 3.5–5.0 per kg, while China stands at 3.75–4 and the US stands at 4.00–4.25.

At present, the world's major economies are conducting research on the application of hydrogen energy technology [7,8]. Wang Yanyu, Fu Guanyun and others mainly analyzed the research in hydrogen energy in the United States, which leads the world in the hydrogen fuel cell vehicle and hydrogen refueling stations [9–11]. Xia Fengjie and others analyzed the national hydrogen energy strategy in Germany, whose main hydrogen energy layout is concentrated in the transportation, aviation, steel, and chemical industries [12]. Ding Man, Wang Lin, and others comprehensively analyzed the development of hydrogen energy applications in Japan and South Korea [13–16]. Hartly and others analyzed Australia's advantages in developing the hydrogen energy industry [17]. Andreasen and others hoped to consider approving a basket of different hydrogen energy applications and configurations to support "open" rather than "closed" innovation and development [18]. This portfolio-funding strategy enables suppliers to experiment, diversify and innovate from the ground up. The research on the hydrogen energy industry mainly focuses on green hydrogen production [19–21], hydrogen storage systems, and transportation (hydrogen fuel cell research and development and hydrogen refueling station construction). Alagan Muthurasu and others considered the importance of designing an efficient, cost-effective, and stable electrocatalyst for the water-splitting process to produce hydrogen [22,23]. Huo Xianxu and others summarized the key technologies of existing hydrogen storage systems [24]. Wan Chao and others provided a novel and efficient strategy for designing efficient catalysts to drive the hydrogen evolution from Formic acid [25]. Ren Zhuanghe and others presented recent research progress of hydrogen storage properties of NaAlH_4 modified by Ti-based catalysts [26]. Burkhardt and others considered the specific environmental impact to produce, compress, and transport hydrogen and conducted a life cycle assessment of the hydrogen refueling station built and operated in Berlin [27]. Calculation results revealed that using the generated hydrogen for power can reduce greenhouse gas emissions by 86–89%. Xu Shisen and others made a general analysis of the main types of hydrogen as a fuel in the power industry [28,29]. Compared with other forms of energy, hydrogen does not have a comparative advantage economically for the time being due to the expensive production cost [30]. In the future, with the large-scale development of renewable energy construction projects dominated by wind and light, electrolysis of green hydrogen will become the main source of hydrogen energy [31,32]. Hosseini and others pointed out that since the cost of electricity plays a critical role in the price of hydrogen, to generate carbon-free hydrogen from solar and wind energy at a price competitive with fossil fuels, the cost of electricity should be four times lower than the retail price of electricity [33,34].

The China Hydrogen Energy Alliance predicts that hydrogen energy will account for about 10% of China's energy system by 2050, with an annual economic output of more than 10 trillion yuan [35]. However, hydrogen energy production and consumption at the commercial level has not yet been formed. In addition to technical reasons, the lack of investment in hydrogen industry is the main reason at the economic level, and the key is that there is no hydrogen energy market yet, thus no effective market incentive can be formed. Therefore, this paper considers the introduction of value-added services in the hydrogen energy market, such as recycling of hydrogen fuel cells, retrofitting of hydrogen energy equipment, and consulting services, in order to improve the economic efficiency of hydrogen energy suppliers and to activate the hydrogen energy investment market. Value-added services were first originated from the telecommunication industry in the 1980s. Soinio and others argued that with the increase of service types and the improvement of service theoretical framework in the previous service models of SMEs, value-added

services should also become a separate service system for in-depth analysis [36]. Dan Bin and others discussed the competition of value-added services from the perspective of channel supply chain and concluded that providing differentiated value-added services to customers has now become an emerging field of competition among enterprises, which can effectively expand the market demand [37–39]. Dou Guowei and others argued that unilateral investment can affect the utility of users and thus the demand and profit of the platform when considering the network externalities of the market [40–42]. Therefore, the importance of value-added services is self-evident for emerging markets, and it will be of great significance to analyze the role of value-added services in the hydrogen energy market.

2. Methodology

2.1. Model Structure

Since the hydrogen energy market is an emerging market, there are no specific regulations in terms of market entry rules and trading mechanisms. As shown hypothetically in Figure 1:

- (1) There are only hydrogen energy suppliers A and B in the hydrogen energy market, and both suppliers are capable of providing hydrogen energy and value-added services. The market always has positive demand for suppliers A and B, which means it is fully covered by suppliers A and B at all times.
- (2) The hydrogen energy of the two suppliers is homogeneous. The intrinsic value of hydrogen energy is v , but the marginal cost $c_{pi}(i = A, B)$ and the intrinsic value $m_i(i = A, B)$ of value-added services are different. The marginal cost of value-added services is c_f , the same for suppliers A and B.
- (3) The value-added services need to be bundled with hydrogen energy, which means the value-added services are not compatible.
- (4) Because the intrinsic value of value-added services is different, consumers with different preferences will make their own choices. Two suppliers are assumed to be located at two ends of a Hotelling line of length 1, that is, $x_A = 0, x_B = 1$, and x is a random variable uniformly distributed within the line, representing the degree of consumer preference [43]. When products or services fail to meet consumers' expectations, the utility loss will occur. Assuming that the unit utility loss is t , the utility loss for the consumer with preference x who chooses supplier A is $t(x - 0)$, and $t(1 - x)$ for consumers who chooses supplier B. Here, t also represents consumers' sensitivity to differences in services [44].
- (5) The total consumer number of hydrogen energy is N . The demand for hydrogen energy and value-added services is in unit demand.

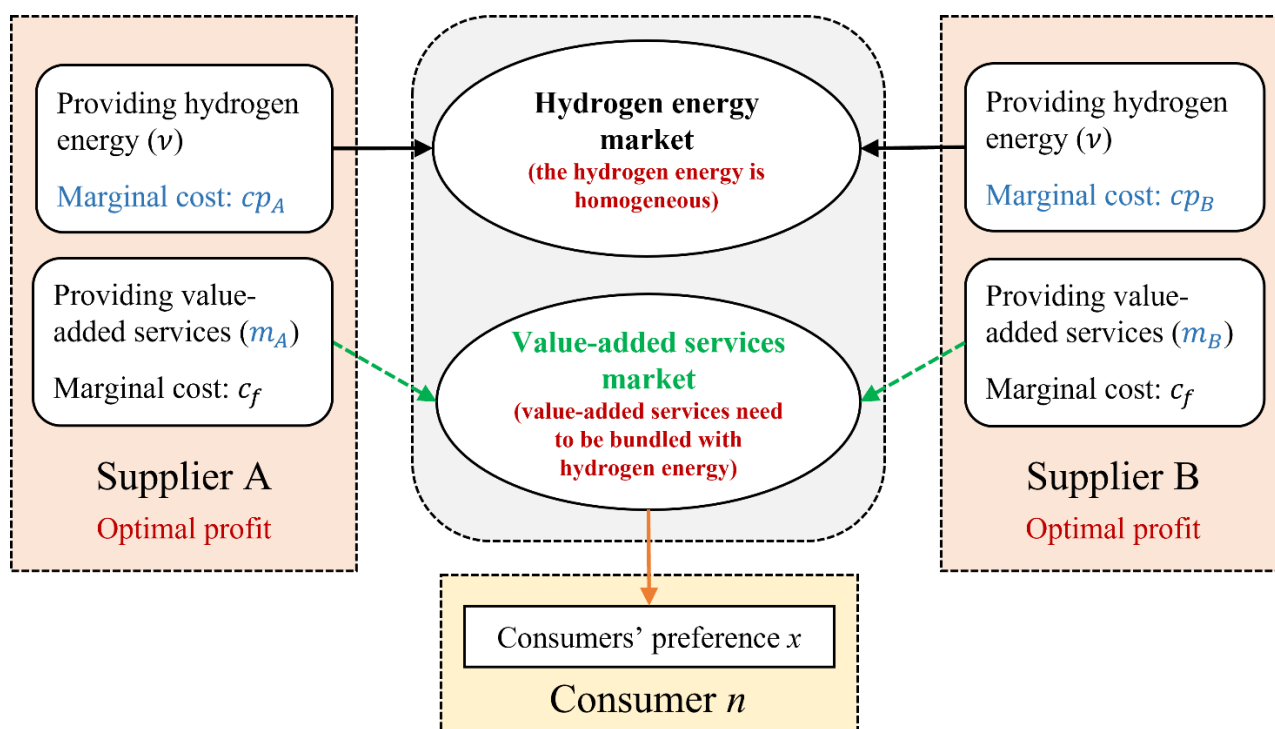


Figure 1. Model structure.

