Jurnal Informasi, Sains dan Teknologi
Vol.7 No.1 Juni 2024
E-ISSN :2829-2758, P-ISSN : 2828-7207, Hal 01-10
DOI : https://doi.org/10.55606/isaintek.v1i7.184

Techno-Economic Analysis Of Hydrogen Storage Technologies For Transport Applications

Fachri Munadi
Department of Chemical Engineering, University of Indonesia
Email: mnd.fachri@gmail.com

Dijan Supramono
Department of Chemical Engineering, University of Indonesia
Email: dsupramo@che.ui.ac.id

*Author Correspondence: mnd.fachri@gmail.com**

Abstract.*The world's energy industries contribute 87% to the increase in global greenhouse gases. To reduce global greenhouse gas emissions, hydrogen as clean energy is an alternative energy source with a gravimetric energy density of 120 MJ/kg and a volumetric density of 0.0824 kg/m3. The main challenge of hydrogen as an energy carrier is its low volumetric density, thus requiring hydrogen storage technology at higher volumetric densities. Hydrogen storage systems are crucial to the hydrogen supply chain process, especially in terms of its economics. The hydrogen storage system consists of hydrogenation, transportation, and dehydrogenation processes. This paper uses the techno-economic analysis of five types of hydrogen storage technologies: compressed hydrogen, liquid Hydrogen, liquid organic hydrogen carrier, metal hydride, and ammonia. Hysys was introduced to help process design, process modeling, and equipment sizing of each technology. System costs ($/kg) are determined based on projected Capital Expenditure (CapEx) and Operational expenditure (OpEx) of each hydrogenation and dehydrogenation process, as well as shipping transportation cost at 2000 km. The results show that liquid organic hydrogen carrier had the lowest system cost of $2.84/kg, followed by metal hydride at $2.95/kg, compressed hydrogen at $3.33/kg, ammonia at $7.21/kg, and liquid hydrogen at $11.51/kg. However, the storage efficiency of liquid organic hydrogen carriers is only 8.73%, compared to compressed hydrogen at 99%. The results show that the cost of hydrogen storage systems needs to be significantly reduced for long-term and large-scale applications.*

Keywords: *Hydrogen, Storage Technology, Transportation, Technical Analysis, Economic Analysis*

Abstrak. Industri energi dunia menyumbang 87% terhadap peningkatan gas rumah kaca global. Untuk mengurangi emisi gas rumah kaca global, hidrogen sebagai energi ramah lingkungan merupakan sumber energi alternatif dengan densitas energi gravimetri sebesar 120 MJ/kg dan densitas volumetrik sebesar 0,0824 kg/m3. Tantangan utama hidrogen sebagai pembawa energi adalah kepadatan volumetriknya yang rendah, sehingga memerlukan teknologi penyimpanan hidrogen pada kepadatan volumetrik yang lebih tinggi. Sistem penyimpanan hidrogen sangat penting dalam proses rantai pasokan hidrogen, terutama dari segi keekonomiannya. Sistem penyimpanan hidrogen terdiri dari proses hidrogenasi, transportasi, dan dehidrogenasi. Makalah ini menggunakan analisis tekno-ekonomi dari lima jenis teknologi penyimpanan hidrogen: hidrogen terkompresi, Hidrogen cair, pembawa hidrogen organik cair, hidrida logam, dan amonia. Hysys diperkenalkan untuk membantu desain proses, pemodelan proses, dan ukuran peralatan dari setiap teknologi. Biaya sistem ($/kg) ditentukan berdasarkan proyeksi Belanja Modal (CapEx) dan Belanja Operasional (OpEx) setiap proses hidrogenasi dan dehidrogenasi, serta biaya transportasi pengiriman pada 2000 km. Hasilnya menunjukkan bahwa pembawa hidrogen organik cair memiliki biaya sistem terendah sebesar $2,84/kg, diikuti oleh hidrida logam sebesar $2,95/kg, hidrogen terkompresi sebesar $3,33/kg, amonia sebesar $7,21/kg, dan hidrogen cair sebesar $11,51/kg. Namun efisiensi penyimpanan pembawa hidrogen organik cair hanya 8,73% dibandingkan dengan hidrogen terkompresi sebesar 99%. Hasilnya menunjukkan bahwa biaya sistem penyimpanan hidrogen perlu dikurangi secara signifikan untuk aplikasi jangka panjang dan skala besar.

