Storage and transportation technology solutions selection for large-scale hydrogen energy utilization scenarios under the trend of carbon neutralization

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Abstract. This paper mainly introduces the main pain point of China's civil hydrogen energy supply chain - the problem of storage and transportation, and analyzes the safety, economy and scale effect and other issues of the existing hydrogen energy storage and transportation, compares with other storage and transportation technology solutions, and comprehensively screens out the storage and transportation technology solution mainly based on liquid hydrogen technology. The liquid hydrogen technology solution has significant advantages over the existing compressed hydrogen system in terms of safety, economy and scale effect, especially for future large-scale hydrogen energy application scenarios. In addition, the future hydrogen energy storage and transportation system based on liquid hydrogen technology can help improve the overall utilization efficiency of country's renewable energy, promote the country's energy transition, promote the electrification of the country's transportation sector, and help achieve China's carbon emission reduction 2030/2060 target.

1. Introduction
In recent years, hydrogen energy has become the most important tool of industrial emission reduction, transportation emission reduction and energy emission reduction under the global trend of carbon neutralization. under the background that General Secretary Xi has announced the 2030/2060 goal of China's carbon neutralization, the importance of hydrogen energy industry is further amplified. One of the main pain points of the current hydrogen energy industry chain is the hydrogen storage and transportation. At present, the civil hydrogen energy supply chain in China is all based on compressed hydrogen technology, whose main problems are high storage and transportation costs, low safety level, and great difficulty in large-scale promotion. For the future large-scale application of hydrogen energy, there must be a hydrogen energy storage and transportation solution that can achieve low-cost, large-scale, long-distance and high-safety level. This paper will discuss this issue.

2. Analysis of the pain points and solutions for the large-scale utilization of hydrogen energy
At present, all hydrogen energy for civil use is transported by 20MPa long tube trailers, which is a relatively mature technology, but the storage and transportation cost is as high as 10 yuan/kg per 100 km, which cannot meet the needs of large-scale civilian use of hydrogen energy in the future; lower safety is also a obvious problem, in the past 2 years, three explosions have occurred in the global compressed hydrogen storage and transportation system, including the explosion accident in South Korea on May 23, 2019, the explosion accident in Norway on June 10, 2019, and the explosion accident in the United States on April 7, 2020, a series of accidents highlight the safety risk of the
current hydrogen energy storage and transportation system; in addition, once there is a large-scale promotion, the scale benefit of the actual storage and transportation system is not obvious, resulting in excessive investment in fixed assets that cannot meet the requirements of large-scale promotion.

Considering the low-cost, large-scale, long-distance, and high-safety level requirements of the future hydrogen energy storage and transportation system, this paper analyzes various storage and transportation technology solutions such as liquid hydrogen, pipeline, organic hydrogen, Mg-based metal hydride hydrogen storage, cryo-compressed hydrogen storage, etc. Select the proper hydrogen energy storage and transportation technology solution that is most likely to meet the above requirements at the same time.

2.1. Liquid hydrogen

2.1.1. Cost. The cost of liquid hydrogen transportation is calculated as follows:

Single payload of liquid hydrogen tanker truck is about 3,600 kg.

Liquid hydrogen tanker costs about 10 yuan per km.

The transportation radius is 100 km, so the round-trip is 200 km.

Thus: the transportation cost per kilogram of liquid hydrogen per 100 kilometers = 10 yuan/km × 200 km/3,600 kg ≈ 0.56 yuan/kg.

Considering the loss of boil off gas of liquid hydrogen (less than 1% per day) and other kinds of uncertain costs, the transportation cost per kilogram of liquid hydrogen per 100 km will not exceed 1 yuan/kg.

The following figure shows the cost of liquid hydrogen versus 20 MPa and 50 MPa compressed hydrogen at different transportation distances, which fully reflects the sensitivity of the transportation cost of the two technical solutions to the transportation distance.