2.2. Sales Strategy

In the hydrogen energy market, hydrogen energy suppliers A and B independently decide to provide value-added services. They implement the pricing strategies through a two-stage game model.

In the first stage, the two hydrogen energy suppliers simultaneously choose the sales strategy to provide value-added services. Therefore, the following four strategy situations will emerge, as shown in Table 1. SS situation: the two hydrogen energy suppliers both provide value-added services. SN situation: supplier A provides value-added services while supplier B does not. NS situation: supplier A does not provide value-added services while supplier B does. NN situation: neither supplier A nor B provides value-added services.

Table 1. Four strategy situations.

	A Provides Value-Added Services	B Provides Value-Added Services
NN	No	No
NS	No	Yes
SN	Yes	No
SS	Yes	Yes

In the second stage, hydrogen energy suppliers determine the optimal pricing of the products and services on the premise of a determined sales strategy. Here, we use the backward induction to determine the sales strategy and the optimal pricing of hydrogen energy and value-added services when the profit is maximized.

2.3. Model Formulation

2.3.1. Consumer Utility Functions

The utility of a hydrogen energy consumer depends on the intrinsic value of hydrogen energy and the value of value-added services. The intrinsic value of hydrogen energy v is the utility consumers obtain when purchasing hydrogen energy. The value of value-added

services consists of two parts. One is the intrinsic value of the value-added service m_i , which is not affected by the purchasing behavior of other consumers. The other is the network effect u_i , whose value depends on the number of people already connected to that network.

In addition, consumers' utility is also related to their preferences and the pricing of hydrogen energy. Based on the analysis above, the utility function of hydrogen energy consumers is obtained as follows:

$$U_A^j = v + \lambda(m_A + u_A N_A) - p_A^j - t(x - 0) \quad (1)$$

$$U_B^j = v + \lambda(m_B + u_B N_B) - p_B^j - t(1 - x) \quad (2)$$

where λ is 0 or 1. $\lambda = 0$ corresponds to the case where the consumer only purchases hydrogen energy, and $\lambda = 1$ corresponds to the case where the consumer simultaneously purchases hydrogen energy and value-added services. N_A and N_B represent the total number of suppliers A and B' users respectively, $N_A + N_B = N$. p_A^j and p_B^j are the pricing of suppliers A and B under the strategy situation $j(j = \text{NN, NS, SN, SS})$, respectively.

2.3.2. Demand and Profit Functions

The consumer preferences indifference point can be calculated based on the consumer utility function. Let $U_A^j(x) = U_B^j(x)$, and we can get a new variable $\hat{x}(N_A)$ representing that the consumer with preference x achieves the same utility value. Further analysis shows that x describes the distribution of consumer preferences and indicates the ratio of consumers who chose supplier A to all consumers [45]. It means that x represents the market share of supplier A, while $(1 - x)$ represents the market share of supplier B. The preference indifference points in the four strategy situations are different, which can be calculated separately by the equation of $U_A^j(x) = U_B^j(x)$. N_A also represents the market demand for supplier A, so we can get $N_A = N\hat{x}(N_A)$, thus getting the demand function $N_A(\cdot)$. Similarly, the demand function $N_B(\cdot)$ of supplier B can also be deduced. We take the SS strategy situation as an example.

The consumer utility functions are as follows:

$$u_A^{SS} = v + m_A + u_A N_A - t\hat{x} - p_A^{SS} \quad (3)$$

$$u_B^{SS} = v + m_B + u_B N_B - t(1 - \hat{x}) - p_B^{SS} \quad (4)$$

Let $u_A^{SS}(\hat{x}) = u_B^{SS}(\hat{x})$, we can get:

$$\hat{x}_{SS}(N_A, N_B) = \frac{t + m_A - m_B + u_A N_A - u_B N_B - p_A^{SS} + p_B^{SS}}{2t} \quad (5)$$

$$N_A = N\hat{x}_{SS}(N_A, N_B) \quad (6)$$

Suppose that the market is completely covered by suppliers A and B, so we have $N_B = N - N_A$. Therefore, the demand function N_A^{SS} and N_B^{SS} can be derived.

$$N_A^{SS} = \frac{N(t - u_B N + m_A - m_B - p_A^{SS} + p_B^{SS})}{2t - N(u_A + u_B)} \quad (7)$$

$$N_B^{SS} = \frac{N(t - u_A N - m_A + m_B + p_A^{SS} - p_B^{SS})}{2t - N(u_A + u_B)} \quad (8)$$

Similarly, the demand functions of suppliers A and B in the four strategy situations can be derived. The results are shown in Table 2.

Table 2. Demand functions.

	Demand Function of Supplier A	Demand Function of Supplier B
NN	$\frac{N(3t - c_{pA} + c_{pB})}{6t}$	$\frac{N(3t + c_{pA} - c_{pB})}{6t}$
NS	$\frac{N(t - m_B - u_B N - p_A^{NS} + p_B^{NS})}{2t - u_B N}$	$\frac{N(t + m_B + p_A^{NS} - p_B^{NS})}{2t - u_B N}$
SN	$\frac{N(t + m_A - p_A^{SN} + p_B^{SN})}{2t - u_A N}$	$\frac{N(t - m_A - u_A N + p_A^{SN} - p_B^{SN})}{2t - u_A N}$
SS	$\frac{N(t - u_B N + m_A - m_B - p_A^{SS} + p_B^{SS})}{2t - N(u_A + u_B)}$	$\frac{N(t - u_A N - m_A + m_B + p_A^{SS} - p_B^{SS})}{2t - N(u_A + u_B)}$

Based on the pricing and demand functions, the profit functions of the two suppliers in the four strategy situations can be derived. The results are shown in Table 3.

Table 3. Profit functions.

	Profit Function of Supplier A	Profit Function of Supplier B
NN	$\pi_A^{NN} = N_A^{NN}(p_A^{NN} - c_{pA})$	$\pi_B^{NN} = N_B^{NN}(p_B^{NN} - c_{pB})$
NS	$\pi_A^{NS} = N_A^{NS}(p_A^{NS} - c_{pA})$	$\pi_B^{NS} = N_B^{NS}(p_B^{NS} - c_{pB} - c_f)$
SN	$\pi_A^{SN} = N_A^{SN}(p_A^{SN} - c_{pA} - c_f)$	$\pi_B^{SN} = N_B^{SN}(p_B^{SN} - c_{pB})$
SS	$\pi_A^{SS} = N_A^{SS}(p_A^{SS} - c_{pA} - c_f)$	$\pi_B^{SS} = N_B^{SS}(p_B^{SS} - c_{pB} - c_f)$

2.3.3. Optimal Pricing and Profit Functions

We first derive the optimal pricing under the four sales strategy situations using the backward induction method. The optimal pricing under different strategies is different, but the deduction process is similar. We take the SS strategy situation as an example to derive the optimal pricing and optimal profit.