Kata Kunci: Hidrogen, Teknologi Penyimpanan, Transportasi, Analisis Teknis, Analisis Ekonomi

Received Maret 31,2024; Accepted April 15,2024; Published Juni 30,2024
* Fachri Munadi, mnd.fachri@gmail.com

INTRODUCTION

The world energy industry is currently facing quite serious problems. Global energy demand is increasing, causing high world energy consumption. As a result, levels of greenhouse gas emissions, such as carbon dioxide, have increased significantly [1]. The world's energy industry contributes 87% to the increase in greenhouse gas emissions. In 2018, the increase in carbon dioxide reached 36.6 billion tonnes and will continue to increase [2]. Various actions are being taken to minimize the negative impacts of global warming and extreme climate change. One way is to develop sustainable and environmentally friendly energy that can be used as an energy carrier [3].

Hydrogen is a potential sustainable energy source that is environmentally friendly because the remaining hydrogen combustion only produces water [4]. Hydrogen has a high gravimetric energy density, namely 120 MJ/kg or 33.3 kWh/kg [5]. Compared with conventional fuel, namely gasoline (44 MJ/kg), the energy density of hydrogen is still much higher [2]. However, hydrogen has a very low volumetric density. Under normal pressure and room temperature, the volumetric density of hydrogen is 0.0824 kg/m^3. Compared with air in the same condition, air has a density of 1.184 kg/m^3 [4]. This is the main problem with hydrogen as an energy carrier, so using hydrogen globally for other industries has yet to be applied [6].

Developments in hydrogen storage technology have been carried out to overcome the low volumetric density of hydrogen. Hydrogen storage technology is the primary key that will lead to the success of increasing the use of hydrogen, especially from an economic perspective. A hydrogen storage system with high gravimetric and volumetric energy density is required [4]. Apart from that, several other important parameters are operating conditions, storage efficiency, durability, standardization, technological maturity, and life cycle [2]. To date, the mature and widely used hydrogen storage technologies are compressed hydrogen storage (CH_2) and liquid hydrogen storage (LH_2) [6].

Hydrogen storage systems can be applied to stationary or mobile [7]. In this paper, hydrogen storage system analysis is carried out for mobile applications, namely the distribution of hydrogen from on-site to the end user. Mobile applications pose a more significant challenge and are crucial for increasing the use of hydrogen as an energy alternative [4]. Various types of storage technologies are analyzed to be used in large-scale hydrogen transportation and distribution. Among them are compressed hydrogen (CH_2), liquid hydrogen (LH_2), liquid organic hydrogen carriers (LOHC), metal hydride (MH), and ammonia (NH_3). The hydrogen storage system can be seen in Figure 1.

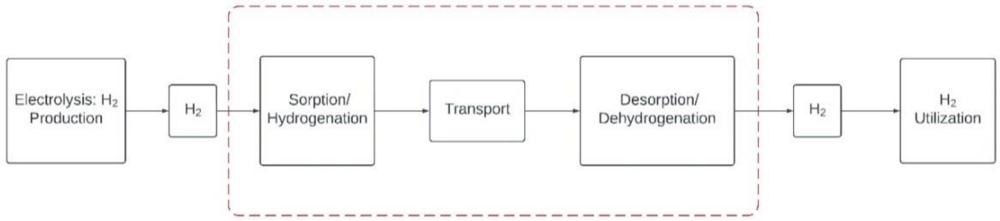

Figure 1. Hydrogen Storage System

Figure 1 also shows the scope of this research. Hydrogen gas must be transported or distributed from hydrogen producers to other industries requiring hydrogen remaining in the gas phase. The main process of a hydrogen storage system consists of hydrogenation, dehydrogenation, and transportation.

Each technology has maturity and readiness to be used as a hydrogen storage method in the next few years. However, each technology has obstacles that will lead to a hydrogen economy. Therefore, a techno-economic analysis of each technology was carried out to determine the technology that can be applied economically and has future development prospects [8]. The results of the techno-economic analysis can identify the problems of each technology so that it becomes a note regarding things that need to be developed and optimized in the future [2].

