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Techno-economic assessment of physical-based hydrogen storage technologies: An efficient refrigeration management

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Abstract

The physical-based storage of hydrogen as a compressed gas or as a liquid has many advantages over material-based methods that may require advanced storage materials, and different charge/discharge rates. However, its high energy demand is an important issue that needs to be addressed. The aim of this work was to evaluate the techno-economic performance indices in terms of energy density and SEC of C_CH_2 over conventional LH_2 and CGH_2 storage under convenient state conditions. The results reveals that under C_CH_2 storage conditions, a higher hydrogen density of≈ 90 kg/m^3 was obtained at 53 K and 700 bar, with an SEC value of 39 kWh/kg. For LH_2 ≈ 71kg/m^3 at 3 bar and 20 K with a SEC of 45 kWh/kg and CGH_2 ≈ 40.5 kg/m^3 at 700 bar and 300 K with a SEC of 35.5 kWh/kg. The hydrogen storage density could be doubled from 40 kg/m^3 at 700 bar and 300 K using CGH_2 to 80 kg/m^3 at ≈ 38 K using C_CH_2, but with only 300 bar. Hence, these optimal points could be viable options for the demand of different applications, such as hydrogen-refueling stations, and for long transport with a certain tradeoff between SEC and energy density.

Keywords: Hydrogen energy storage, cryo-compressed hydrogen (C_CH_2), industrial refrigeration, storage density, energy penalty.

1.INTRODUCTION

1.1. Background information

Considering the current global energy crisis and the potential depletion of oil reserves, decarbonization, energy efficiency, and sustainability are among the most important issues of concern for energy systems. One of the clean energy options to achieve this vision is the introduction of hydrogen as a new renewable energy vector. However, storage is a major hurdle due to its low density (0.08988 g/l, at 1 atm or 101.325 kPa). Material-based i.e. LOHCs, ammonia, hydride, and physical-based storage methods, such as liquid hydrogen (LH_2), compressed hydrogen (CGH_2), and cryo-compressed hydrogen (C_CH_2), are commonly used storage schemes at particular temperature and pressure conditions based on the type of hydrogen demand [1]. Despite several years of intensive research in this field, meeting all the best indicators of hydrogen energy storage efficiency remains a great challenge. None of the storage schemes have optimally fulfilled all the different storage evaluation metrics set by the US DOE, such as storage capacity, density (volumetric/gravimetric), energy efficiency, operating temperature, cycle life, system life, and fill time [2]. As a result, to achieve a high hydrogen energy density with a lower energy penalty of the process, different storage technologies have been developed. In material-based hydrogen storage schemes, metal hydrides, carbon nanotubes, ammonia, activated carbon, and LOHCs can be used based on absorption/physisorption, adsorption, and chemical reactions. With these storage methods, a hydrogen capacity of 5-7wt% can be achieved, depending on the material type and the operating conditions for loading hydrogen into the storage [3, 4, 5]. However, this method is limited by the high energy demand for unlocking hydrogen molecules from storage materials, lower cyclability (<20 cycles), lower volumetric hydrogen density, and slow kinetics/absorption/desorption rates. On the other hand, LH_2 (cooling at below lower that its boiling point and close to ambient pressures) storage offers a good figure of merit in terms of high energy density (70 kg/m^3 at 1 atm) as well as very low temperature and pressure storage conditions. Nevertheless, this approach encounters challenges associated with reduced energy efficiency, increased specific energy consumption (SEC), and elevated rates of boil-off gas during storage and transportation. Compressed hydrogen (CGH_2) is the most commonly used and mature physical-based storage technology for hydrogen vehicles. Although this method offers a low storage density of 11-39 kg/m^3 at 15-700 bar and 300 K, it has a lower energy penalty than C_CH_2 and LH_2 [6]**.** To achieve a high energy density with a possible energy penalty, cryo-compressed hydrogen (C_CH_2) (cooling + compression) could be a better solution with a specific storage temperature and pressure combination, usually in the range of 35-110 K and 50-700 bar [7]. The exergy efficiency and specific energy consumption values of different liquefaction technologies for producing LH_2 and C_CH_2 are summarized in Fig. 1.