According to the profit function, the optimal profits of the two suppliers are as follows:

$$\max \pi_A^{SS} = N_A^{SS}(p_A^{SS} - c_{pA} - c_f) \quad (9)$$

$$\max \pi_B^{SS} = N_B^{SS}(p_B^{SS} - c_{pB} - c_f) \quad (10)$$

We can derive the partial derivatives with respect to p_A^{SS} and p_B^{SS} in Equations (9) and (10), respectively. Let $\frac{\partial \pi_A^{SS}}{\partial p_A^{SS}} = 0$, $\frac{\partial \pi_B^{SS}}{\partial p_B^{SS}} = 0$, and we can derive the optimal pricing p_{A*}^{SS} and p_{B*}^{SS} of the two suppliers.

$$p_{A*}^{SS} = \frac{3t + 3c_f - N(u_A + 2u_B) + m_A - m_B + 2c_{pA} + c_{pB}}{3} \quad (11)$$

$$p_{B*}^{SS} = \frac{3t + 3c_f - N(2u_A + u_B) - m_A + m_B + c_{pA} + 2c_{pB}}{3} \quad (12)$$

Then we find $\frac{\partial^2 \pi_A^{SS}}{\partial p_A^{SS2}} \Big|_{p_A^{SS}=p_{A*}^{SS}} < 0$, $\frac{\partial^2 \pi_B^{SS}}{\partial p_B^{SS2}} \Big|_{p_B^{SS}=p_{B*}^{SS}} < 0$, which means the maximum exists.

Therefore, p_{A*}^{SS} and p_{B*}^{SS} are the optimal pricing of the two suppliers.

We can obtain the optimal profit by substituting the optimal pricing (Equations (11) and (12)) into the profit function (Equations (9) and (10)). The optimal profits are as follows:

$$\pi_A^{SS} = \frac{N(3t - N(u_A + 2u_B) + m_A - m_B - c_{pA} + c_{pB})^2}{9(2t - N(u_A + u_B))} \quad (13)$$

$$\pi_B^{SS} = \frac{N(3t - N(2u_A + u_B) - m_A + m_B + c_{pA} - c_{pB})^2}{9(2t - N(u_A + u_B))} \quad (14)$$

Similarly, the optimal pricing and the optimal profit under the four strategy situations can be derived. The results are shown in Tables 4 and 5.

Table 4. The optimal pricing functions.

	The Optimal Pricing of Supplier A	The Optimal Pricing of Supplier B
NN	$\frac{3t+2c_{pA}+c_{pB}}{3}$	$\frac{3t+c_{pA}+2c_{pB}}{3}$
NS	$\frac{3t+c_f-2u_B N-m_B+2c_{pA}+c_{pB}}{3}$	$\frac{3t+2c_f-u_B N+m_B+c_{pA}+2c_{pB}}{3}$
SN	$\frac{3t+2c_f-u_A N+m_A+2c_{pA}+c_{pB}}{3}$	$\frac{3t+c_f-2u_A N-m_A+c_{pA}+2c_{pB}}{3}$
SS	$\frac{3t+3c_f-N(u_A+2u_B)+m_A-m_B+2c_{pA}+c_{pB}}{3}$	$\frac{3t+3c_f-N(2u_A+u_B)-m_A+m_B+c_{pA}+2c_{pB}}{3}$

Table 5. The optimal profit functions.

	The Optimal Profit of Supplier A	The Optimal Profit of Supplier B
NN	$\frac{N(3t-c_{pA}+c_{pB})^2}{18t}$	$\frac{N(3t+c_{pA}-c_{pB})^2}{18t}$
NS	$\frac{N(3t+c_f-2u_B N-m_B-c_{pA}+c_{pB})^2}{9(2t-u_B N)}$	$\frac{N(3t-c_f-u_B N+m_B+c_{pA}-c_{pB})^2}{9(2t-u_B N)}$
SN	$\frac{N(3t-c_f-u_A N+m_A-c_{pA}+c_{pB})^2}{9(2t-u_A N)}$	$\frac{N(3t+c_f-2u_A N-m_A+c_{pA}-c_{pB})^2}{9(2t-u_A N)}$
SS	$\frac{N(3t-N(u_A+2u_B)+m_A-m_B-c_{pA}+c_{pB})^2}{9(2t-N(u_A+u_B))}$	$\frac{N(3t-N(2u_A+u_B)-m_A+m_B+c_{pA}-c_{pB})^2}{9(2t-N(u_A+u_B))}$

3. Model Discussion

3.1. Application Scenarios

According to the optimal profit functions shown in Table 4, under the NN strategy situation, the optimal profit is independent of the intrinsic value of value-added services and the network effect of value-added services, so it is not overly analyzed. Generally, it is considered that the network effect of value-added services is different among suppliers. However, the same network effect of value-added services should be considered when the two suppliers provide value-added services. Therefore, four scenarios in Table 6 will be discussed.

Table 6. Application scenarios.

Scenarios	A Provides Value-Added Services	B Provides Value-Added Services	The Network Effect of Value-Added Services Is the Same
S ₁	Yes	Yes	No
S ₂	Yes	No	No
S ₃	No	Yes	No
S ₄	Yes	Yes	Yes

3.2. Influencing Factors for Optimal Profits

The equivalent constraints of Assumption (1) can be obtained based on the above calculation results as follows:

$$-3t + N(u_i + 2u_j) + c_{pi} - c_{pj} < m_i - m_j < 3t - N(2u_i + u_j) + c_{pi} - c_{pj} \quad (15)$$

$$c_f - 3t + u_i N + c_{pi} - c_{pj} < m_i < 3t - 2u_i N + c_f + c_{pi} - c_{pj} (i, j = A, B, i \neq j) \quad (16)$$

$$|c_{pi} - c_{pj}| < 3t \quad (17)$$

$$2t > N(u_A + u_B) \quad (18)$$

where Equations (15)–(17) are positive demand constraints, corresponding to the cases where both suppliers provide value-added services, only one supplier provides value-added services, and neither supplier provides value-added services, respectively. Equation (18) is an additional constraint to Equations (15) and (16) to prevent the occurrence of an empty set.

3.2.1. Network Effects

1. Under scenario S_1 , we take the supplier A as an example:

$$\begin{aligned}\frac{\partial \pi_A^{SS}}{\partial u_A} &= \frac{\partial}{\partial u_A} \frac{N(3t - N(u_A + 2u_B) + m_A - m_B - c_{pA} + c_{pB})^2}{9(2t - N(u_A + u_B))} \\ &= -N_A^{SS} \frac{N(t - m_A + m_B - u_A N + c_{pA} - c_{pB})}{3(2t - N(u_A + u_B))}\end{aligned}\quad (19)$$

where N_A^{SS} is always positive, and $2t - N(u_A + u_B) > 0$. If and only if $m_A > m_B + t - u_A N + c_{pA} - c_{pB}$, $\frac{\partial \pi_A^{SS}}{\partial u_A} > 0$.

$$\begin{aligned}\frac{\partial \pi_A^{SS}}{\partial u_B} &= \frac{\partial}{\partial u_B} \frac{N(3t - N(u_A + 2u_B) + m_A - m_B - c_{pA} + c_{pB})^2}{9(2t - N(u_A + u_B))} \\ &= -N_A^{SS} \frac{N(5t - m_A + m_B - N(3u_A + 2u_B) + c_{pA} - c_{pB})}{3(2t - N(u_A + u_B))}\end{aligned}\quad (20)$$

where N_A^{SS} is always positive. We next discuss $5t - m_A + m_B - N(3u_A + 2u_B) + c_{pA} - c_{pB}$. According to Equation (15), we know that $3t - N(2u_A + u_B) + c_{pA} - c_{pB} - m_A + m_B > 0$, and $[5t - m_A + m_B - N(3u_A + 2u_B) + c_{pA} - c_{pB}] - [3t - N(2u_A + u_B) + c_{pA} - c_{pB} - m_A + m_B] = 2t - N(u_A + u_B) > 0$, so $\frac{\partial \pi_A^{SS}}{\partial u_B} < 0$ always holds.

Similarly, $\frac{\partial \pi_B^{SS}}{\partial u_A}$ and $\frac{\partial \pi_B^{SS}}{\partial u_B}$ can be derived.

