Proceedings of the 3rd International Conference on Modern Medicine and Global Health
DOI: 10.54254/2753-8818/2025.24109

A Comparative Study of the Production and Storage Cost Optimization of Liquid Hydrogen and Ammonia as Green Energy Carriers

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Abstract: As the world's largest energy-consuming and carbon-emitting country, China's dependence on fossil fuels is very serious, so its environmental protection issues will be crucial. The Chinese government also claims to gradually promote carbon neutrality between 2030 and 2060. In this context, China will actively promote the use and construction of clean energy, and hydrogen energy will be a key development target of clean energy as it could reduce carbon emissions and promote the realization of carbon neutrality. However, the biggest challenge in the current use and popularization of hydrogen energy lies in its high storage and security maintenance cost owing to the instability of hydrogen gas and vague construction goals. Regarding this, Safer hydrogen energy carriers such as NH_3 and liquified H_2 are promising candidates as an energy vector. To determine the appropriate carrier, this study has adopted an optimization model to explore the minimum cost and optimal construction scale of production and storage steps for two different hydrogen energy carriers (liquefied hydrogen and ammonia) within one year. It shows that liquefied hydrogen had a lower unit cost, which makes it a more economical hydrogen energy carrier than ammonia gas, greatly reducing the unit cost of hydrogen energy and factory construction costs. This study provides economic guidance for future hydrogen energy production and construction, avoids more expenses being wasted, and promotes the popularization of hydrogen energy.

Keywords: carbon neutrality, hydrogen energy, optimization models, economic benefit

1. Introduction

Currently, the use of fossil fuels (oil, coal, natural gas) accounts for nearly 80% of energy consumption [1], and greenhouse gases such as CO2 will cause severe global warming. The problem of global warming is accompanied by various serious ecological issues such as an increase in the incidence of severe weather, rising sea levels, and reduced biodiversity worldwide, which will ultimately have a significant impact on humanity. Therefore, achieving carbon neutrality as soon as possible will be a major issue that governments around the world need to consider. It is expected that by 2030, China will still be in a period of rising carbon emissions, but between 2030 and 2060, China will strive to achieve carbon neutrality [2]. During this process, hydrogen energy has become a highly competitive energy choice due to its high energy density and low carbon emissions and will occupy an important position in future national energy development.

Hydrogen energy is recognized as a clean, renewable, storable, and high-energy-density energy source. Water vapor is the only product of hydrogen combustion, fundamentally solving the generation of greenhouse gases such as CO_2. At the same time, the water produced by hydrogen combustion can be reused in the electrolytic manufacturing process of hydrogen energy, achieving its renewable characteristics. Secondly, taking the low-temperature storage of liquefied hydrogen and the room-temperature storage of ammonia as examples, the storability of hydrogen energy can be demonstrated. Finally, compared to traditional fossil fuels, hydrogen can store more energy with the same amount of hydrogen energy [3].

At present, research on hydrogen energy mainly focuses on exploring more new methods to produce hydrogen gas and more new application scenarios, and to a large extent, neglects to further explore the optimization of existing methods. One of the limitations of current hydrogen energy applications is its high cost, which makes it difficult for people to use hydrogen, an excellent energy source, in large quantities. However, research has found that hydrogen in hydrogen can be stored in other forms of hydrogen-containing substances through physical or chemical means, such as liquefied hydrogen (LH_2) obtained through physical means. Its acquisition method is simple, only requiring compression of hydrogen at a specific temperature and pressure. However, storing liquid hydrogen also requires extremely low temperatures, which can result in additional expenses; Therefore, there is currently research exploring ammonia (NH_3) as a hydrogen energy carrier, as ammonia has the characteristic of being storable at room temperature [4].

Therefore, this study will focus on the costs of two common hydrogen energy carriers [LH_2, NH_3] and compare their economics, to select the more economical hydrogen energy carrier. In this work, it will discuss the processes of production and storage of two hydrogen carriers, carrier 1: liquefied hydrogen (LH_2) and carrier 2: ammonia (NH_3). The innovation of this research lies in providing people with a new approach to hydrogen energy selection. By using computer methods to compare the economics of two common hydrogen energy carriers, the more economical hydrogen energy carrier can be selected. This comparative selection approach will have significant implications for various hydrogen energy issues in the future.

