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Liquid Hydrogen for Sustainable Energy Systems: Latest Development, Challenges, and Opportunities

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Abstract. Liquid hydrogen (LH2) is emerging as an effective way to store, transport, and deliver green energy produced using renewable energy sources. The major challenge of hydrogen as an energy carrier is its low volumetric energy density, even when stored under high pressure. LH2 addresses the challenge of low volumetric energy density. The promise of green hydrogen for sustainable energy systems, along with the technologies necessary to realize this promise, is discussed. The challenges associated with the large-scale liquefaction, storage, and transportation of hydrogen are discussed. The round-trip efficiency, electricity-hydrogen-electricity cycle, and the ongoing technological developments to improve the cycle efficiency are discussed. New developments in magnetocaloric refrigeration for liquefaction, zero boil-off tanks for storage and transportation, and efficient liquid transfer systems are also discussed.

1. Introduction

Green hydrogen(H2) as an energy carrier is being explored to revolutionize our energy system, which will enable renewable power generated by variable resources (wind and solar) in remote areas to be delivered to urban centres [1], [2]. H2 is a sustainable, efficient, and clean energy vector with no hazardous emissions. It is a versatile energy carrier for power generation, energy storage, transportation, and energy-intensive industries, as well as a feedstock for the chemical and fertilizer industries [3]. It has a high gravimetric energy density of 120-142 MJ/kg compared to hydrocarbons of 44 MJ/kg [4].

One of the significant challenges of gaseous hydrogen (GH2) is its lower volumetric energy density compared to hydrocarbons [5]. Liquefaction increases the volumetric energy density significantly compared to compressed gas or cryo compressed gas storage options [6]. As a result, liquid hydrogen (LH2) is expected to play a major role in bulk storage, hydrogen fuelled electric aircraft, and many other applications that require large-scale energy storage [7]. The cryogenic temperature of LH2 provides significant benefit in certain applications, such as superconducting power devices that require cryogenic operation. The feature of LH2 serving as a cryogenic heat sink in the thermal management of superconducting power devices and cryogenic power conversion systems is being explored [8].

The full exploitation of green LH2 in sustainable energy systems relies on efficient liquefaction, storage, transportation, and delivery systems [4]. This paper reviews the LH2 technologies, their stages of development, and the research and development activities worldwide in these areas aiming to enable the widespread deployment of LH2 in sustainable energy systems.

2. Hydrogen and the Net-Zero Emission (NZE) Nexus

The world is shifting away from fossil fuel energy sources due to their high carbon footprints, low efficiencies, and non-sustainability. This has necessitated an increasing interest in alternative energy sources that are sustainable [2]. As a result, there has been an unprecedented global renewable energy deployment with over 560 GW of new installed renewable capacity in 2023 [9]. Recently, high demand for electrical energy caused by electrification of transportation, information technology, artificial intelligence (AI), and data centres [10], [11], has caused disparity between energy demand and supply. Renewable energy (RE) could play a major role in meeting this demand, yet it suffers from dispersed geographic location, and the intermittent nature of wind and solar energy sources necessitates GW-level energy storage [12], [13], [14]. Additionally, the electric power transmission systems are at full capacity and under stress [14]. As a result, producing LH2 and transporting it through pipelines for various applications is being considered as an option to move large amounts of RE from remote generation locations to urban areas [15], [16].

3. Thermodynamic Properties of Hydrogen

Key thermodynamic properties form the bedrock for H2 applications, either as GH2 or LH2, and their properties at different temperatures and pressures. It is essential to understand these properties to select materials, designs, transportation, and storage systems for LH2.

3.1 Liquid Hydrogen (LH2)

H2 consists of two isomers, which occur as orthohydrogen and parahydrogen[17]. The two forms behave like a mixture of two species whose relative concentrations depend on the temperature and pressure [18]. When the temperature reaches 80 K, the ortho gains more energy and the concentration reaches equilibrium with 50% orthohydrogen and 50% parahydrogen. At room temperature, the composition becomes 75% ortho and 25% para, also known as "normal hydrogen" because at room temperature, there is enough thermal energy to excite all the possible substates [18]. GH2 must be liquefied and used as a cryogenic liquid containing 99.75% parahydrogen [19]. LH2 is versatile for several applications [19]. For example, hydrogen fuel cells for rail and maritime transport, rocket propellant for aerospace, cryogenic research, and as a feedstock for the chemical industry [3].

