Liquid hydrogen carriers: Linking renewable energies for a carbon-neutral future

Baowen Zhou[1,*]
[1]Key Laboratory for Power Machinery and Engineering of the Ministry of Education, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
*Correspondence: zhoubw@sjtu.edu.cn

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The rapid growth of the installed capacity of photovoltaic and wind turbines shows a grand perspective that the economy can be powered by renewable energies in a carbon-neutral manner. At the end of 2022, the installed capacity of renewable energies in China reached 1.213 billion kilowatts, outperforming that of coal-fired power plants for the first time, which is regarded as a landmark in energy history. However, the intermittent, fluctuating, and low-density properties of renewable energies pose many challenges for their widespread applications. Large-scale energy storage technology is of vital importance for addressing the critical challenges arising from the domination of renewable energies in the foreseeable future. Among a diversity of energy storage technologies such as the battery, compressed air, and pumped hydroelectric energy, the production of chemical fuels driven by renewable energies presents an appealing route for long-term storage of renewable energies at a grid scale (Figure 1).[1] The pursuit of a suitable energy carrier is at the core of this grand topic. The high gravimetric energy density (143 kJ/kg), carbon-neutral, and pollution-free properties of H_2 make it a unique energy carrier. Further, the earth-abundant, low-cost, renewable, and widespread-distribution properties of solar, wind, and water make the tremendous production of green hydrogen globally feasible. It is essentially different from the gray hydrogen with a heavy carbon footprint that originates from fossil fuel reforming. However, owing to the unique physical and chemical properties of H_2 (e.g., light weight, low boiling point (-253°C), high reactivity, and inflammability), the established technologies (e.g., high-pressure compression and low-temperature liquefaction) cannot meet the practical requirements of large-scale and long-distance hydrogen storage and transportation. There is a huge gap between remoted hydrogen generation from renewable energies and on-site hydrogen utilization. It is thereby imperative to explore disruptive technologies for addressing this issue, which is critical for the achievement of linking renewable energies toward economic sectors.