RESEARCH METHOD

Techno-economic analysis was done using Aspen Hysys software in the process design stage. The fluid package used is Peng-Robinson. Aspen Hysys simulates simple processes for the five hydrogen storage technology types: CH_2, LH_2, LOHC, MH, and NH_3. Each technology has different operating conditions, as shown in Table 1.

Table 1. Operational Conditions of Each Technology

Operational Condition	Compressed Hydrogen	Liquid Hydrogen	Liquid Organic Hydrogen Carriers	Metal Hydride	Ammonia
Hydrogen Production Capacity (tonne/year)	8000000	8000000	8000000	8000000	8000000
Transportation Distance (km)	2000	2000	2000	2000	2000
Hydrogenation – Pressure (bar)	700	1	19	55	150
Hydrogenation – Temperature (°C)	45	-253.15	150	500	581
Dehydrogenation – Pressure (bar)	-	-	7	150	15
Dehydrogenation – Temperature (°C)	-	-	300	650	650

The process simulation results from Aspen Hysys are used in the equipment design process and balance and mass calculations. Economic analysis of hydrogen storage technology is carried out based on calculations of capital expenditure, operational expenditure, transportation costs, and total system costs. Capital expenditure is determined based on the total investment costs for main equipment from the hydrogenation and dehydrogenation processes. Operational expenditure is determined based on the total raw material, electricity, labor, and maintenance costs from the hydrogenation and dehydrogenation processes. Transportation costs are determined based on the fuel cost approach. The total system cost is determined based on the economic calculations of CapEx, OpEx, and Transportation Costs.

RESULT AND DISCUSSION

Capital Expenditure

A comparative analysis of capital expenditure (CapEx) was carried out to determine the investment costs for each technology. In a hydrogen storage system, the total capital expenditure consists of inside battery limit (ISBL) costs and tube trailer investment costs. ISBL cost is calculated based on

$$C_{design} = C_{base}\left(\frac{IV_{design}}{IV_{base}}\right)$$

Here, C_{base} is the material investment cost in the base year, obtained based on the equipment design results from Aspen Hysys. Then, IV_{base} is the index value based on the base year, while IV_{design} is the index value for the year specified in the project, in this case, 2030. The index value is determined based on the forecasting of the Chemical Engineering Plant Cost Index (CEPCI). Main equipment investment costs in the projected year (2030) are obtained based on the C_{design} calculation above.

The investment cost in a tube trailer is an investment in a hydrogen storage tank ready to be transported. Tube trailers from each technology have different specifications. The total investment cost of a tube trailer depends on the volumetric hydrogen density and operating conditions.

A comparison of the CapEx profiles of each technology can be seen in Figure 2.

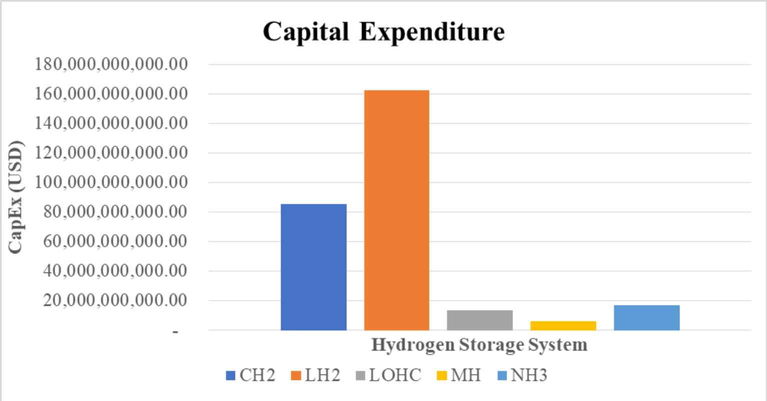

Figure 2. Capital Expenditure

Figure 2 shows that compressed hydrogen (CH_2) and liquid hydrogen (LH2) have very high investment costs compared to other storage technologies. The main equipment investment costs in CH_2 are in the form of compressors and storage tanks, while the investment costs in LH_2 are in the form of main cryogenic heat exchangers and refrigeration systems. Both CH_2 and LH_2 have the highest investment costs in tube trailer costs. Compressed hydrogen requires a tube trailer with materials that can withstand extreme pressure. Liquid hydrogen requires a tube trailer that can isolate heat transfer and is supported by a refrigeration system during transportation.

