Frontiers in Business, Economics and Management
ISSN: 2766-824X | Vol. 5, No. 2, 2022

Liquid Hydrogen Production, Transportation and Economic Analysis

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Abstract: With rapid development of hydrogen energy industry in China, liquid hydrogen transportation mode with high energy storage density has great advantages over the current high-pressure gaseous transportation mode, and will become an important and efficient carrier to realize the large-scale development of hydrogen energy. The high economic efficiency of liquid hydrogen can be better applied to civil market with cost sensitivity. This paper describes the current global liquid hydrogen production capacity and distribution, summarizes the liquefaction methods and transportation technical characteristics of liquid mode, and analyzes the economic cost composition of the liquid hydrogen technology route. It is concluded that liquid mode as hydrogen carrier of large-scale development of hydrogen energy will be suitable for the development route of civil hydrogen energy in China. Suggestions are also put forward for the future development of hydrogen energy in China.

Keywords: Hydrogen, Liquefaction, Transportation, Economical efficiency.

1. Introduction

With the development of science and technology, various countries pay more attention to environmental protection, especially in reducing carbon dioxide emissions, which accelerates the transformation to the energy structure of less dependence on fossil fuels. Hydrogen, as one kind of zero carbon energy, is the representative of clean energy and will flourish in the near future [1]. On October 24, 2021, the CPC Central Committee and the State Council issued the opinions on completely, accurately and comprehensively implementing the new development concept and executing in carbon peak and carbon neutralization [2]. The opinions clearly pointed out to comprehensively promote the whole chain of hydrogen energy, including production, transportation and refueling, and to strengthen the research and development, demonstration and large-scale application of key technologies about hydrogen energy.

As an important industrial raw material at present and a possible main energy source in the future, the industrialization of hydrogen energy is up against many key problems, especially the economic efficiency of production and transportation. The liquid hydrogen could realize the large-scale, low-cost and long-distance transportation of hydrogen, which can be used as an effective way to solve the restriction caused by the low energy density of gaseous hydrogen. Current hydrogen energy transportation is mainly performed by high-pressure gaseous mode in China. With the rapid development of China's hydrogen energy application industry [3,4], low-temperature liquid transportation mode is more efficient on low comprehensive economic cost, with the advantage of high energy density [5], low transportation cost, high vaporization purity, low storage pressure and high security.

Considering the status quo in China and referring to the development route of hydrogen energy technology in foreign countries at the same period, the liquid hydrogen mode has better economic effect based on the advantages of production and transportation, and is suitable for the large-scale and commercial supply of hydrogen energy chain. This paper introduces the hydrogen liquefaction capacity in the world and basic characteristics of liquid hydrogen production and transportation. By comparing the expenditures of liquid hydrogen mode and high-pressure gaseous mode, the economic advantages of liquid hydrogen production, transportation and refueling are analyzed with rapid development of hydrogen energy terminal application industry. It concluded that liquid hydrogen is more suitable for the future hydrogen energy technology route and economic development in China.

2. Global Hydrogen Liquefaction Capacity

The volumetric energy density of liquid hydrogen, which possesses the largest effective hydrogen storage density, is about three times that of 350bar high-pressure gaseous hydrogen and about 1.8 times that of 700bar hydrogen. The global capacity of hydrogen liquefaction plants in operation has reached 358.9tpd (ton per day), as shown in Figure 1. There are 9 plants in operation in the United States, with a total capacity of 214tpd. Canada has 5 units in operation with 81tpd. The total liquid hydrogen production capacity of these two countries in North America accounts for more than 80% of the global production share. Other countries with hydrogen liquefaction plants include Japan 27.3tpd, France 10tpd, Germany 9.4tpd, Netherlands 5tpd, French Guiana 5tpd, China 4.5tpd and India 2.7tpd.

There is still a large difference between developed countries and China in liquid hydrogen capacity, especially for civil utilization. The first domestic liquid hydrogen plant for civil use with a capacity of 0.5tpd has been successfully implemented by Beijing Institute of Aerospace Test Technology in April 2020 in China, as well as the first 2tpd plant based on helium expansion refrigeration cycle with independent intellectual property rights deployed in September 2021 [6].