During liquefaction, the conversion from orthohydrogen to parahydrogen occurs at intermediate temperatures of ~20-33 K close to that of liquid hydrogen [17], [20]. Even though normal hydrogen reaches equilibrium, all the molecules gain enough thermal energy and become excited. However, above room temperature, all the possible states of hydrogen (ortho or para) will maintain a ratio of about 75% ortho and 25% parahydrogen. This process plays a critical role in industrial-scale hydrogen storage and transportation. This conversion from ortho to para is exothermic, which releases ~525 kJ/kg of heat [19], [21].

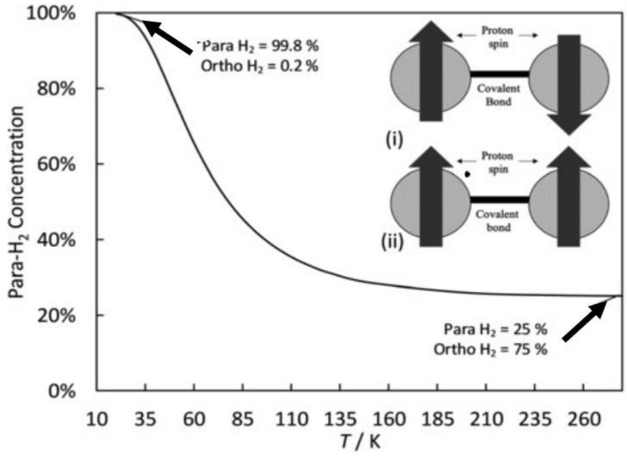

Figure 1(i) para-, (ii) orthohydrogen spin isomers, and (iii) parahydrogen concentration of hydrogen at equilibrium as a function of temperature [19].

3.2 Characteristic points on hydrogen phase diagram

The triple point refers to the temperature and pressure where hydrogen exists in solid, liquid, and gas phases at the same time. For normal hydrogen, a mixture of 3:1 ortho and para hydrogen, it is 13.8 K and 7.04 kPa for temperature and pressure, respectively [19]. During the transition from ortho to para, for example, a Chromium (III) oxide (Cr_2O_3) or Nickel (Ni) [22] catalyst can be used to speed up the reaction when H2 is cooled from a normal state to a cryogenic state. Otherwise, the ortho-para conversion process will continue for several days or weeks [17], [18]. During the ortho-para conversion reaction, adequate time is required for the kinetics to rapidly liquefy normal hydrogen to avoid large quantities of boil-off gas being released, which results in losing over 70% of the stored hydrogen [17], [20]. According to Leachman *et al.*, the equation of state (EOS) for para, ortho, and normal hydrogen that is suitable for each fluid triple point temperature is valid from ~ 14 K to 1000 K at a pressure of 2000 MPa [23].

4. Round-Trip Efficiency of Hydrogen

The round-trip efficiency of GH2 represents the energy retained when electricity is converted to hydrogen for storage and then reconverted back to electricity. It assesses hydrogen's effectiveness as an energy storage medium. A round-trip efficiency involves (i) using electricity to split water (H2O) molecules into H2 and O2[4]. This stage is 60-70% efficient[24], (ii) the hydrogen produced is stored, liquefied, or transported using additional energy during which 10 - 15% of the energy is lost [7], (iii) the hydrogen is converted back to electricity using a combustible engine that is 35-50% efficient or fuel cell that is 50-60% efficient [19]. As summarized in Fig. 2, a round-trip efficiency of 30-40% implies that only 30–40 kWh is recovered from every 100-kWh used to produce hydrogen. Figure 2 shows the various efficiencies of the round-trip process [25].