Compared with chemical storage (LOHC, MH, and NH_3), the CapEx of all three is still relatively low compared to physical storage (CH_2 and LH_2). Capital expenditure from LOHC technology is worth 15.69% of capital expenditure for CH_2, MH is 13.10%, and NH3 is 13.38%. These LOHC, MH, and NH_3 have simpler process mechanisms and operating conditions that are less extreme than CH_2 or LH_2. The most significant investment of these three technologies is generally in reactors, both for the hydrogenation and dehydrogenation processes. These LOHC, MH, and NH_3 can be stored in tube trailers under moderate operating conditions; they can comply with previously existing fuel storage standards.

Operational Expenditure

Operational expenditure (OpEx) analysis is carried out to compare operational costs for each technology, on an annual basis. Total OpEx is calculated based on the sum of raw material costs, electricity costs, labor costs, and maintenance costs. A comparison of the OpEx profiles of each technology can be seen in Figure 3.

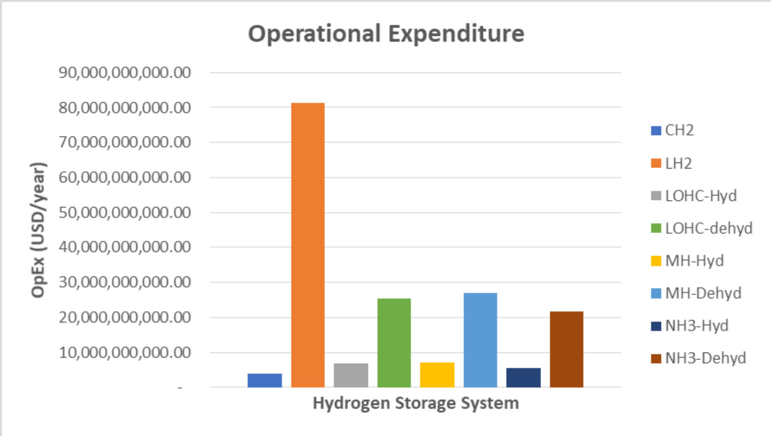

Figure 3. Operational Expenditure

Compressed and liquid hydrogen do not have a dehydrogenation process because they are both types of physical storage. Both CH_2 and LH_2 can be used directly, depending on the industry that requires it. Even though LH_2 does not have a dehydrogenation process, the operational costs of LH_2 are still the highest compared to other storage technologies. This is due to the very extreme operating conditions of LH_2, where liquefaction is carried out up to a cryogenic temperature of 20 K. The highest operational cost burden on LH_2 is electricity costs, which is 68.47%.

Compressed hydrogen has the lowest operational costs compared to other technologies. The basic principle of a compressed hydrogen system is periodic compression up to 700 bar to reduce the workload of each compressor. The result is that electricity costs are much reduced, so this is a solution for industries that want to store hydrogen at high-pressure stationary.

Chemical storage (LOHC, MH, and NH_3) each has a hydrogenation and dehydrogenation process. The hydrogenation process is carried out on-site in a hydrogen plant, while dehydrogenation occurs at the end user after the transportation process. These LOHC, MH, and NH_3 have low operational costs in the hydrogenation process. For LOHC, the highest operational cost is raw material costs because it requires toluene as the primary material for methylcyclohexane. The electricity cost of LOHC is low because it operates at a temperature of 150 ^oC and is assisted by a catalyst. For MH, operational costs are found in raw material and electricity costs. The raw material needed is Mg as the primary material for MgH_2. Electricity costs for MH are higher than LOHC because the operating conditions for making MgH_2 are relatively high at a temperature of 500 ^oC. Meanwhile, for NH_3, the operational costs of the hydrogenation process are electricity costs. This is because the operating conditions in the reactor are high at a temperature of 580 ^oC.

The operational expenditure of the dehydrogenation process, be it LOHC, MH, and NH_3, is much higher than the operational expenditure of the hydrogenation process. This is due to the large amount of energy required for the process of releasing bound hydrogen into the form of pure hydrogen. Both LOHC, MH, and NH_3 have the highest electricity loads on dehydrogenation reactors, which also causes operational electricity costs to be high. The high operational costs involved in the dehydrogenation process are one reason hydrogen storage is better directly. For example, they are using ammonia directly as fuel. And the high operational costs of the dehydrogenation process are why the use of hydrogen by other industries is still hampered, because it will cause the price of the hydrogen gas, they receive to be higher.