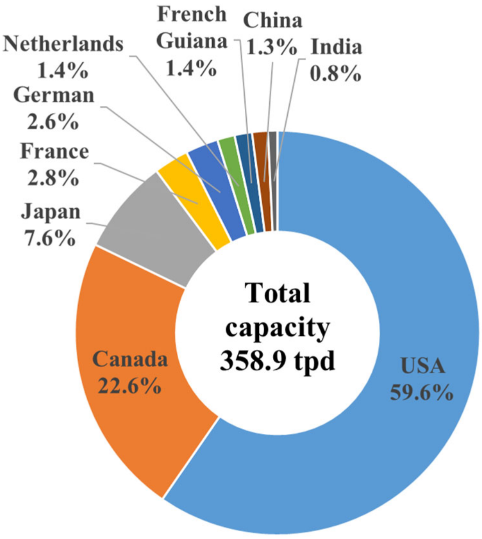

Figure 1. Global capacity distribution of liquid hydrogen.

3. Hydrogen Liquefaction and Transportation

The technical threshold is pretty high in hydrogen liquefaction and transportation, which restricts the scale of liquefaction plant and results in poor economic efficiency.

3.1. Hydrogen Liquefaction

Hydrogen is difficult to liquefy, which is second only to helium. The cryogenic technology used to obtain liquid hydrogen at 20.3K employs a series process of compression, pre-cooling, refrigeration and conversion from orthohydrogen(o-H2) to parahydrogen(p-H2). The liquid hydrogen product obtained will be stored in a special insulated container.

Different liquefaction methods could be classified according to expansion process, heat exchange process or their combination. The common methods used in industry contain simple Linde-Hampson method using Joule-Thompson effect for throttling expansion and adiabatic expansion method combined with turbine expander cooling. In the actual production process, adiabatic expansion is divided into reverse Brayton method and Claude method by the capacity scale. The reverse Brayton method uses helium as medium expansion refrigerant to reach low temperature around hydrogen boiling point, while the Claude method utilizes a part of high-pressure feed hydrogen as adiabatic expansion refrigerant to cool the feed itself.

Among these three basic methods mentioned above, the specific energy consumption(SEC) of Linde-Hampson throttling cycle, which is suitable for small-scale hydrogen liquefaction plants with a capacity of less than 2tpd, especially laboratory level, is higher than others with low efficiency. The SEC and efficiency of helium reverse Brayton cycle lie in the middle level of the basic cycles, which is suitable for small- and medium-sized plants below 5tpd. The Claude cycle has a low SEC and high efficiency, and is suitable for medium- and large-scale hydrogen liquefaction plants.

The conversion from o-H_2 to p-H_2 is essential in the liquefaction process in order to extend a long-term storage period. Due to the characteristics of hydrogen, the spin directions of the two nuclei constituting hydrogen molecules are different, which defines two spin isomers. The hydrogen molecule with same rotation direction of the two nuclei is o-H_2 and the opposite is p-H_2.

Normal hydrogen (n-H_2) in the equilibrium state at room temperature contains 75% o-H_2 and 25% p-H_2, while the content of o-H_2 is 0.2% and p-H_2 is 99.8% in the equilibrium state of liquid hydrogen at boiling point temperature. During the liquefaction process, liquid hydrogen will tend to equilibrium showing a spontaneous conversion from o-H_2 to p-H_2. The conversion is very slow, with heat releasing 523kJ/kg when the hydrogen temperature is below 77K, which is greater than the latent heat of vaporization of liquid hydrogen(443kJ/kg) [7]. The evaporation loss of liquid hydrogen, which interrupts the long-term stable storage, is caused by this spontaneous and slow heat release of unconverted o-H_2, if no active measure is taken to catalyze the ortho-para hydrogen process and to remove the conversion heat. Therefore, catalyst such as $Fe_2O_3 \cdot nH_2O$ is added to implement the conversion in the liquefaction process [8], in order to ensure the final equilibrium liquid hydrogen product with qualified content of o-H_2 and p-H_2 for long-term stable storage.

3.2. Liquid Hydrogen Transportation

Liquid hydrogen transportation is the basis of hydrogen energy technology application in a safe, efficient, large-scale and low-cost way. Liquid hydrogen can be transported with containers commonly or using pipelines for spaceport. The container transportation generally adopts spherical and cylindrical storage tank using trailers, railway carriers and dropships.