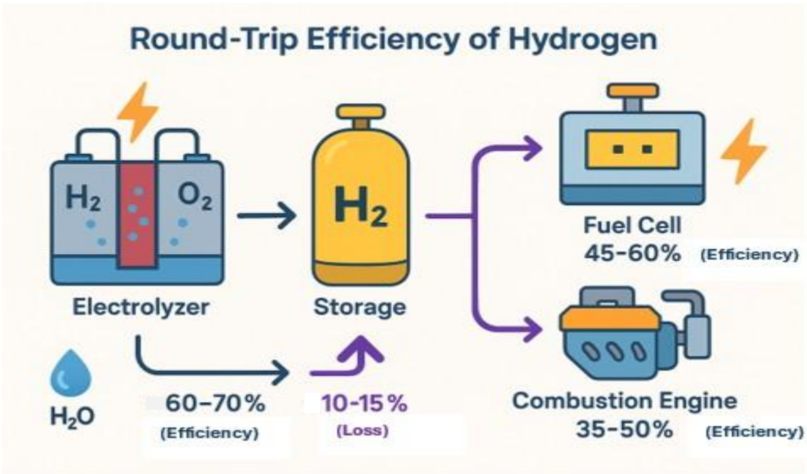

Figure 2 Typical efficiencies at various conversion stages [image drawn using OpenAI 2025]

5. Hydrogen Liquefaction

LH2 is primarily transported and delivered in liquid form when large volumes are required, particularly in regions without pipeline infrastructure. LH2 production is energy-intensive and costly as it requires the compression and liquefaction of GH2, which has a low volumetric energy density [21]. The liquefaction process entails cooling GH2 to cryogenic temperatures to reach its liquid state at 20 K[18], [23].

Fig. 3 illustrates the stages of a basic liquefaction process known as the Claude Cycle, which is one of the methods used for liquefaction. During liquefaction, GH2 at 298 to 313 K and 0.1 to 3 MPa, consisting of approximately 25% parahydrogen, is fed to a compressor where it is compressed to 2 to 8 MPa. It then undergoes precooling to 80 K, followed by passage through a series of heat exchangers (HX1, HX2, HX3 as shown in Fig. 3) for further cooling via a closed-loop cryogenic refrigeration cycle, facilitating the ortho-to-parahydrogen conversion. Prior to reaching each heat exchanger, an adsorption process removes impurities that may freeze out during the cryogenic liquefaction process. Subsequently, the LH2 reaches a Joule-Thompson valve, where it experiences an adiabatic expansion, resulting in the formation of liquid LH2. This liquid then moves to a separator, yielding 99% parahydrogen at 20 to 23 K and 0.1 to 0.2 MPa, which is then stored [19].

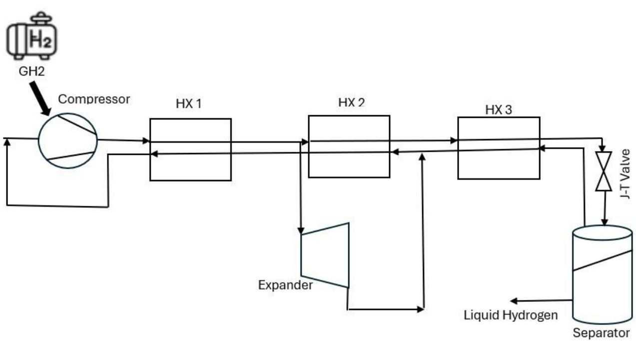

Figure 3 Stages of a simple Claude Cycle liquefaction process [46]

However, magnetocaloric liquefaction (ML) achieves a higher efficiency in thermodynamic cycles, up to 60% (compared with about 35% for cycles based on the compression and expansion of a working gas) [26]. Nevertheless, the conventional liquefier is limited to ~0.35 figure of merit (FOM) [27]. To improve the FOM, the ML is identified as the most efficient method [28].