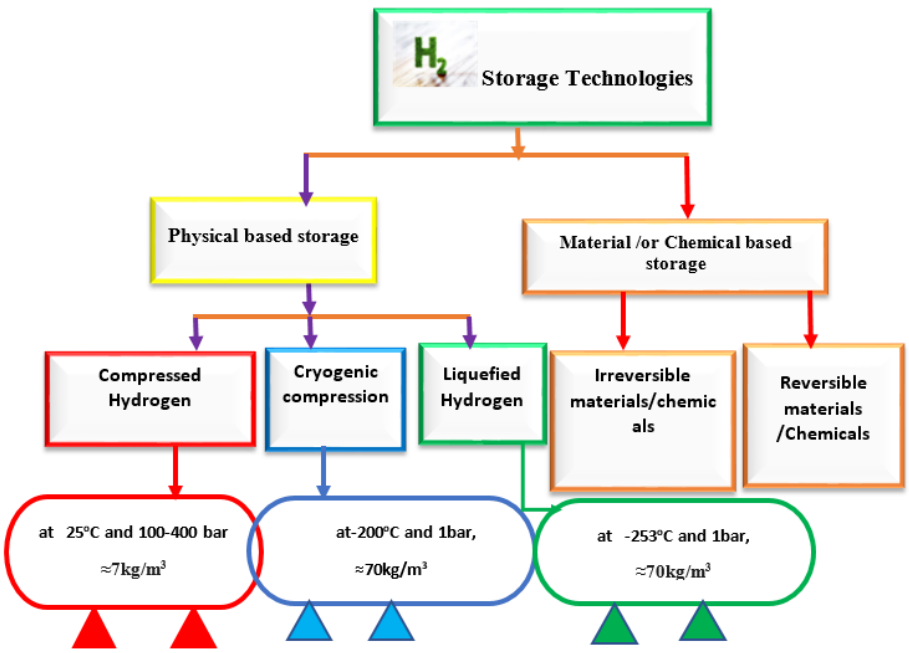

Figure 1. Hydrogen storage technologies [8].

Hence, the aim of this study was the thermodynamic evaluation and analysis of C_CH_2 at different state points of storage pressures and temperatures against CGH_2 and LH_2. The storage process performance was evaluated under a set of cryo-compressed hydrogen (C_CH_2) storage points in comparison with liquefied hydrogen (LH_2) and CGH_2 storage conditions. Moreover, this work aims to investigate the issues associated with low-density high-pressure gas hydrogen storage (CGH_2) and boil-off gas phenomena in LH_2 storage by proposing the optimal points of C_CH_2 hydrogen storage density and energy penalty as available options for hydrogen storage. The results were presented in response to storage density, specific energy consumption, cooling, exergy and compression power requirements, heat of combustion of hydrogen per total power consumption, and density of hydrogen per total power consumption.