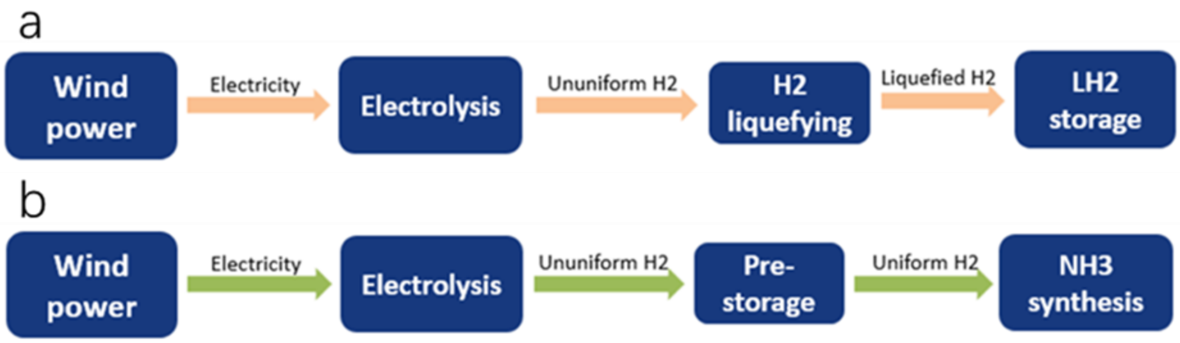

Figure 1: System design for (a) LH2 and (b) NH3

2. Method

2.1. System description

The hydrogen production and storage system of this study is shown in Figure 1, which varies depending on the hydrogen carrier. The two systems have the same steps of wind power generation and electrolytic hydrogen production; At the same time, it varies depending on the hydrogen carrier. When the hydrogen carrier is LH_2, the hydrogen production and storage system have the following additional steps: hydrogen liquefaction and liquid hydrogen storage; When the hydrogen carrier is NH_3, the hydrogen production and storage system have additional hydrogen pre-storage and ammonia synthesis. The pre-storage of hydrogen is to increase the stable hydrogen gas flow input for the ammonia synthesis step, to achieve the goal of stable synthesis of ammonia from hydrogen and nitrogen in the air.

2.2. Optimization mode

2.2.1. Objective function

The purpose of this study is to compare the costs of two hydrogen carriers and optimize the acquisition and storage costs of hydrogen energy carriers.

The total cost of LH_2 (TC1) consists of wind energy investment (W), LH_2 storage investment (LHS), LH_2 liquefaction investment (LH), electrolytic cell investment (ELE), Wind energy capacity (WC), liquid hydrogen storage capacity (LHSC), hydrogen liquefaction capacity (LHC), and electrolysis cell capacity (ELEC). The formula is as follows:

$$\mathrm{TC1} = \mathrm{W} * \mathrm{WC} + \mathrm{LHS} * \mathrm{LHSC} + \mathrm{LH} * \mathrm{LHC} + \mathrm{ELE} * \mathrm{ELEC} \tag{1}$$

Similarly, the cost investment of NH_3 (TC2) includes wind energy investment (W), H_2 storage investment (HS), ammonia synthesis investment (NH), electrolytic cell investment (ELE), wind energy capacity (WC), hydrogen storage capacity (HSC), ammonia synthesis capacity (NHC), and electrolytic cell capacity (ELEC). The formula is as follows:

$$\mathrm{TC2} = \mathrm{W} * \mathrm{WC} + \mathrm{HS} * \mathrm{HSC} + \mathrm{NH} * \mathrm{NHC} + \mathrm{ELE} * \mathrm{ELEC} \tag{2}$$

2.2.2. Constraints

For system A (LH_2): (a1) power supply

Constraints1:Wind power supply - Electricity consumption for electrolysis of water-Electricity consumption of liquefied hydrogen - Electricity consumption of storing LH_2 >= 0 (The input of wind energy should be no lower than the energy consumption of the entire system)

Constraints2:Electricity consumption for electrolysis of water <= Electric energy production (The generated electrical energy should be greater than the electrical energy required for electrolysis)