In addition to considering the impact, vibration and other factors involved in the process of conventional liquid transportation, the liquid hydrogen transportation need to reduce heat leakage strictly or to store in a lossless way to eliminate the overpressure risk and venting loss caused by vaporization as much as possible due to the extremely low boiling temperature, small latent heat of vaporization and easy evaporation.

The passive insulation method is always adopted to reduce heat conduction in liquid hydrogen transportation [9]. High vacuum-jacketed adiabatic container, high vacuum multilayer adiabatic method and high vacuum powder adiabatic method are main technical ways used to minimize heat radiation on the basis of reducing heat conduction and convection. Due to the inevitable heat leakage, the active refrigeration technology, such as liquid nitrogen cold shield and small refrigerator, is often added as a supplementary [10] to reduce further heat leakage or generate additional cooling capacity for heat neutralizing [11].

4. Economic Analysis

The economic efficiency of liquid hydrogen technology should be evaluated especially for civil use, under the high reliability of technology. The comprehensive cost of liquid hydrogen is lower enough to be competitive to that of current 20MPa high-pressure gaseous hydrogen.

4.1. Liquefaction Expenditure

The influence of production to liquefaction expenditure mainly contains the production scale and conventional economic efficiency of civil liquid hydrogen technology route, which refers to the development of foreign hydrogen energy route [12,13]. The raw feed cost, capital expenditure (CAPEX), operating expenditure (OPEX) and electrical expenditure (EEX) of a 30tpd plant, which is a common type with 8000h annual operation time and 10kWh/kgLH2 SEC, are assessed and calculated.

The depreciation period of fixed assets could be evaluated as 20 years for 1 billion CNY CAPEX. OPEX could be 15million CNY annually, including expenditure of water utilization, salary, maintenance etc. The cost of hydrogen raw feed, which meets China's industrial by-product hydrogen standard of purity for fuel cell, is estimated to 1.5CNY/Nm3. The EEX is 0.6CNY/kWh.

From information mentioned above, the production cost of liquid hydrogen is calculated to be 29.5CNY/kgLH2, and the composition is shown in Figure 2. The largest proportion is the expenditure of hydrogen raw feed accounting for 58%, followed by the EEX for 20%, CAPEX 17% and OPEX 5%. The top two parts domain the production expenditure, which accounts for feed hydrogen type and electricity price locally. While the feed cost is also related to the electricity price, especially gaseous hydrogen from electrolysis of water. Hydrogen production plant located in areas with renewable energy, such as northwest area or offshore abundant in wind energy and solar energy [14,15], could combine the water electrolysis process with liquefaction. The combination could completely utilize low-cost electricity from renewable energy, which calculated to be 0.3CNY/kWh, for water electrolysis and liquefaction, so as to minimize the production expenditure of liquid hydrogen to 25.3CNY/kgLH2 and avoid the impact of grid connection between renewable energy power and general power grid to peak adjusting capacity [16].

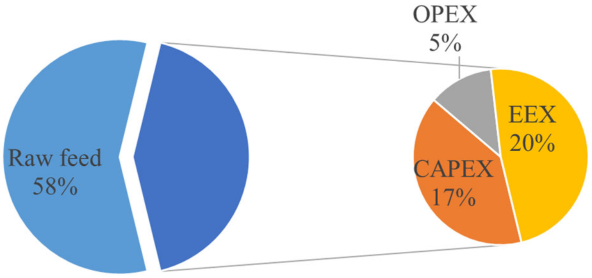

Figure 2. Composition of liquefaction expenditure for per unit mass.

4.2. Transportation and Refueling Expenditure

The cost of liquid hydrogen transportation is calculated according to a single liquid hydrogen carrier vehicle with a 40m^3 volume tanker. The assessment of relevant cost composition is shown in Table 1.

Table 1. Composition of liquid hydrogen carrier cost.