According to the Department of Energy (DOE) as of May 2024, the liquefaction capacity of the United States is 794 metric tons per day (mtpd) from fourteen liquefaction plants. However, several plants are under construction that will add an additional 10-90 mtpd. This initiative by the DOE and its collaborating partners is, for example, that the "1-1-1" target to produce clean hydrogen at $1 per 1 kg within 1 decade by 2031 which is set to boost the hydrogen economy of the U.S. [29].

The process of H2 liquefaction has undergone significant advancements. However, the overall efficiency of the liquefaction process has not improved much. Currently, industrial GH2 liquefaction processes exhibit specific energy consumption (SEC), which indicates the energy requirements per 1 kg hydrogen liquefaction of 43.2-55.8 MJ/kg LH2, with exergy efficiency between 19.0 and 23.6% [30]. A thoughtful choice of precooling refrigerant and an optimal arrangement of the thermodynamic layout in the precooling stage present viable avenues for reducing overall energy consumption during the liquefaction process and for efficient LH2 storage [1].

6. LH2 Storage and Transportation

Various forms of LH2 or GH2 storage are increasingly being adopted, especially compressed gas storage and cryogenic tank storage. Other forms of storage, like chemically bounded storage, for example, clathrate hydrates, metal hydrides (MHs), and chemical hydrides, as well as physically bound options like carbon-based materials, metal organic frameworks (MOFs), Covalent organic frameworks (COFs), and zeolites, are still in the research and development stage [31].

Among all these storage technologies, the liquid form is the preferred method, because the process increases hydrogen's volumetric energy density to ~8.5 MJ/L with a gravimetric energy density of ~120-142 MJ/kg [31]. It enables low pressure storage, increases safety, makes thermal management easier, supports lightweight cryogenic tank designs, and guarantees quick dispersal [12]. These properties make it ideal for long-term storage and long-distance transportation [33]. LH2 has a high expansion rate when the temperature increases significantly. As a result, the storage tank must be filled to 95% capacity for stationary storage or transportation [31]. Currently, LH2 is transported by cryogenic tanks in locations where there is significant demand for LH2. Similarly, for international H2 trade, liquid tankers onboard marine vessels are used [16].

For transporting 2–4 tonnes of LH2 over 25–150 km from the production site to refuelling stations or load centres [34], double-walled insulated trailers (30–60 m^3) are the most cost-efficient option [18], [35], [36]. Cryogenic tanks are designed to minimize heat transfer and maintain a stable and low temperature for transportation. The tanks are kept in an insulated casing with a safety mechanism to release built-up pressure [37]. However, releasing the build-up gas from the ullage into the environment is not sustainable because H2 is an indirect greenhouse gas [38].

Compared to GH2, LH2 at cryogenic conditions of 20 K rises from about 0.089 kg/m^3 for GH2 at 1 bar to ~70 kg/m^3 for LH2 [48]. This higher density allows more hydrogen to be stored in the same volume. However, LH2 has a low specific heat capacity, which makes it thermally sensitive and requires excellent thermal insulation [38]. This condition requires continuous

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thermal insulation management that involves significant maintenance expenses and high operational energy demand for industrial-scale applications and transportation [39], [40]. LH2 is transported in double-walled containers with inner insulation and outer protection, maintaining a temperature of 20 K until it reaches a refuelling station [36]. Figure 4 shows a sectional view of an LH2 storage tank [47].

LH2 storage produces excessive boil-off which may lead to a high-pressure build-up in the storage tank, posing safety concerns. Up to 25% of incidents during the loading or unloading of LH2 are caused by excessive boil-off [42]. To manage this boil-off, it is desirable to maintain the temperature of LH2 at 20 K [43]. This helps to reduce the heat losses and to ease the vaporization of the LH2. Different technologies for boil-off management, such as reliquefaction, thermal insulation with active cooling technologies, and catalytic GH2 combustion, have been developed and applied for various applications [44].