2. METHODOLOGY

2.1. Refrigeration models, process description and performances under different set of parameters

In this study, a pre-cooled Claude cycle, which is a modified version of the classical Claude cycle, was used for the process modelling and simulation. This liquefaction technology is the most commonly used advanced technology because it allows the large-scale production of liquefied hydrogen. Its performance was evaluated using the C_CH_2 and LH_2 process methods. The results were also compared with those of three-stage CGH_2. This liquefaction cycle is known for its intermediate exergy efficiency and specific energy consumption (SEC) as compared to others as (Fig 2). The process components of the cycle are as follows (Fig 2): COMP (compressor), Recup (recuperator) as a pre-cooler, INTERCO (intercooler), GREENHY (green hydrogen), LIQUR (liquefied hydrogen reservoir), and TROTTL (throttling–JT valve). C_CH_2 process temperatures of (33-293) K and a storage pressure of (50-700) bar were used to observe their effect on the objective variables of the process. The results were compared with low-pressure and low-temperature storage (LH_2) and ambient compressed gas hydrogen (CGH_2). The process variables were modeled, simulated, and analyzed using the Engineering Equation Solver (EES) and plotted using sigma plot software [7]. The temperature ranges considered in this study were the operating storage pressure and temperature ranges commonly used in hydrogen storage and natural gas refrigeration processes [9]. Therefore, a range of pressures and temperatures for storage were chosen based on the most widely accepted standards for hydrogen storage points for end-user consumption, for example, tube tracks, heavy-duty vehicles (HDV), and hydrogen fueling stations.

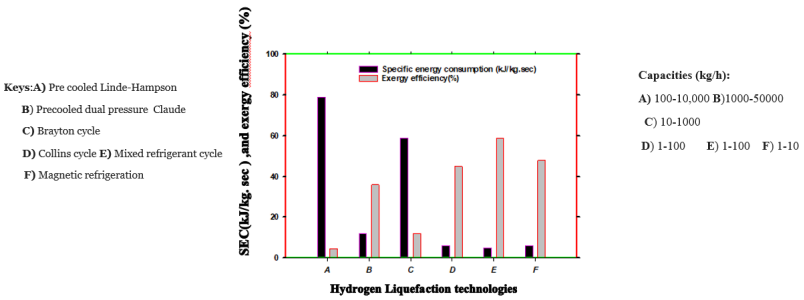

Figure.2, Performance summary of different refrigeration cycles.

These hydrogen storage points were considered to determine the effect of increasing the storage pressure on the overall storage density achieved and other thermodynamic performance indices. A static thermodynamic liquefaction process model for each storage method was employed based on the energy balance of isentropic P-T relation principles. In addition, at optimum storage densities, the volumetric energy densities and the total combustible energy stored of hydrogen at optimal storage conditions were estimated based on the context of combustible energy release per unit mass of

hydrogen as per the methods reported in [10]. All the detailed model equations are presented in the full-length version of this document up on request.

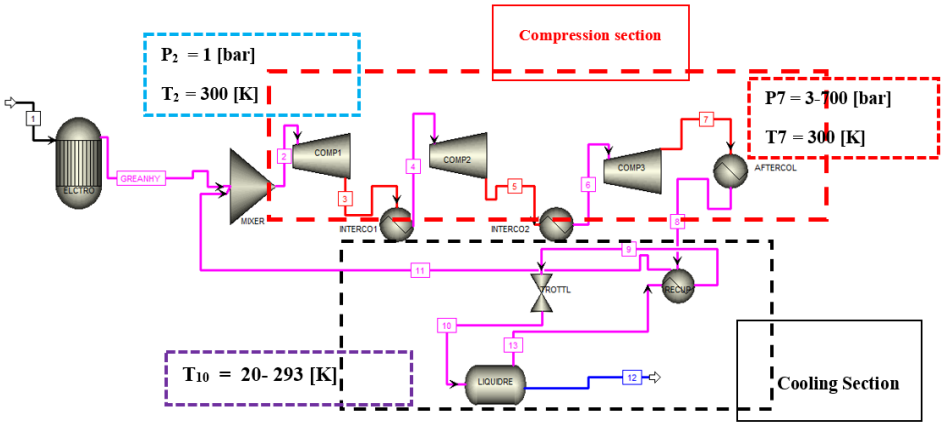

Figure 3. Precooled Claude hydrogen liquefaction cycle.