Therefore, we can get Result 1: Under the market equilibrium of scenario S_1 where both suppliers provide value-added services, when $m_A > m_B + t - u_A N - (c_{pB} - c_{pA})$, the profit of supplier A increases as the network effect of supplier A's value-added services u_A increases, while the profit of supplier B always decreases as u_A increases. When $m_B > m_A + t - u_B N - (c_{pA} - c_{pB})$, the profit of supplier B increases as the network effect of supplier B's value-added services u_B increases, while the profit of supplier A always decreases as u_B increases.

2. For scenarios S_2 and S_3 , we take S_2 as an example:

$$\begin{aligned}\frac{\partial \pi_A^{SN}}{\partial u_A} &= \frac{\partial}{\partial u_A} \frac{N(3t - c_f - u_A N + m_A - c_{pA} + c_{pB})^2}{9(2t - u_A N)} \\ &= N_A^{SN} \frac{N(-t + u_A N - c_f + m_A - c_{pA} + c_{pB})}{3(2t - u_A N)}\end{aligned}\quad (21)$$

where N_A^{SN} is always positive. If and only if $m_A > c_f + t - u_A N + c_{pA} - c_{pB}$, $\frac{\partial \pi_A^{SN}}{\partial u_A} > 0$.

$$\begin{aligned}\frac{\partial \pi_B^{SN}}{\partial u_A} &= \frac{\partial}{\partial u_A} \frac{N(3t + c_f - 2u_A N - m_A + c_{pA} - c_{pB})^2}{9(2t - u_A N)} \\ &= N_B^{SN} \frac{N(-5t + 2u_A N + c_f - m_A + c_{pA} - c_{pB})}{3(2t - u_A N)}\end{aligned}\quad (22)$$

From Equation (18), we know that $2t - u_A N > 0$. From Equation (16), we know that $-3t + u_A N + c_f - m_A + c_{pA} - c_{pB} < 0$. Additionally, $(-5t + 2u_A N + c_f - m_A + c_{pA} - c_{pB}) - (-3t + u_A N + c_f - m_A + c_{pA} - c_{pB}) = -2t + u_A N < 0$, so $\frac{\partial \pi_B^{SN}}{\partial u_A} < 0$.

Therefore, we can get Result 2: Under the market equilibrium of scenario S_2 where only supplier A provides value-added services, when $m_A > c_f + t - u_A N - (c_{pB} - c_{pA})$, the profit of supplier A increases as the network effect of supplier A's value-added services u_A increases, while the profit of supplier B always decreases as u_A increases.

The Result 3 can also be drawn: Under the market equilibrium of scenario S_3 where only supplier B provides value-added services, when $m_B > c_f + t - u_B N - (c_{pA} - c_{pB})$,

the profit of supplier B increases as the network effect of supplier B's value-added services u_B increases, while the profit of supplier A always decreases as u_B increases.

3. For scenario S_4 :

$$\begin{aligned}\frac{\partial \pi_A^{SS}}{\partial u} &= \frac{\partial}{\partial u} \frac{N(3t-3uN+m_A-m_B-c_{pA}+c_{pB})^2}{18(t-uN)} \\ &= \frac{N^2}{18} \left(\frac{(m_A-m_B-c_{pA}+c_{pB})^2}{(t-uN)^2} - 9 \right)\end{aligned}\quad (23)$$

From Equations (15) and (18), we know that $\frac{m_A-m_B-c_{pA}+c_{pB}}{t-uN} > -3$, so $\frac{\partial \pi_A^{SS}}{\partial u} < 0$. Similarly, we can prove $\frac{\partial \pi_B^{SS}}{\partial u} < 0$.

Therefore, we can draw Result 4: Under the market equilibrium of scenario S_4 where both suppliers provide value-added services, when $u_A = u_B = u$, the profit of suppliers A and B both decrease as the network effect of the value-added services u increases.

3.2.2. Market Size

1. For scenario S_1 :

$$\begin{aligned}\frac{\partial \pi_A^{SS}}{\partial N} &= \frac{\partial}{\partial N} \frac{N(3t-N(u_A+2u_B)+m_A-m_B-c_{pA}+c_{pB})^2}{9(2t-N(u_A+u_B))} \\ &= \frac{2}{3} N_A^{SS} \left(\frac{t(3t-N(u_A+2u_B)+m_A-m_B-c_{pA}+c_{pB})}{N(2t-N(u_A+u_B))} - u_A - 2u_B \right)\end{aligned}\quad (24)$$

If and only if $\frac{t(3t-N(u_A+2u_B)+m_A-m_B-c_{pA}+c_{pB})}{N(2t-N(u_A+u_B))} - u_A - 2u_B > 0$, that is, $m_A > m_B + 6Nu_B + 3Nu_A - (c_{pB} - c_{pA}) - 3t - N^2(u_A + u_B)(u_A + 2u_B)/t$, $\frac{\partial \pi_A^{SS}}{\partial N} > 0$ holds. Similarly, we can prove π_B^{SS} .

Therefore, we can draw Result 5: Under the market equilibrium of scenario S_1 where both suppliers provide value-added services, when $m_A > m_B + 6Nu_B + 3Nu_A - (c_{pB} - c_{pA}) - 3t - N^2(u_A + u_B)(u_A + 2u_B)/t$, the profit of supplier A increases as the market size N increases. When $m_B > m_A + 6Nu_A + 3Nu_B - (c_{pA} - c_{pB}) - 3t - N^2(u_B + u_A)(u_B + 2u_A)/t$, the profit of supplier B increases as the market size N increases.

2. For scenarios S_2 and S_3 , we take S_2 as an example:

$$\begin{aligned}\frac{\partial \pi_A^{SN}}{\partial N} &= \frac{\partial}{\partial N} \frac{N(3t-c_f-u_A N+m_A-c_{pA}+c_{pB})^2}{9(2t-u_A N)} \\ &= \frac{2}{3} N_A^{SN} \frac{N^2 u_A^2 - t(c_f - 3t + 3Nu_A - m_A + c_{pA} - c_{pB})}{3N(2t-u_A N)}\end{aligned}\quad (25)$$

If and only if $\frac{u_A^2 N^2 - t(c_f - 3t + 3Nu_A - m_A + c_{pA} - c_{pB})}{3N(2t-u_A N)} > 0$, that is, $m_A > c_f + 3Nu_A + c_{pA} - c_{pB} - 3t - N^2 u_A^2 / t$, $\frac{\partial \pi_A^{SN}}{\partial N} > 0$ holds. Similarly, we can prove π_B^{SN} .

Therefore, we can draw Result 6: Under the market equilibrium of scenario S_2 where only supplier A provides value-added services, when $m_A > c_f + 3Nu_A - (c_{pB} - c_{pA}) - 3t - N^2 u_A^2 / t$, the profit of supplier A increases as the market size N increases.

Similarly, Result 7 is drawn: Under the market equilibrium of scenario S_3 where only supplier B provides value-added services, when $m_B > c_f + 3Nu_B - (c_{pA} - c_{pB}) - 3t - N^2 u_B^2 / t$, the profit of supplier B increases as the market size N increases.

4. Numerical Analysis

From the perspective of hydrogen energy suppliers, they are particularly concerned with choosing the sales strategy in the early stages of selling hydrogen energy and value-added services. In this section, we analyze the mathematical relationship between the supplier's optimal profit and market size and the intrinsic value of value-added services under different scenarios based on hydrogen energy market data in Shanghai, China.

Additionally, in Section 4.3, we specifically analyze how suppliers apply the model for strategy selection.

4.1. Data

The setting of the parameters in the model first needs to satisfy the constraints in the model assumptions, i.e., Equations (15)–(18). Secondly, the other parameters are distinguished while ensuring the consistency of the intrinsic value of the hydrogen energy, the unit utility loss, and the marginal cost of the value-added services. The data comes from the hydrogen energy market in China, which is currently in the preparatory stage of construction. The current cost of hydrogen production from coal is 10–15 RMB, so we set the intrinsic value of hydrogen energy at 12 RMB per unit. The marginal cost is conservatively considered about 10% of the intrinsic value. In a perfectly competitive market, the marginal cost of value-added services should be consistent with the product's intrinsic value. As a critical research point, the intrinsic value of value-added services is set to 0–45 RMB per unit (about twice the price) by referring to the price of hydrogen refueling stations. We set the marginal cost of hydrogen energy of supplier A higher than that of supplier B to study the changes in profits of the two hydrogen energy suppliers when the intrinsic value and network effects of value-added services are in different scenarios. The parameters are set as shown in Table 7.