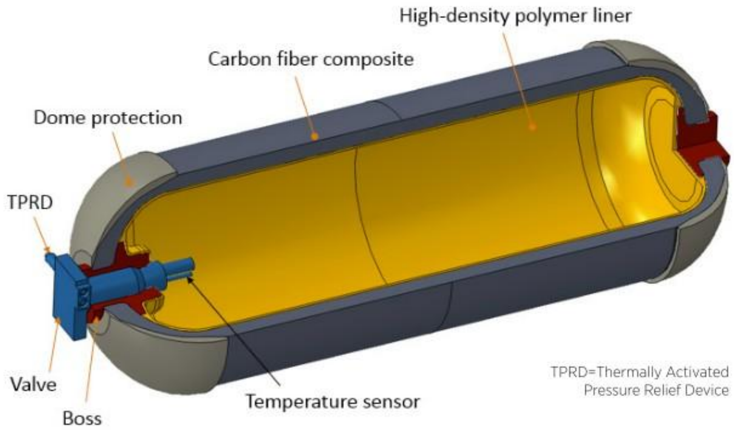

Figure 4 Liquid hydrogen storage technology[33]

Liquid hydrogen handling and storage experience considerable losses at various stages. For example, a daily loss of up to ~1% in passive storage tanks occurs through evaporation as the liquid warms and vents; while offloading from tanker trucks to bulk tanks results in ~10–30% loss from eruptions and venting of the hydrogen due to rapid evaporation and in dispensing operations, cavitation in pumps can cause a further ~3% loss [45]. Eruption is a sudden and violent release of H2 vapour when the vessel container experiences rapid pressure increases due to boiling and expansion of LH2 [46], [47]. To address this, a refrigerated storage is the most effective way to reduce boil-off [18]. This enables the liquid to remain sub-cooled and prevents evaporation, which eliminates venting that could result in losing a substantial quantity of H2 [28].

LH2 must be stored in a non-vented manner to avoid the flammable boil-off gas from venting out of the tank. The thermal conditions in the tank, such as temperature stratification and buoyancy flow, increase the pressure build-up and reduce the hold time of the tank [48]. The thermal insulation performance can be estimated from the normal evaporation rate (NER) using equation (1)

$$NER = \frac{Q}{\varphi \rho_1 V_{tank} \gamma} \quad (1)$$

Where φ is the liquid fill ratio, ρ_l is the liquid density, V_{tank} is the volume of the tank, γ is the latent heat of evaporation, and Q is the total heat leak into the LH2 tank[49]. With a fixed volume and initial liquid fill ratio, the NER measures the heat leak into the LH2 tank. To minimize this heat leak, it's essential to create high-performance thermal insulations for LH2 temperatures [49].

Research and development are ongoing to manage the boil-off problem. According to Leachman *et al.*, multilayer insulation (MLI) can be used to minimize the radiative heat load of cryogenic tanks like the vacuum environment in orbit. This is achieved by constructing layers of metallized (aluminum, gold) substrate films (Mylar Kapton) with a high reflective radiation shield. Demonstrating this technology, NASA has developed a method to intercept the structural heat load of cryogenic tanks using heat flux sensors providing a better interpretation of MLI [48]. A group of consortia led by Shell has also developed a vacuum tank concept for large-scale LH2 storage (up to 100,000 cubic meters). Other zero boil-off tank (ZBOT) technologies include integrated refrigeration and storage (IRAS) to manage LH2 for NASA. Examples of the systems in development stages are reliquefaction systems, integrated hybrid systems, and active cooling loops[28].

7. Summary

The low volumetric energy density challenge of GH2 as an energy carrier can be addressed by utilizing LH2. The promise of green H2 for sustainable energy systems can only be achieved by improving the round-trip efficiency of the electricity-hydrogen-electricity cycle. Efficient liquefaction, storage, transport, and delivery or transfer technologies are essential to realizing the promise of green LH2. New developments in magnetocaloric refrigeration for liquefaction, zero boil-off tanks for storage and transportation, and efficient liquid transfer systems are promising. Further developments in these technologies will accelerate the commercial deployment of LH2 technologies, enabling the achievement of sustainable energy systems.

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