(a2) mass balance

Constraints3:H_2 produced - H_2 demand >= 0 (The energy of hydrogen produced cannot be less than the demand)

Constraints4:Hydrogen storage level=Hydrogen storage valley, Hydrogen storage level<=Hydrogen storage peak (The hydrogen storage capacity should be between the peak and valley of hydrogen energy)

For system B (NH_3): (b1) power supply

Constraints1:Wind power supply - Electricity consumption for electrolysis of water- Electricity consumption for preH_2 - Electricity consumption of synthetic NH_3 >= 0 (Wind energy input exceeds system energy consumption)

Constraints2:Electricity consumption for electrolysis of water <= Electric energy production (The generated electrical energy should be greater than the electrical energy required for electrolysis)

(b2) mass balance

Constraints3:H_2 produced - H_2 demand >= 0 (The energy of hydrogen produced cannot be less than the demand)

Constraints4:Hydrogen storage level>=Hydrogen storage valley, Hydrogen storage level<=Hydrogen storage peak (The hydrogen storage capacity should be between the peak and valley of hydrogen energy)

2.2.3. Decision variables, data sources and parameter [5-7]

The decision variables for systems a and b are shown in Table 1 and Table 2. Hourly wind energy data for one year was collected from https://www.renewables.ninja/. Hydrogen energy demand was constant, and it is set at 1kg/hour (Figures 2a and 2b). The parameters used in this study were summarized in Table 3 and Table 4.

Table 1: Decision variables for system A (LH$_2$)

variables	Content
windCapacity	Wind energy capacity (WC)
electrolserCapacity	electrolysis cell capacity (ELEC)
LHStorageValley	Peak value of liquid hydrogen storage (LHSP)
LHStoragePeak	Valley value of Liquid hydrogen storage (LHSV)
PowerInputElectrolyser	Power Input Electrolysis cell (PELE)
PowerInputLH$_2$	Power Input Liquefying hydrogen (PLH)
LHCapacity	Liquid hydrogen storage capacity (LHC)
storage_level	Liquid hydrogen storage level (LHSL)

Table 2: Decision variables for system B (NH$_3$)

variables	Content
windCapacity	Wind energy capacity (WC)
electrolserCapacity	electrolysis cell capacity (ELEC)
PreH$_2$StorageValley	Peak value of hydrogen storage (HSP)
PreHStoragePeak	Valley value of hydrogen storage (HSV)
PowerInputElectrolyser	Power Input Electrolysis cell (PELE)
PowerInputPreH$_2$	Power Input hydrogen storage (PHS)
PreH$_2$Capacity	Hydrogen storage capacity (HSC)
Prestorage_level	Hydrogen storage level (HSL)

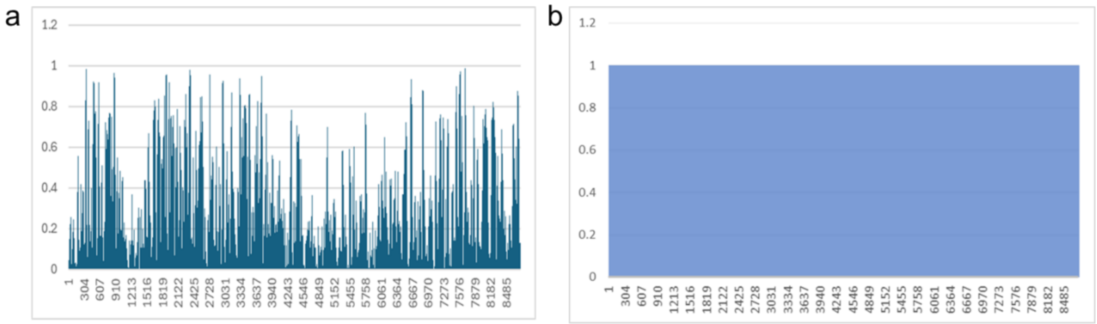

Figure 2: Input data of (a) wind power data per hour whole year; (b) hydrogen energy demand per hour whole year

Table 3: Parameters of system A (LH$_2$)

Parameter	Value
Wind energy investment cost	1202.62/20/1000 \$/MW/day
Investment cost of electrolysis	586.71/20/1000 \$/MW/day
Storage cost of liquid hydrogen	225.03 * 120/1000/20 \$/kg/day