3. RESULTS AND DISCUSSION

3.1. Performance studies of CcH2, LH2 and CGH2 storage conditions

As it is depicted in Fig 4, at the CcH_2 storage conditions higher hydrogen density was obtained (≈ 90 kg/m^3) at about 53 K and 700 bar (blue arrow) with the SEC value of 39 kWh/kg. On the other hand, LH_2 ≈ 71 kg/m^3 at 3 bar and 20 K with a SEC value of 45 kWh/kg (purple arrow), and CGH_2 ≈ 40.5 kg/m^3 at 700 bar and 300 K with SEC value of 35.5 kWh/kg (red arrow). Storage densities for C_CH_2 storage conditions were calculated at the temperature and pressure ranges of (33-160) K and (350-700) bar. A lower energy penalty is obtained at 293 K and 700 bar. The value of LH_2 energy penalty reveals that almost 15 % less than that obtained at the very low cryogenic temperature of 33 K, which is the critical point of hydrogen. However, the storage temperature may not be the only factor affecting liquefaction efficiency, as it has been reported some elsewhere [10,13]. Besides, the calculated values of the storage densities reveal that as are as the storage temperature getting lower the density was going up. This is due to the fact that, as the molecule of hydrogen gains energy its kinetic energy getting high leading them to decreases its density [14].

More importantly, at higher densities and optimal storage conditions, the total combustible energy stored of hydrogen ($TCESH_2$), (i.e. which is the total amount of energy released when burning one kilogram of hydrogen) were obtained to be 2997, 2198, and 1348 kWh for CcH_2, LH_2, and CGH_2, respectively. Also at optimum storage conditions, the corresponding volumetric energy density (Table1) at the optimum storage conditions were calculated to be 10789 MJ/m^3, 7912 MJ/m^3, and 4855MJ/m^3 in the respective order of CcH_2, LH_2, and CGH_2 .

Hence, the model result reveals that at optimal CcH_2 storage conditions higher energy density could be obtained than LH_2 with additional energy cost of compression plus cooling but intermediate pressure and temperature.

Table 1. Calculated volumetric energy densities at optimal points.

Storage conditions	*Storage conditions: Pressure[bar] and temperature[K]*	*Storage densities (kg/m^3)*	*Volumetric energy densities [MJ/m^3]*
CcH2	[700, 53]	90	10789
LH2	[3, 20]	71	7912
CH2	[700, 300]	40.5	4855

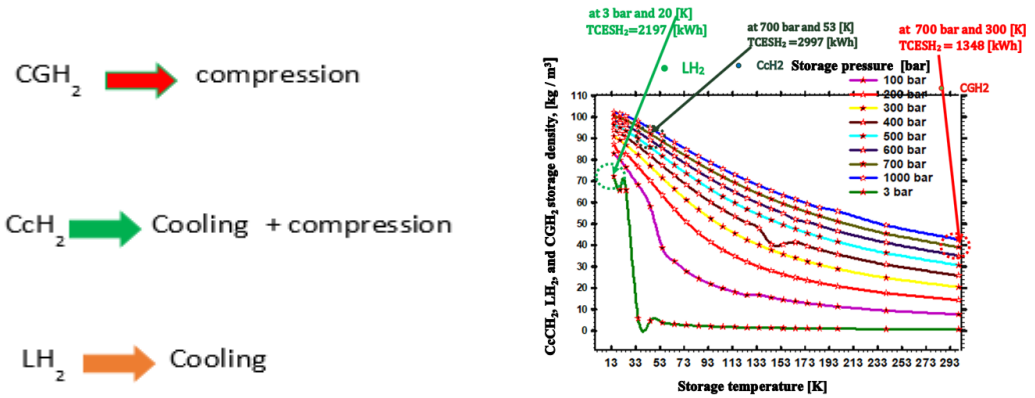

Figure 4. CcH_2, LH_2 and CGH_2 storage densities and $TCESH_2$ at various storage pressure and temperatures.