Transportation Cost

Transportation cost analysis was carried out by comparing the transportation costs of each technology with a large hydrogen capacity and a long transportation distance of 2000 km. The transportation mechanism used in this research case study is shipping transportation. Transportation costs are calculated simply by calculating the total fuel costs required by the ship to distribute the total hydrogen. A comparison of transportation costs for each technology can be seen in Figure 4.

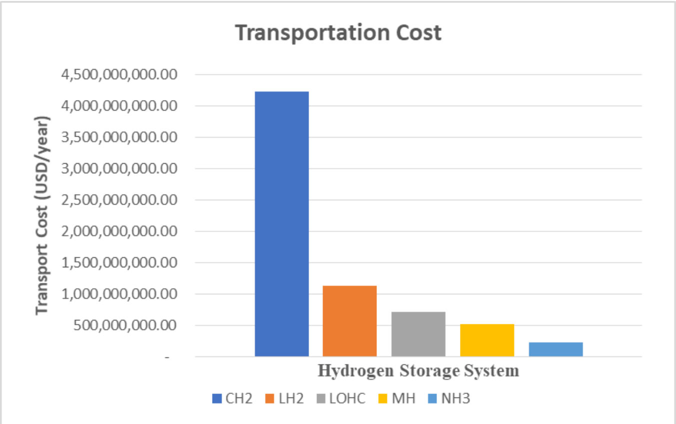

Figure 4. Transportation Cost

Figure 4 shows the transportation costs of each technology, where compressed hydrogen has the highest transportation costs. Even though the hydrogen gas pressure has been increased to 700 bar, the volumetric density of hydrogen gas is still lower compared to other technologies. The number of tube trailers needed depends on the volumetric density of each technology. The low volumetric density of compressed hydrogen indicates that the number of tube trailers required is higher. The more tube trailers, the higher the number of ships needed, which will cause higher fuel costs. LH_2, LOHC, MH, and NH_3 have the same transportation system as existing fuels because they have a liquid phase (solid for MH). It can be concluded that hydrogen gas transportation over very long distances, is not suitable for global application in hydrogen supply chain systems.

Total System Cost

Total system cost is the total cost resulting from calculations of capital expenditure, operational expenditure, and transportation costs of the entire process in the hydrogen storage system. A comparison of the total system cost of each technology can be seen in Figure 5.

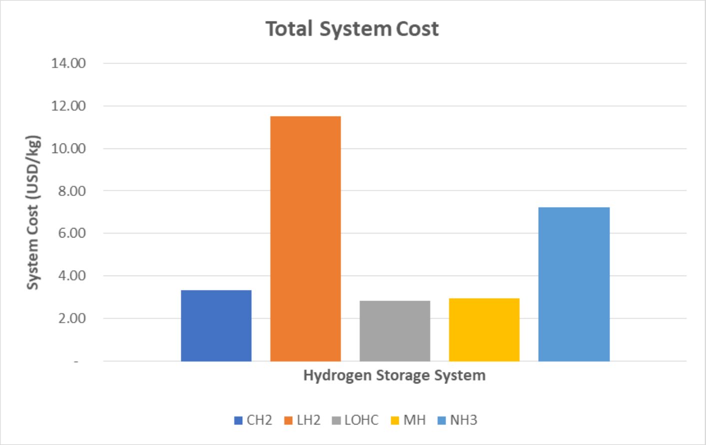

Figure 5. Total System Cost

Figure 5 shows that liquid hydrogen has the highest total system cost compared to other technologies. The total system cost of LH_2 is \$11.51/kg, followed by NH_3 is \$7.21/kg; CH_2 is \$3.33/kg; MH, \$2.95/kg; and LOHC, \$2.84/kg. The high total system cost of LH_2 is caused by the high operational cost burden shown in the operational expenditure profile. Extreme operating conditions, reaching cryogenic temperatures of 20 K, require very high energy. These results support that liquid hydrogen cannot be applied globally as a hydrogen storage technology because it will cause a drastic increase in hydrogen prices.