Table 3: (continued)

Investment cost of hydrogen liquefaction	5.31 * (365 * 24)/20 $/kg/day
Electrolytic hydrogen production efficiency	0.68
Hydrogen liquefaction efficiency	0.95
Electricity price	22.2 $/GJ

Table 4: Parameters of system B (NH_3)

Parameter	Value
Wind energy investment cost	1202.62/20/1000 $/MW/day
Investment cost of electrolysis	586.71/20/1000 $/MW/day
Investment cost for hydrogen pre-storage	1065 * 120/1000/20 $/kg/day
Investment cost of synthetic ammonia	0.6595 * (365 * 24)/20 $/kg/day
Electrolytic hydrogen production efficiency	0.68
Cost of cracking ammonia	50.06 $/kg/day
Ammonia cracking efficiency	0.60
Electricity price	22.2 $/GJ

3. Result

3.1. H_2 storage level

The relationship between time and the hydrogen storage level of the liquid hydrogen tank is shown in Fig. 3a. Among them, each represents the hydrogen storage level for 6 hours; The bars below 0 represent that the LH_2 storage tank is releasing H_2, as the demand is higher than the H_2 produced at that time. For those bars above 0, this means that the LH_2 tank is storing H_2 because the demand is lower than the H_2 produced at that time. Similar to system A, Figure 3b shows the relationship between time and the hydrogen storage level of the liquid hydrogen tank. Among them, each represents the hydrogen storage level for 6 hours; A bar below 0 represents that the NH_3 storage tank is releasing NH_3 because the demand is higher than the H_2 produced at that time. For those bars above 0, this means that the NH_3 storage tank is storing NH_3 because the demand is lower than the H_2 produced at that time.

By comparing Fig. 3a and Fig. 3b, it is not difficult to find that the hydrogen storage levels of the two systems are significantly different, and then comparing Fig. 3a and Fig. 3b with Fig. 4 respectively, it can be found that the storage level of NH_3 has a great correlation with wind energy, while the storage level of LH_2 has a lag relative to wind energy, which indicates that the hydrogen energy produced by wind energy electrolysis exceeds the hydrogen energy demand to a certain extent, so there is a lag hydrogen storage phenomenon.