![Figure 1. Comparison of distance sensitivity of liquid/compressed hydrogen transport.](image)

2.1.2. Safety. The hydrogen supply system based on liquid hydrogen technology is much safer than the current hydrogen supply system based on compressed hydrogen technology for the following reasons:

- The liquid hydrogen storage and transportation system (tanker truck, liquid hydrogen tanks, etc.) does not withstand very high pressure, the design pressure is generally 0.6-0.8 MPa, so the technology to controlling leakage is less difficult and the probability of leakage is substantially reduced;[5]
- the adiabatic expansion energy of liquid hydrogen is less than one-thirtieth of that of compressed hydrogen, as detailed in Figure 2;
- The boiling temperature of liquid hydrogen is 20K (-253°C), and it needs to absorb a large amount of heat before it may burn or explode.
2.1.3. Scale effect. A hydrogen supply system of 5,000 tons/day is showed here below as an example to illustrate the scale advantage of liquid hydrogen over existing compressed hydrogen storage and transportation systems.

| Table 1. Comparison of total investment in large-scale application scenarios of compressed hydrogen/liquid hydrogen. |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 5000 tons/day hydrogen supply system | Compressed hydrogen (50 MPa) | Liquid hydrogen |
| Total investment | 87.5 billion | 68.0 billion |
| 20MPa hydrogen transport | 30,000 long tube trailers payload: 400 kg | N/A |
| 50MPa hydrogen transport | 15,000 long tube trailers payload: 800 kg | N/A |
| Main station compressor | 5 million single system * 10,000 units=50 billion | N/A |
| Investment in trailer | 1.5 million/vehicle * 30,000=45 billion | N/A |
| Liquid hydrogen tanker | N/A | 2,000 vehicles (payload: 3 tons/vehicle) |
| Liquefaction system | N/A | 60 billion (Large-scale liquid hydrogen plant cost 12 million/ton) |
| Investment in liquid hydrogen tanker | N/A | 4 million/vehicle * 2000 vehicles =8 billion |
### Table 2. Comparison of compressed hydrogen/liquid hydrogen refueling stations.

| Technical solution | Investment on building station | Floor space | Operating cost | Safety | Operational reliability |
|--------------------|--------------------------------|-------------|---------------|--------|----------------------------|
| Liquid hydrogen refueling station | 8 million-1 ton/10 million-2 tons (excluding land cost) | 1,000 m²-1 ton/1,200 m²-2 tons | < 8 yuan/kg | Significantly higher than compressed hydrogen stations (can be built in residential areas) | High pressure liquid hydrogen pump with low cost, easy maintenance and multiple backups |
| Compressed hydrogen refueling station | 13 million-1 ton/18 million-2 tons (excluding land cost) | 3,000 m²-1 ton/4,500 m²-2 tons | Average 10~15 yuan/kg | Higher safety spacing requirements than liquid hydrogen stations | High compressor cost, high maintenance time cost and expense |

As seen in Tables 1 and 2 above:
- Large-scale liquid hydrogen supply system has lower fixed asset investment than compressed hydrogen supply system.
- The demand for liquid hydrogen tankers in the public transportation network is much lower than that of long-tube trailers, which substantially reduces the risk of accidents.
- The floor space, investment, operation cost and failure rate of liquid hydrogen refueling station with the same refueling capacity are lower than that of compressed hydrogen refueling station, especially the advantage of small floor space, which greatly reduces the difficulty and cost of site selection and construction of future hydrogen refueling stations.

In summary, liquid hydrogen has more scale benefits than compressed hydrogen.

#### 2.2. Pipeline hydrogen

There are two prerequisites for long-distance pipeline hydrogen transportation:
- The transportation volume is large enough, normally means over 4 million tons/year. In addition, pure hydrogen pipeline needs to build a pressurizing station every 100 km, at present there is no mature product for high-capacity compressor for pure hydrogen, which is very difficult to develop, because the hydrogen molecules are very small. Without a large capacity compressor, the long-distance pipeline of pure hydrogen is not technically feasible.
- Both upstream hydrogen production and downstream applications are continuous and stable. Since the future hydrogen will mainly come from wind-powered and solar power in the "Three North-Areas", it will naturally have the problem of unstable supply, and because the hydrogen production capacity is largely distributed, it is difficult to build pure hydrogen pipelines for hydrogen distribution.

From an economic point of view, the investment in pipeline construction is huge. The payback period of investment is generally considered more than 30 years. In addition, there is also the problem of difficulty in land acquisition, so the implementation feasibility is very low. Therefore, the construction of long-distance pipelines in China is basically led by government.

Regarding the pure hydrogen pipelines in Europe and the United States, they are basically pipelines within 50 km, and most of them are no more than 20 km. The mileage of their pure hydrogen pipelines is the mileage obtained by adding up multiple pipelines, not a single pipeline.