Ammonia has the second highest total system cost after liquid hydrogen. This is because the NH_3 dehydrogenation process requires a very high energy level in the reactor compared to other technological dehydrogenation processes. As with liquid hydrogen, operational expenditure is the main reason for the high total system cost. However, ammonia transportation is still safer than liquid hydrogen transportation.

Compressed hydrogen storage has a total system cost that is relatively cheaper than LH_2 and NH_3. This is supported by the low operational costs of the gradual compression process of hydrogen gas, even though capital expenditure and transportation costs are higher than other technologies. Even though the total system cost of CH_2 storage is low, CH_2 storage cannot be applied as a storage medium on a large scale in the hydrogen transportation process. The main problem with CH_2 storage is that the pressure is too high and is unsafe in the transportation process scheme.

Metal hydride and liquid organic hydrogen carriers have almost the same total system cost profile. Both technologies have relatively cheap total system costs and have the potential to be applied globally in hydrogen storage transportation schemes. However, the main reason these two technologies still cannot be applied is because the hydrogen storage efficiency of these two technologies is still very low. LOHC has a storage efficiency of 8.7%, and MH has a storage efficiency of 7%. So, there is still much room for this technology to improve.

Total system cost can determine the price of hydrogen when it is distributed or arrives at the end user. Total system cost can be used as the lowest price margin of the hydrogen price. So, the higher the total system cost of a technology, the higher the price of the hydrogen produced. Overall, chemical storage (LOHC, MH, and NH_3), can still be developed, especially from the dehydrogenation process which has high operational costs.

CONCLUSIONS

The paper analyzes the techno-economic feasibility of 5 types of hydrogen storage technology, namely compressed hydrogen (CH_2), liquid hydrogen (LH_2), liquid organic hydrogen carriers (LOHC), metal hydride (MH), and ammonia (NH_3). Comparative analysis was carried out based on each technology's capital expenditure, operational expenditure, and transportation costs. The results of the CapEx, OpEx, and transportation cost calculations produce the total system cost. The total system cost shows the minimum margin on the hydrogen sales price. Based on the results, the lowest total system cost is shown by LOHC at \$2.84/kg, followed by MH at \$2.95/kg, CH_2 at \$3.33/kg, NH_3 at \$7.21/kg, and LH_2 at \$11.51/kg. Both LOHC and MH can compete techno-economically. Meanwhile, neither CH_2 nor LH_2 are suitable for use as hydrogen storage technology for the transportation process. Overall, each technology still requires development, especially in the dehydrogenation process. These LOHC, MH, and NH_3 have operating conditions that are still quite high, causing high operational costs. Based on the research results, operational costs are the most important factor in determining total system costs.

REFERENCES

Abdin, Z., and W. Mérida. "Hybrid Energy Systems for Off-Grid Power Supply and Hydrogen Production Based on Renewable Energy: A Techno-Economic Analysis." *Energy Conversion and Management*, vol. 196, 2019, pp. 1068–1079.

Aziz, Muhammad, et al. "Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization." *Energies*, vol. 13, no. 12, 2020, p. 3062.

Abdin, Zainul, et al. "Projecting the Levelized Cost of Large Scale Hydrogen Storage for Stationary Applications." *Energy Conversion and Management*, vol. 270, 2022, p. 116241.

Usman, Muhammad R. "Hydrogen Storage Methods: Review and Current Status." *Renewable and Sustainable Energy Reviews*, vol. 167, 2022, p. 112743.

Preuster, Patrick, et al. "Hydrogen Storage Technologies for Future Energy Systems." *Annual Review of Chemical and Biomolecular Engineering*, vol. 8, no. 1, 2017, pp. 445–471.

Zhang, Fan, et al. "The Survey of Key Technologies in Hydrogen Energy Storage." *International Journal of Hydrogen Energy*, vol. 41, no. 33, 2016, pp. 14535–14552, doi:10.1016/j.ijhydene.2016.05.293.

Moradi, Ramin, and Katrina M. Groth. "Hydrogen Storage and Delivery: Review of the State of the Art Technologies and Risk and Reliability Analysis." *International Journal of Hydrogen Energy*, vol. 44, no. 23, 2019, pp. 12254–12269.

Wang, Mengjiao, et al. "Review of Renewable Energy-Based Hydrogen Production Processes for Sustainable Energy Innovation." *Global Energy Interconnection*, vol. 2, no. 5, 2019, pp. 436–443.