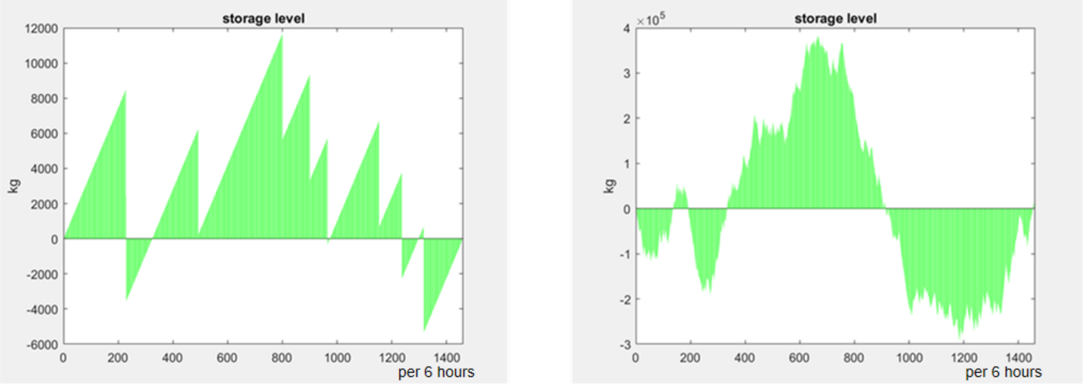

Figure 3: The storage level every 6 hours within one year of (a)LH_2 and NH_3

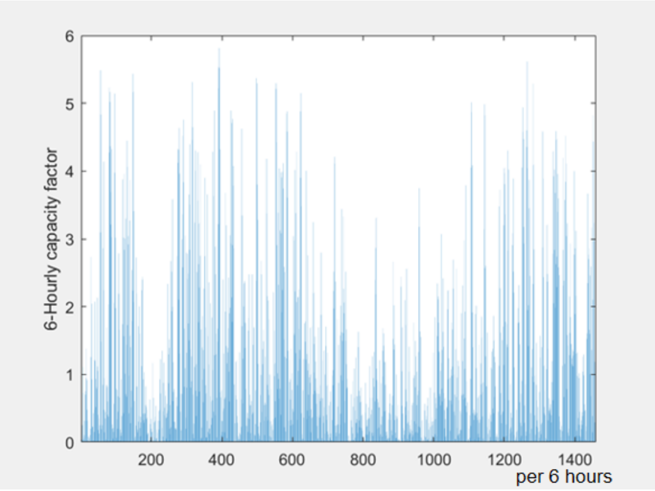

Figure 4: The amount of wind energy per 6 hours over a year

3.2. Cost analysis

The total cost, hydrogen unit price, electrolytic cell capacity, and storage tank capacity of two hydrogen energy carriers through this program were obtained and shown in Table 5. When LH_2 is used as a hydrogen energy carrier, the unit price of hydrogen energy per kilogram is $1.61, and the annual cost of the system is $14,086,000; When NH_3 is used as a hydrogen carrier, the unit price of hydrogen energy per kilogram is $4.86, and the annual cost of the system is $42,546,000.

Table 5: The total cost, hydrogen unit price, electrolytic cell capacity, and storage tank capacity of two hydrogen energy carriers

	LH_2	NH_3
Total yearly cost ($)	14,086,000	42,546,000
Unit H_2 price ($)	1.61	4.86
Electrolysis capacity (MW)	308.92	583.51
Storage capacity (kg)	16,983	673,530

4. Discussion

By comparing the total cost, hydrogen unit price, electrolytic cell capacity, and storage tank capacity of the two paths, it can be easily found that using LH_2 as the hydrogen carrier in system A is much cheaper than using NH_3 as the carrier throughout the entire manufacturing and storage process. The hydrogen unit price of system A is also more economical than system B. By analysing a series of research data, it can be easily found that using LH_2 as a hydrogen carrier is a more economical choice for NH_3 as a carrier. At the same time, when the electrolytic cell capacity is 308.92MW and the LH_2 storage tank capacity is 16,983kg, the annual cost of this cycle is the smallest, at $14,086,000, and only $1.61 per kilogram of hydrogen is needed, which is a very cheap price in any situation [5]. After comparison, it was found that the annual cost of NH_3 as a hydrogen carrier is almost three times that of the LH_2 carrier, indicating that NH_3 is not a good choice for hydrogen carriers. Choosing LH_2 as a hydrogen carrier is more cost-effective.

However, there is still room for exploration in the above conclusions. During the writing process of this article, our team discovered that for both LH_2 and NH_3 carriers, there is an important step from production to use, which is transportation. Our team has learned that LH_2 transportation must be carried out at extremely low temperatures, and there will be a certain amount of loss as transportation time increases[6]. NH_3 only needs to be transported at room temperature, so perhaps adding transportation costs as a consideration criterion may result in different outcomes.

5. Conclusions

This experiment proposed the idea of exploring the cost optimization of hydrogen energy by analyzing the current carbon neutrality background in China. Using MATLAB as a computer program, real economic problems were combined with computer problems, and the optimization model was used to obtain the lowest cost of production and storage steps for two different hydrogen energy carriers (liquefied hydrogen and ammonia). At the same time, the total cost and unit price of hydrogen energy produced by the two paths were obtained. By comparison, liquefied hydrogen will be a more economical choice for hydrogen energy carriers. Through this experiment, our team firmly believes that it can have a profound impact on China's future energy transition and hydrogen energy production choices. In this study, there are many areas that can be improved; For example, in the process of path optimization, the excess electricity generated by wind energy can be utilized in the storage of H_2 and LH_2 and the synthesis of NH_3, which can further save costs.

In future research, it is hoped to further explore the costs of two hydrogen energy carriers and plan the costs of each step in more detail. Due to the loss of LH_2 during transportation and the need for low-temperature storage, NH_3 has no loss and can be transported at room temperature. Therefore, in future research, the cost of two hydrogen energy carriers during transportation will be added, and the total cost will be compared to observe whether the same results will still be obtained.

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