Parameter	Value	Remark
Carrier purchase	2,500,000CNY	Including tanker, depreciation period: 10 years
Labor cost[17]	650,000CNY/a	
Fuel cost	195CNY/100km	Fuel consumption: 30L/100km
Tolls, parking fees, etc	130CNY/100km	
Insurance and maintenance	56CNY/100km	

The transportation expenditure of liquid hydrogen could be controlled to less than 5CNY/kgLH2 in consideration of 90% filling rate, residual liquid volume, transfer period, 80km/h speed limit and other influencing factors. The transportation cost of current 20MPa high-pressure gaseous hydrogen trailer is also compared, as shown in Figure 3. The liquid hydrogen transportation expenditure increases very slowly with distance growth, whose low sensitivity leads to a much smaller cost rise comparing to that of high-pressure gaseous hydrogen.

The refueling terminal is generally located in urban area corresponding to 0.7CNY/kWh electricity price. The refueling SEC of liquid hydrogen station is about 0.75kWh/kgLH2, and that of high-pressure gaseous is 5kWh/kgLH2. The refueling expenditure is also depicted in Figure 3, which remains unchanged with distance variation. Liquid hydrogen also keeps advantages in other cost in the refueling station, such as smaller land cost, less operators and higher operation safety in terms of the high energy density, low storage pressure and high vaporization purity.

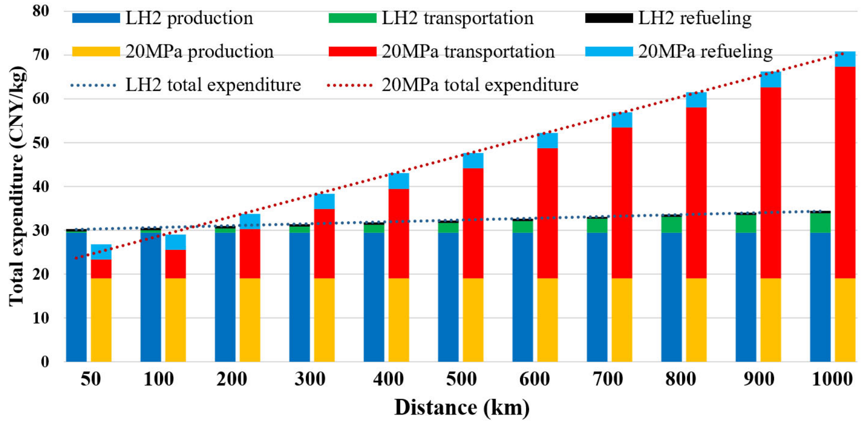

Figure 3. Economic comparison between liquid and compressed hydrogen along with distance

4.3. Total Comprehensive Cost

The production cost of 20MPa high-pressure gaseous hydrogen is about 10.5CNY/kg lower than that of liquid hydrogen. In terms of transportation cost increment per 100km, the transportation cost of high-pressure mode increases by 4.63CNY/kg/100km and that of liquid hydrogen is 0.44CNY/kg/100km. The accumulation of transportation distance leads to the rapid rise of high-pressure transportation cost.

Figure 3 shows the comprehensive costs of production, transportation and terminal refueling. The balance point of these two modes is 134km, i.e., when transport distance is less than 134km, the comprehensive cost of 20MPa high-pressure gaseous hydrogen is lower, and that of liquid hydrogen mode is lower for distance over 134km. In renewable energy source area, the balance distance could be further decreased by renewable energy-related electric hydrogen system [18]. The advantages of liquid hydrogen technology route will be more obvious. Liquid hydrogen production and transportation are more suitable for long-distance hydrogen transportation with good economic efficiency.

5. Conclusions

The liquid hydrogen technology route is applicable to the large-scale transportation and application of civil used hydrogen. The independent production capacity of liquid hydrogen in China can only meet the promotion and application of hydrogen demanded in current initial demonstration stage. It is extremely necessary to develop and explore the production and transportation technology of liquid hydrogen in the future. The capacity of liquid hydrogen plant is a key factor determining the liquid hydrogen economic expenditure.

The comprehensive cost of liquid hydrogen technology route is lower than that of commonly employed high-pressure gaseous route under the long-distance transportation condition. The high energy consumption and expenditure of liquid hydrogen production could be balanced by the insensitivity of liquid hydrogen transportation cost to distance variation, as well as the combination with renewable energy-related electric hydrogen system, which could further reduce the expenditure.

Acknowledgment

This investigation was funded by the Project of Science and Technology Plan of Beijing Science and Technology Commission (No. z201100004520030).

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