#### 2.3. Organic hydrogen storage

Take Chiyoda Corporation’s technology as an example to analyze the economics of organic hydrogen storage.

Regardless of the investment and energy consumption on the hydrogenation side, simply consider the economy of the dehydrogenation side (assuming that the price of the hydrogen source is the same as the price of the liquid hydrogen source):
The process of dehydrogenation requires a high temperature above 300°C, and the energy consumption is about 10 kWh/kgH₂, which is calculated at 0.6 yuan/kWh, the cost of dehydrogenation is 6 yuan/kg; in addition, due to the deterioration of the quality of hydrogen released by organic hydrogen storage, additional purification cost is about 2 yuan/kg. The subsequent steps are similar to compressed hydrogen, which is transported to compressed hydrogen refueling stations through compression and long tube trailer.[4]

For organic hydrogen storage, the cost of dehydrogenation and purification is as high as 8 yuan/kg, which is close to the total cost of compressed hydrogen, adding subsequent compression cost and transportation and distribution cost, the total cost will inevitably be higher than that of compressed hydrogen, and much higher than that of liquid hydrogen technology.

In addition, this model does not consider the policy risk and land requirement of building chemical plants near the hydrogen refueling stations.

In a few special application scenarios where waste heat is available at the dehydrogenation side, its storage and transportation costs will be significantly reduced, but it does not meet the main scenario requirements for large-scale hydrogen energy applications in the future, so it will not be discussed too much here.

2.4. Mg-based metal hydride
Similar to organic hydrogen storage, the dehydrogenation stage of Mg-based metal hydride hydrogen storage also requires a high temperature above 300°C, and the unit energy consumption of dehydrogenation is about 10 kWh/kgH₂. The quality of dehydrogenation after metal hydrogen storage will not decrease, but the hydrogen weight density and the rate of hydrogen release are lower than organic hydrogen storage, so its economic performance is even worse. It is not repeated here.

2.5. Cryo-compressed hydrogen
Cryo-compressed hydrogen is actually converted from liquid hydrogen. Compared with liquid hydrogen technology solution, cryo-compressed hydrogen and liquid hydrogen have their own advantages, depending on different scenarios. Compared to other storage and transportation technology solutions, the comprehensive advantages of cryo-compressed hydrogen are very obvious.

2.5.1. Economy. The mass energy density and volume energy density of cryo-compressed hydrogen can approach or even exceed that of liquid hydrogen (depending on different pressures). In addition, cryo-compressed hydrogen has no evaporation losses, which is an advantage compared to liquid hydrogen, but considering the difference in cost between liquid hydrogen storage tanks and cryo-compressed hydrogen tanks, the transportation cost of cryo-compressed hydrogen technology solution will be slightly higher than liquid hydrogen in most cases, but still much lower than other storage and transportation technology solutions.

2.5.2. Safety. Due to the high pressure of cryo-compressed hydrogen, the leakage control requirements of the storage and transportation system are higher, and the risk of leakage is higher. Therefore, the safety of the cryo-compressed hydrogen technical solution is lower than that of the liquid hydrogen technical solution.

Compared with compressed hydrogen, cryo-compressed hydrogen is safer than compressed hydrogen because of its lower temperature and lower possibility of combustion or explosion.

2.5.3. Scale effect. The hydrogen energy supply system based on cryo-compressed hydrogen technology has an extra set of gasification & pressurizing device than the liquid hydrogen plant (normally, high-pressure liquid hydrogen pumps are used to directly realize phase change & pressurizing), the number of vehicles at the transportation end is comparable to the liquid hydrogen system, and the hydrogen is supplied to the existing compressed hydrogen refueling station system.

In general, the fixed asset investment at the front end is slightly higher than that of liquid hydrogen,
and the scale effect of the compressed hydrogen refueling station at the back end is not obvious, therefore, in general, its scale effect is not as good as that of the hydrogen supply system based on liquid hydrogen.

The above analysis shows that, considering the requirements of low-cost, large-scale, long-distance and high-safety level of the future hydrogen energy storage and transportation system, liquid hydrogen technology is the best solution that meets all the above requirements.

3. The significance and value of large-scale utilization of liquid hydrogen technology
At present, the domestic hydrogen energy industry has gradually formed a consensus on accelerating the R&D of liquid hydrogen technology, which can promote the rapid development of the hydrogen energy industry, at the same time, it also has greater strategic value for the country.