Table 7. Parameters values.

Parameters	Value	Parameters	Value
N	0–1000	u_A	0.005
m_A	0–45	u_B	0.001–0.01
m_B	0–40	c_f	12
v	12	c_{pA}	1.5
t	6	c_{pB}	1

4.2. Network Effects Analysis

The following discusses the impact of the network effect of value-added services on the optimal profit and optimal pricing of suppliers under a specific market size.

Here we assume that supplier A's network effect of value-added services remains unchanged, and supplier B's gradually increases from 0 to 0.01. In this case, only two situations need to be considered: suppliers A and B provide value-added services simultaneously, supplier A does not provide value-added services while supplier B provides value-added services, because other situations are unaffected by the change in u_B .

1. The SS situation:

Figure 2 describes how the optimal profits and optimal pricing of suppliers A and B under the SS situation change with the increase of supplier B's network effect of value-added services. We find that when the market size is certain, the optimal pricing decreases linearly with the increase of the network effect of supplier B's value-added services u_B , and the rate of decrease of supplier A is twice as fast as that of supplier B. The difference between the prices is determined by the marginal cost of hydrogen energy and the intrinsic value of value-added services. Since the market size is fixed, the decline in prices leads to a decline in overall profits. However, Result 1 is not satisfied with the increase of the network effect of supplier B's value-added services because the market size is relatively small, thus resulting in the decrease of supplier B's profit. However, the magnitude of the decrease in the profit of supplier B is lower than that of supplier A. Regardless of the market size, supplier A is bound to decrease the optimal profit as the network effect of supplier B increases.

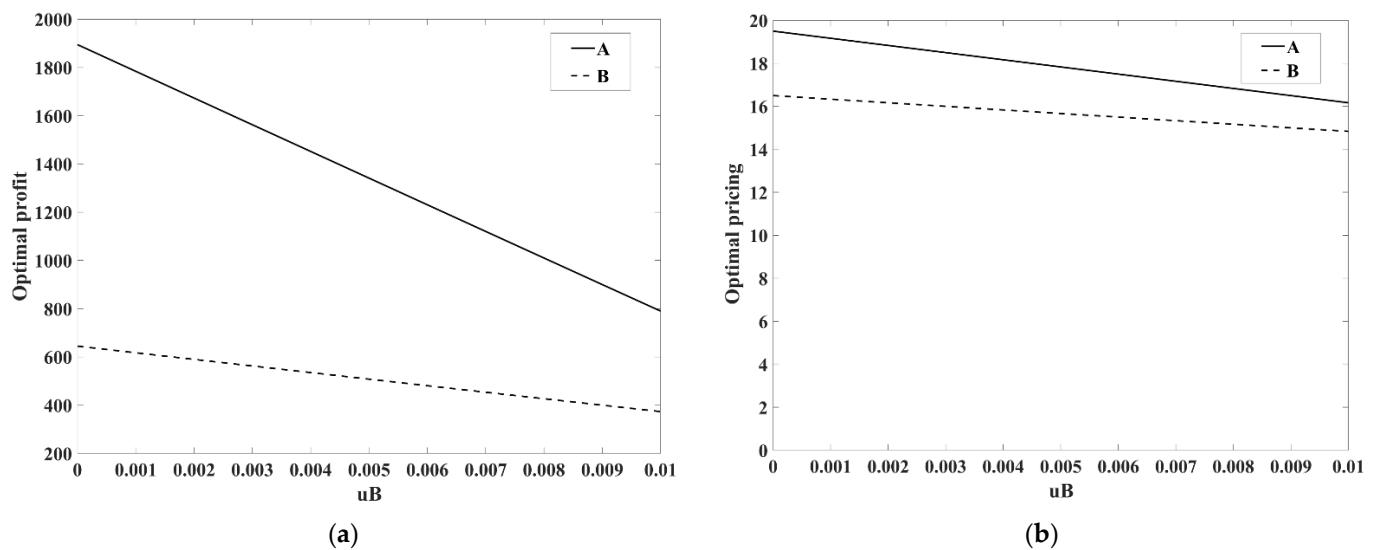


Figure 2. Analysis results under the SS situation: (a) the optimal profit; (b) the optimal pricing.

2. The NS situation:

Figure 3 describes the changes in suppliers A and B's optimal profits and optimal pricing under the NS situation. In the case that supplier A does not provide value-added services, because supplier B provides value-added services and its network effect is increasing, and supplier A's cost of hydrogen energy itself is higher than that of supplier B, supplier A's profit and pricing are always lower than supplier B's. As supplier B provides value-added services, suppliers A and B reduce prices to occupy the market and reach a new equilibrium. According to Result 3, the optimal profit of supplier A will inevitably decrease continuously, while the optimal profit of supplier B will first decrease and then increase. This is because the condition of Result 3 is satisfied when $u_B = 0.006$, so the optimal profit of supplier B starts to increase as the network effect increases.

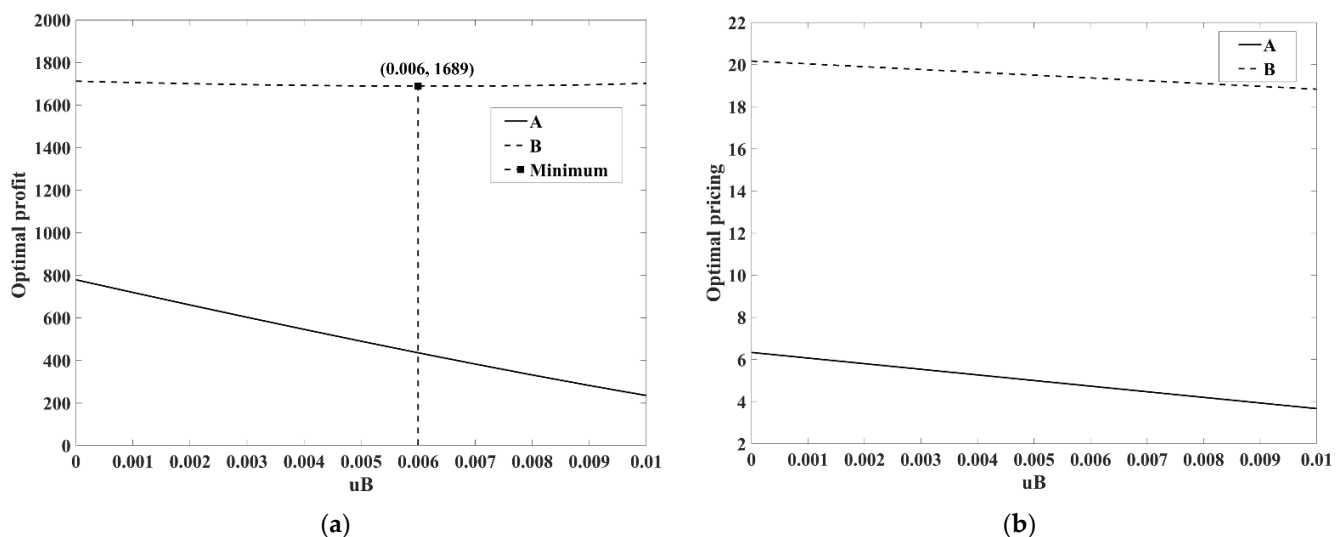


Figure 3. Analysis results under the NS situation: (a) the optimal profit; (b) the optimal pricing.

4.3. Market Size Analysis

In this section, we set $m_A = 18$, $m_B = 15$, $u_B = 0.001$.