3.2. Cooling power, exergy requirement and specific power consumption

The physical based hydrogen storage system performance was evaluated under a set of storage conditions and standard requirements for consumption. The values of the cooling and exergy requirements under different sets of hydrogen storage pressures and temperatures points (20-300) K and (3 –700 bar) were calculated. At higher temperatures, the storage pressure had a less significant impact on the cooling and exergy requirements, resulting in almost similar values. On the other hand, the useful or available energy in a system is represented by its energy and exergy losses in the compression and cooling processes of hydrogen storage, which are caused by inefficiencies. Higher storage temperatures resulted in a greater overall exergy loss from the temperature change than from the exergy losses related to pressure changes, as reported elsewhere [8,11].
More importantly, the specific energy consumption of the process to produce CGH_2, CcH_2, and LH_2 was calculated in terms of work + heat for the compression and cooling sections of the process, respectively. The specific energy consumption of conventional liquefied hydrogen is much higher than that of conventional cryogenic points (very close to 1 bar and < 123 K) at high-density cryogenic states (350–700 bar and <20 K) and compressed gas (300-700 bar, and 300 K) storage points. The higher the order of the hydrogen storage temperature, the lower the specific energy requirement. This essentially is because elevated temperature storage avoids the substantial energy consumption associated with achieving or maintaining cryogenic temperature associated to cooling [8,12,13].
Under CcH_2 storage conditions, a higher hydrogen density (≈ 90 kg/m^3) was obtained at 53 K and 700 bar, with an SEC value of 39 kWh/kg. On other hand, LH_2, ≈ 71 kg/m^3 at 3 bar and 20 K with a SEC of 45 kWh/kg, and CGH_2 ≈ 40.5 kg/m^3 at 700 bar and 300 K with a SEC of 35.5 kWh/kg. These values were evaluated based on the higher storage densities achieved for CcH_2 storage with a temperature and pressure ranges of (33-160) K, and (350-700) bar. Moreover, under CCH_2 storage conditions with a pressure of 700 bar, a lower energy penalty (at 293 K) was obtained. More importantly, at higher densities and optimal storage conditions, the total combustible energy stored of hydrogen ($TCESH_2$), (i.e. which is the total amount of energy released when burning one kilogram of hydrogen) were 2997, 2198, and 1348 kWh for CcH_2, LH_2, and CGH_2, respectively. Also at optimum storage conditions, the corresponding volumetric energy density was 10789 MJ/m^3, 7912 MJ/m^3, and 4855 MJ/m^3 in the respective order for CcH_2, LH_2, and CGH_2.

4. CONCLUSION

This study mainly aims to investigate the issues of low-density high-pressure gas hydrogen (CGH_2) and boil-off gas phenomena associated with LH_2 storage. A pre-cooled Claude thermodynamic process cycle was used to investigate the optimal points of CcH_2 hydrogen storage density and energy penalty. The storage ranges of (20-300) K for temperatures and of (3-700) bar were considered as the key process parameters to calculate the hydrogen storage density, specific cooling power and exergy requirement, and specific energy consumption of the storage conditions.
In summary, LH_2 achieves higher energy densities than CGH_2 but at a higher energy cost. However, it could be possible to achieve higher densities than LH_2 using compression at cryogenic temperatures with a

considerable energy penalty or on the other hand, we get a similar cost to that of LH_2 but at an intermediate temperatures and pressures between LH_2 and CGH_2. At C_CH2 storage conditions, the hydrogen density of ≈ 90 kg/m^3 was obtained at 53 K and 700 bar, with an SEC value of 39 kWh/kg lower than LH2 (≈ 71 kg/m3 at 3 bar and 20 K) which shows a SEC of 45 kWh/kg. CGH2 has the lowest density ≈ 40.5 kg/m3 (at 700 bar and 300 K) but with the lowest SEC (35.5 kWh/kg). More importantly, CcH2 shows the best Energy Stored per kg of hydrogen (TCESH2) 2997 kWh/kg and most favorable volumetric energy density that was 10789 MJ/m^3 among the three considered physical based storage methods for hydrogen.

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