3.1. Improving the efficiency of China's clean energy macro-utilization
China's high-quality wind and solar energy resources are distributed in the "Three North Areas", and majority of China's high-quality hydropower resources are distributed in the southwest area.[5]

![Figure 3. Wind and solar resources quality distribution map.](image)

At present, there is a large amount of abandoned power in wind-power, solar-power in the “Three North Areas”, as well as hydropower in the southwest. With the rapid increase of renewable energy installed capacity in the future, the abandoned power of wind, solar, and hydropower will rise further.

Based on the advantages of liquid hydrogen technology, most of the abandoned power in the future can be used to produce hydrogen by electrolysis of water, then liquefied and shipped to the consumer market in economically developed areas, thus providing another means of large-scale energy transmission in addition to the power grid, improving the efficiency of renewable energy utilization in China from a macroscopic perspective, and realizing the optimal resource allocation nationwide.

3.2. Contribute to China's energy transition
In recent years, the trend of energy transition in China has become more and more obvious. Hydrogen energy will play an important role in the future energy system of China. The basic concept of future energy system is shown in Figure 4 below:
Figure 4. Vision of the future energy system.

Characteristics of this system:
- Multi-energy complementarity based on the power grid, that is, a complementary system of electricity, wind, solar, water, and hydrogen;
- Based on energy storage technology including hydrogen storage, it can achieve partial and intermittent off-grid;
- Electricity is no longer the only energy carrier; hydrogen assumes part of the energy carrier function.

In the above system, hydrogen plays three key roles:
- Energy storage medium: The key supporting technology for multi-energy complementation system is energy storage technology. Without energy storage technology, multi-energy complementation system cannot be truly achieved, because most renewable energy sources have obvious volatility and uncertainty. There must be a large and cheap enough energy storage method to smooth the fluctuations of various power generation capabilities. Partially and intermittent off-grid is completely dependent on energy storage technology, and it is almost impossible to achieve true off-grid without effective energy storage technology.
- End-consumption energy: In the future, hydrogen energy will be directly used as an energy product for civil consumption. The main civil consumption scenarios include fuel cell vehicles and natural gas pipeline hydrogen mixing, etc. The utilization of this energy will significantly accelerate the decarbonization of the existing energy system.
- A chemical raw material: Hydrogen produced from renewable energy will directly participate in most petrochemical and metallurgical production processes, solving the problems of high carbon emissions and low efficiency in the original production system.

From the above analysis, it can be seen that hydrogen energy will play a variety of key roles in the future energy system, and the large-scale civil use goal of hydrogen energy cannot be achieved without the support of liquid hydrogen technology.

3.3. Help China achieve the carbon emission reduction 2030/2060 target
On September 22, 2020, President Xi Jinping solemnly promised that China’s carbon dioxide emission is expected to peak before 2030 and China aims to achieve carbon neutralization before 2060.
Figure 5. President Xi Jinping’s solemn commitment on carbon emission reduction.

Liquid hydrogen technology can promote the rapid development of civil hydrogen energy. In this process, it has the following two important meanings for carbon emission reduction:

One is to replace fossil energy, especially in the transportation sector. In 2019, China's oil consumption in the transportation sector was high up to about 66% of total oil consumption. If all the vehicles can be mostly replaced by hydrogen fuel cell vehicles, it will greatly reduce direct CO₂ emissions.

The second is to support the development and promotion of CCUS (Carbon Capture, Utilization and Storage) technology. At present, CCUS technology is developing rapidly around the world. The key point of CCUS technology is the efficient comprehensive utilization of CO₂. Currently, most of the technical solutions with carbon neutralization capabilities use hydrogen as the reductant for the catalytic reaction. If CCUS technology is widely promoted in the future, cheap and large amount of hydrogen will be the guarantee of this technical solution.

4. Conclusion and recommendations
Combining the above analysis and demonstration, the promotion and application of liquid hydrogen technology can significantly reduce the cost of hydrogen energy supply system, improve safety level and have a better scale effect; meanwhile, the development of liquid hydrogen technology can help improving the macro utilization efficiency of clean energy, accelerating the energy transformation in China and helping China to achieve the carbon emission reduction 2030/2060 target as soon as possible. Therefore, it is recommended to strengthen the R&D of liquid hydrogen technology and international cooperation to promote the rapid implementation of liquid hydrogen technology, help the development of China's hydrogen energy industry.

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