1. Scenario S_1 :

Figure 4 describes the impact of increasing market size on the optimal profit and the optimal pricing of suppliers A and B in scenario S_1 . We found that the optimal pricing

declines linearly with the market size increase, but suppliers A and B's optimal pricing declines at different rates. According to the optimal pricing in Table 4, it is known that the declining rate of the optimal pricing is determined by the network effect of the value-added services. The larger the network effect, the lower the declining rate of the optimal pricing, which means the larger the network effect is, the less sensitive the supplier is to changes in the market size. In the same market size, the difference between the optimal pricing is determined by both the intrinsic value of the value-added service and the marginal cost of the hydrogen energy. The higher the intrinsic value of the supplier's value-added service and the higher the marginal cost of the hydrogen energy, the higher the optimal pricing.

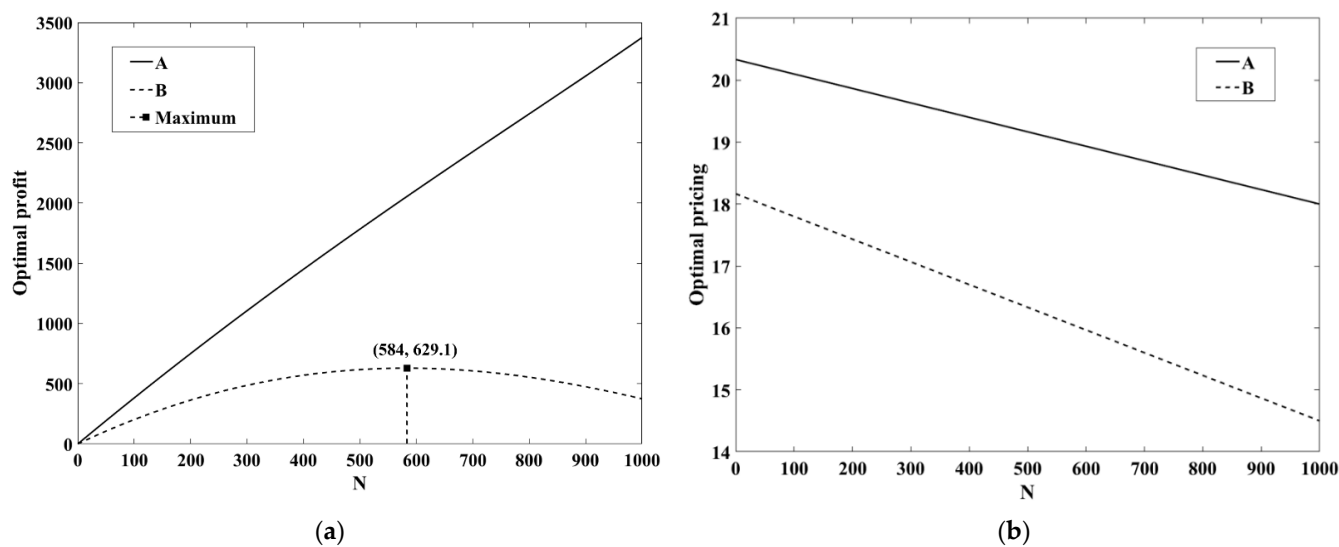


Figure 4. Analysis results under scenario S_1 : (a) the optimal profit; (b) the optimal pricing.

Although the optimal prices are both decreasing, the trend of the profits of the two suppliers is different. Because the intrinsic value of supplier A satisfies the condition in Result 5, the optimal profit increases with the increase of the market size. Supplier B satisfies Result 5 only when $N < 584$, so its optimal profit increases first and then decreases, achieving a maximum at $N = 584$. It is mainly due to the increasing demand for the supplier that has an advantage in the intrinsic value of value-added services and network effects in the process of price reduction. According to the results in Figure 4a, it can be found that the expansion of the market size in the early stage has brought an increase in profits to both suppliers. Still, when the size increases to a certain level, B's market is quickly replaced by A's, and the profit begins to decline.

2. Scenario S_2 :

Figure 5 describes the changes in the optimal profits and the optimal pricing of the two suppliers in scenario S_2 . From the perspective of the optimal pricing, supplier B's optimal pricing is much lower than supplier A's since it does not provide value-added services. Moreover, as the market size expands, the declining rate of the optimal pricing is also lower than that in scenario S_1 . It is due to the lack of market competition, which causes suppliers to be in an oligopolistic position in the provision of value-added services and are unwilling to reduce prices to obtain higher profits significantly. In particular, the difference can be seen in the optimal profit. For the parameters satisfying Result 6, the optimal profit of supplier A increases as the market size increases, and the profit of supplier A in scenario S_2 is much higher than that in scenario S_1 . In contrast, the optimal profit of supplier B is slightly lower than that in scenario S_1 . We find that supplier B's intrinsic value of value-added services and network effects in scenario S_1 is lower than supplier A's. Still, the loss of customers is not much different from scenario S_2 , so it is mainly due to the loss of pricing power resulting in lower profit.

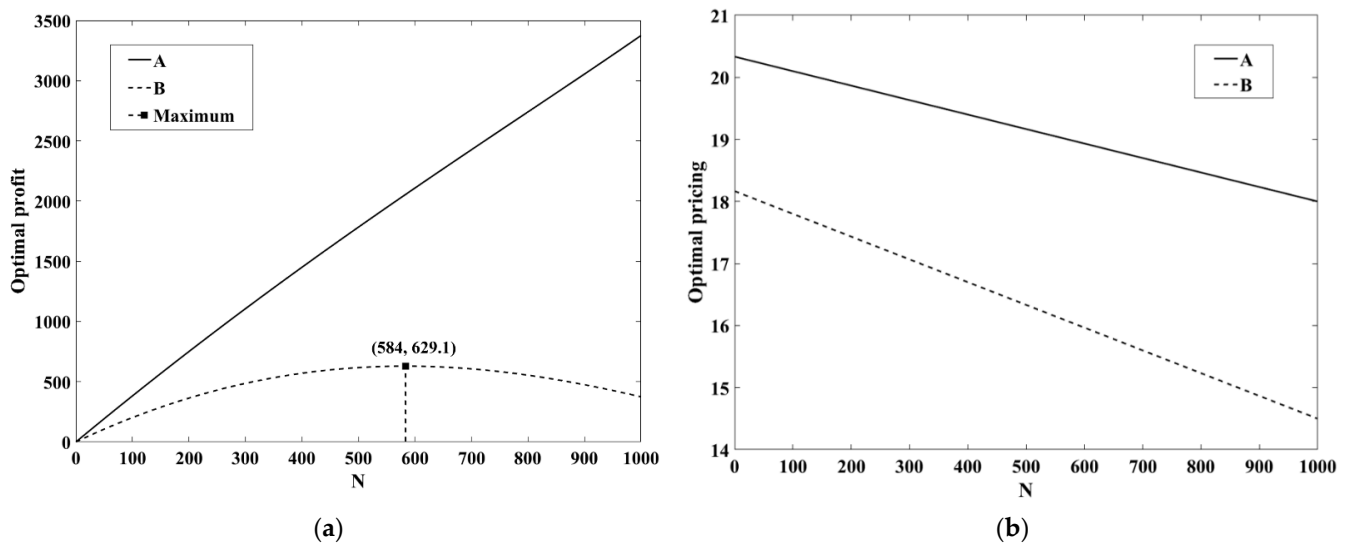


Figure 5. Analysis results under scenario S_2 : (a) the optimal profit; (b) the optimal pricing.

3. Scenario S_3 ;

Figure 6 describes the changes of the optimal profit and the optimal pricing of the two suppliers in scenario S_3 . The difference from scenario S_2 is that supplier B, which provides value-added services at this time, has a smaller intrinsic value and network effect of value-added services. Supplier B obtains the pricing power due to its oligopolistic position, and its optimal pricing is much higher than that of supplier A. According to Result 7, the optimal profit of supplier B increases with the increase of the market size. Due to the smaller intrinsic value and network effect, supplier B's optimal profit in scenario S_3 is lower than supplier A's in scenario S_2 in terms of quantity and growth rate.

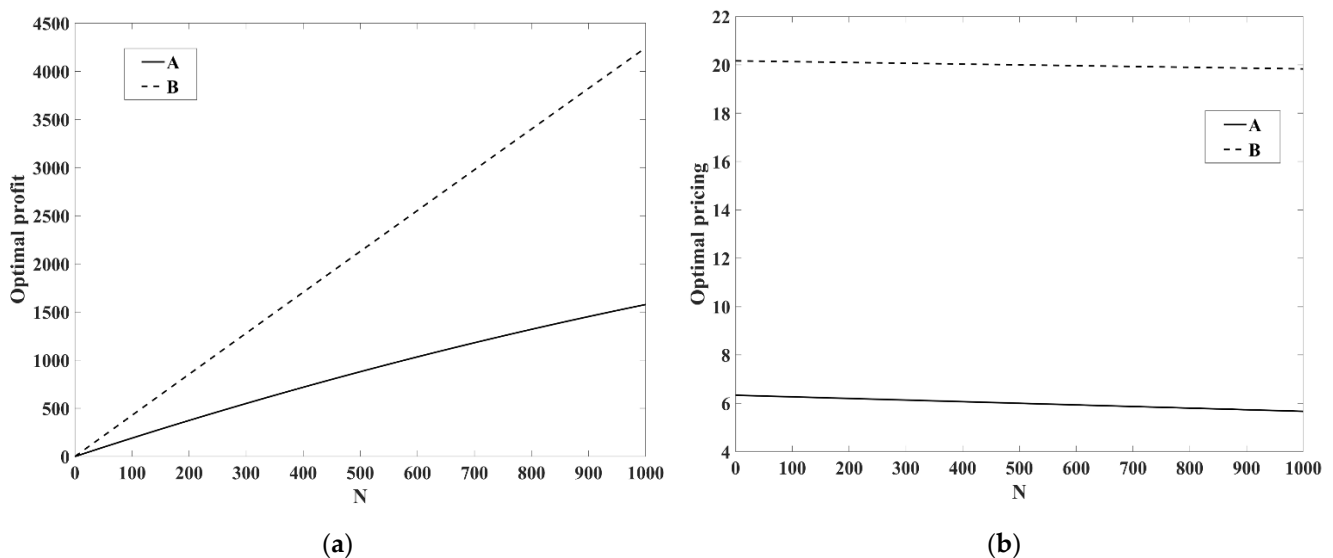


Figure 6. Analysis results under scenario S_3 : (a) the optimal profit; (b) the optimal pricing.

4. Scenario S_4 ;

Figure 7 describes the changes of the optimal profits and the optimal pricing of the two suppliers in scenario S_4 . Under the circumstance that the network effects of the two suppliers are the same, we find that the decline in optimal pricing in scenario S_4 is consistent with that in scenario S_1 . When the network effects are the same, the competition between the two suppliers becomes more intense. This homogeneous and vicious competition

causes suppliers to engage in price wars to gain each other's market, but this is positive for consumers. Therefore, at the same market size, the profits of the two suppliers are lower than that in scenario S_1 , and the increase in the optimal profit also appears to be weaker.

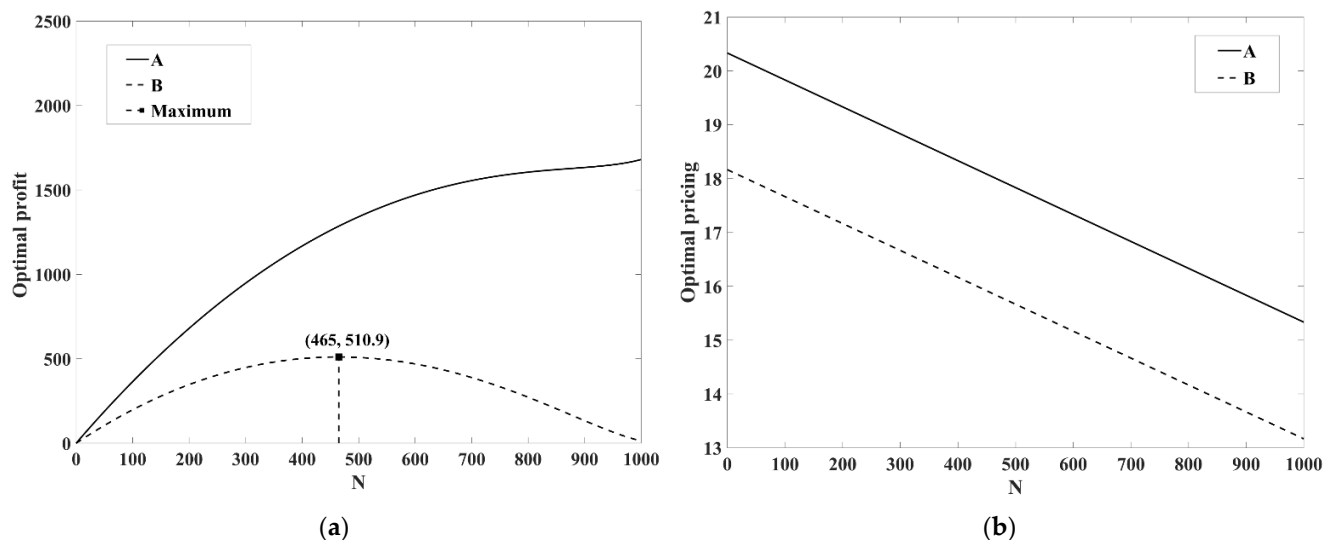


Figure 7. Analysis results under scenario S_4 : (a) the optimal profit; (b) the optimal pricing.

4.4. Sales Strategy Analysis

This section selected two hydrogen energy suppliers in Shanghai, China as a simulation case. The quality of hydrogen energy provided by these two suppliers is the same, but the marginal cost is different. In order to broaden the business scenario, both suppliers consider providing value-added services, but the content and scope of the services are different. In order to analyze whether there is a need for these two suppliers to provide value-added services, we conduct an example analysis based on the model constructed in this paper, and the analysis process is shown in Figure 8. The input parameters for the two suppliers are shown in Table 8. According to the calculation result in Table 9, $\pi_A^{SS} > \pi_A^{NS}$ and $\pi_B^{SS} > \pi_B^{SN}$, so both suppliers A and B should provide value-added services.

Table 8. The input parameters for the simulation case.

Parameters	Value	Parameters	Value
N	1000	u_A	0.005
m_A	20	u_B	0.001
m_B	18	c_f	12
v	12	c_{pA}	1.5
t	6	c_{pB}	1

Table 9. Calculation results of hydrogen energy suppliers' optimal profits in different situations.

	π^{SS}	π^{SN}	π^{NS}	π^{NN}
Supplier A	2893.52	6670.63	911.62	2835.65
Supplier B	560.19	3.97	5578.28	3168.98

Furthermore, to facilitate supplier judgment, we directly calculated the parameter space of suppliers A and B regarding the intrinsic value of value-added services, as shown in Figure 9. It describes the strategy selection of the two hydrogen energy suppliers in the (m_A, m_B) parameter space. Where areas I, II, III, and IV represent SS, SN, NS, and NN market strategy equilibrium, respectively. The conditions of area I are $\pi_A^{SS} > \pi_A^{NS}$ and $\pi_B^{SS} > \pi_B^{SN}$; the conditions of area II are $\pi_A^{SN} > \pi_A^{NN}$ and $\pi_B^{SN} > \pi_B^{SS}$; the conditions of

area III are $\pi_A^{NS} > \pi_A^{SS}$ and $\pi_B^{NS} > \pi_B^{NN}$; the conditions of area IV are $\pi_A^{NN} > \pi_A^{SN}$ and $\pi_B^{NN} > \pi_B^{NS}$. The straight line in Figure 9 represents $m_A = m_B$, that is, the intrinsic value of value-added services of suppliers A and B are the same.

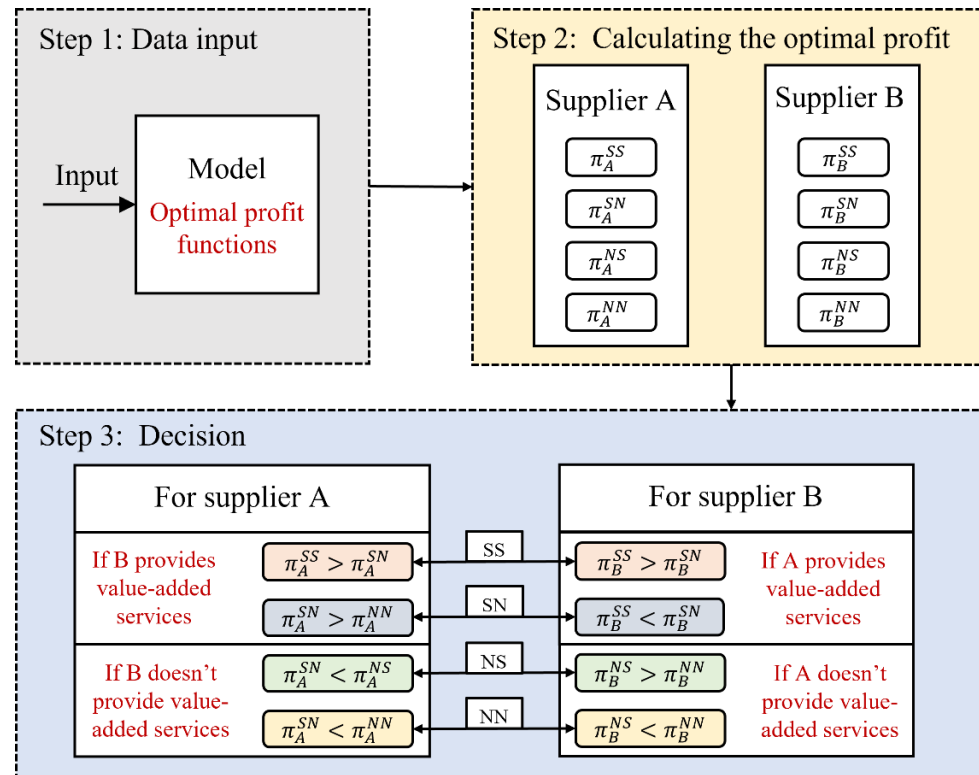


Figure 8. The decision sequence for hydrogen energy suppliers.

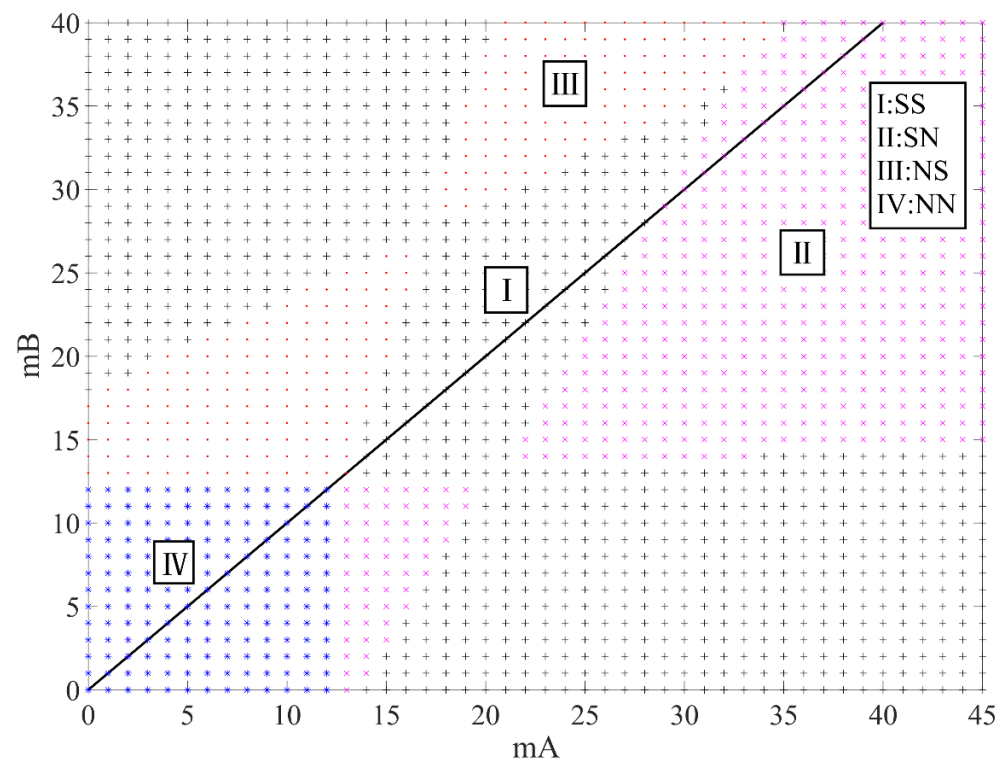


Figure 9. Sales strategy equilibrium of hydrogen energy suppliers in the (m_A, m_B) parameter space.

When the intrinsic value of the value-added services of the two suppliers is low, it is a better choice not to provide value-added services because the profit from the sale of hydrogen energy is higher than the value-added services. When the intrinsic value of the value-added services is greater than a certain threshold, the choice to provide value-added services may bring higher profits to the hydrogen energy suppliers. Under the conditions set in this section, when $m_A > m_B$ (i.e., below the straight line) and m_A is greater than a certain threshold (i.e., exceeding the area IV), supplier A should provide value-added services (i.e., areas I and II below the straight line). Moreover, when $m_A < m_B$ (i.e., above the straight line) and m_B is greater than a certain threshold (i.e., exceeding the area IV), supplier B should also provide value-added services in most cases when the m_A is small (i.e., areas I and III above the straight line), but should choose not to provide value-added services when the m_A is relatively large (Region IV). The reason for this difference is that the network effect of supplier B's value-added services is smaller than that of supplier A.

5. Conclusions

This study developed a two-stage sales strategy model for hydrogen energy and its value-added services based on the Hotelling model considering consumer network effects and preferences. It aimed to verify that hydrogen energy suppliers can improve their economic efficiency by introducing value-added services that can activate the hydrogen energy market and form an effective market incentive. The following conclusions are drawn:

- (1) A hydrogen energy supplier's provision of value-added services does not necessarily increase its profits. Only when the intrinsic value of its value-added services exceeds a certain threshold its profits will increase, and the threshold varies in different scenarios;
- (2) The profit of a hydrogen energy supplier is affected by four key factors: the intrinsic value of value-added services, the network effect of value-added services, the size of consumers, and the sales strategies of competitors. When the intrinsic value of value-added services is higher than the threshold, the profit of the hydrogen energy supplier increases with the increase of its service network effect and consumer network size but decreases with the increase of competitors' value-added services network effects. When the intrinsic value of value-added services is lower than the threshold, it shows the opposite trend.
- (3) When the two hydrogen energy suppliers both provide value-added services, their profits will decrease with the increase of value-added service network effects, independent of the intrinsic value of the value-added services, so hydrogen energy suppliers should avoid vicious competition in the value-added services market. Finally, this paper obtains the optimal sales strategies for two suppliers in a specific scenario with the different intrinsic values of value-added services, which is quite practical for the application in a practical scenario.

In addition, some limitations in this paper need further improvement. On the one hand, this paper only studies the case of two oligopolistic hydrogen energy suppliers in the market. When there are multiple hydrogen energy suppliers in the market, the analysis can be performed by combining other hydrogen energy suppliers into one competitor. However, the computational volume of model solving will increase significantly with more market players, and such problems will be solved with the help of intelligent algorithms in the future. On the other hand, quantitatively analyzing the intrinsic value and network effects of value-added services and analyzing the market equilibrium problem when value-added services are compatible will be the focus of our and other scholars' research in the future.

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