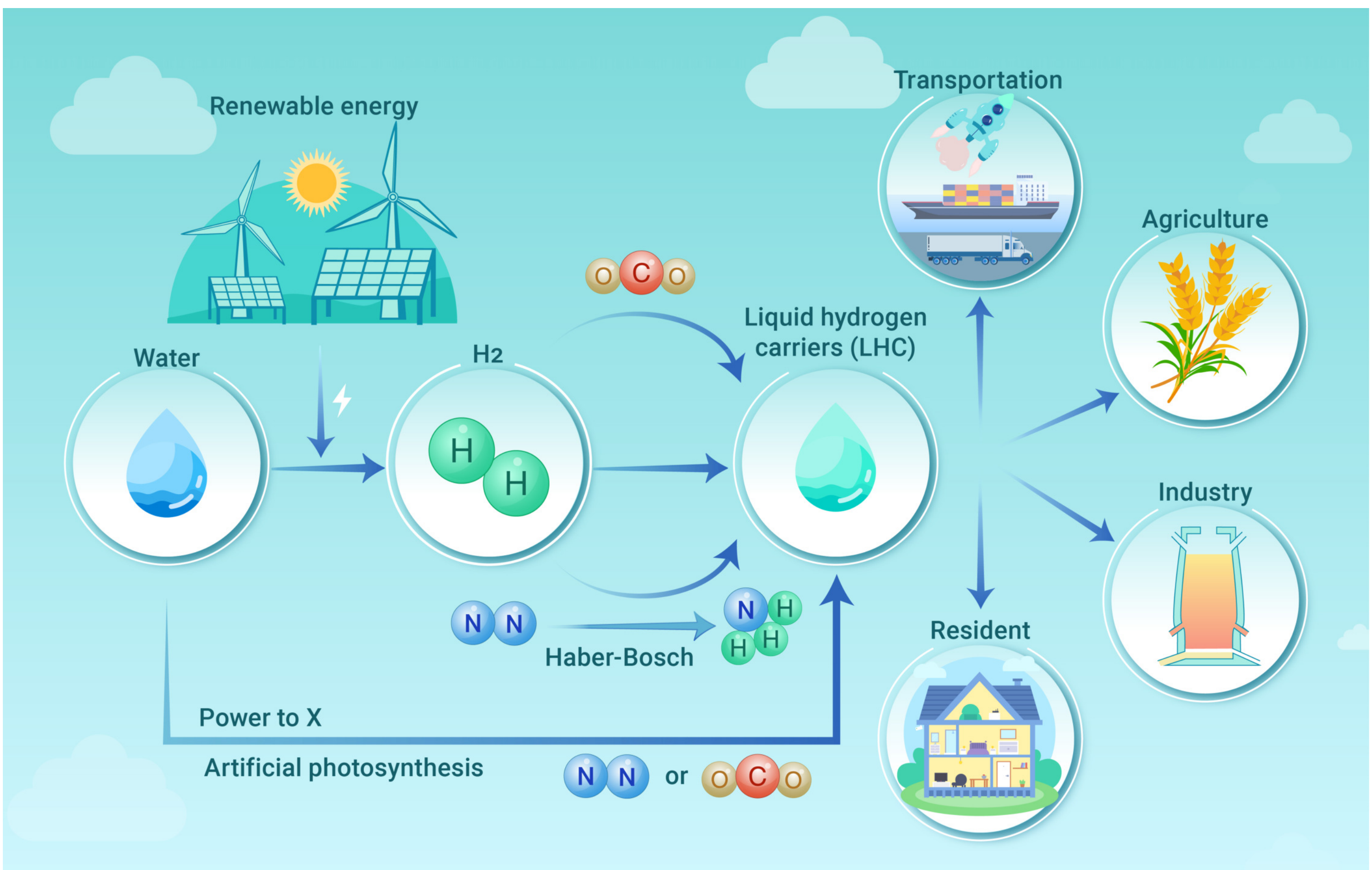

Figure 1. Liquid hydrogen carriers: Linking renewable energies for a carbon-neutral future.

Despite a series of severe consequences (e.g., climate change, energy crisis, and environmental pollution), the utilization of liquid fuels from fossil fuels has promoted the unprecedented advance of human beings' civilization. It is mainly attributed to the superior properties of high energy density, ease of storage, and transportation of liquid fuels. Thus far, the infrastructures of storage (tank, petrol station), transportation (pipe, trailer, ship), and utilization (internal combustion engine, aero-engine, etc) of liquid fuels have been well established in the era of fossil fuels. It is of great interest if green hydrogen can be stored, distributed, and utilized by using the existing infrastructures for liquid fuels. As a matter of fact, compared to high-pressure compression and low-temperature liquefaction, on-site hydrogen production from liquid hydrogen carriers (LHCs) has recently emerged as a promising method for hydrogen storage and transportation because of the following merits. First of all, LHCs are liquid under ambient conditions, which is highly compatible with the widely available infrastructures for liquid fuels. Meanwhile, the high hydrogen density of LHCs endows their storage, transportation, and utilization with technological and economic benefits. For example, the hydrogen density of 1 liter CH_3OH (a typical representative of liquid hydrogen carrier) is equivalent to that of about 1100 liter H_2 under standard conditions (101.325 KPa, 273K). Over the past years, considerable efforts have been devoted to exploring catalytic systems for hydrogen storage in LHCs, followed by in situ hydrogen liberation from LHCs on demand. Thus far, methylcyclohexane (MCH), decahydronaphthalene (DEC), etc have been employed as the conventional LHCs, which are primarily obtained from fossil fuels. Despite the proper physicochemical properties for H_2 storage/liberation, the aforementioned conventional liquid hydrogen carriers are not suitable for coupling with renewable energies because of their high cost and difficulty of accessibility.

From the viewpoints of practical applications and sustainability, it is appealing to produce liquid hydrogen carriers from green feedstocks that are widely available in nature, especially if they are readily coupled with renewable energies.[2] Among a broad range of LHCs, HCOOH, CH_3OH, and NH_3 have attracted particular interest. They can be produced from water, CO_2, N_2, and even biomass powered by renewable energies through various routes e.g. photocatalysis,[3] electrocatalysis,[4] thermocatalysis, or their combination. Of note, the renewable, broadly available, and nearly free properties of these feedstocks, which is similar to that of renewable energies, make the large-scale storage of renewable energies into LHCs possible. The recent years have witnessed many inspiring advances in this field. For example, in Iceland, CH_3OH was produced by CO_2 hydrogenation with the use of green H_2 from water splitting powered by geothermal electricity. Moreover, as a pioneering practice of liquid sunshine in China, green CH_3OH was successfully produced at industrial scale by coupling photovoltaic with water electrolysis, followed by thermocatalytic CO_2 hydrogenation in Gansu Province (Located in Northwestern China with abundant solar and wind). The aforementioned achievements hold grand promise for not only storing renewable energies but also offering a promising solution for addressing the critical issues associated with H_2 storage and transportation. In these cases, carbon dioxide is an abundant and renewable feedstock for the production of chemical fuels. It is estimated that up to 4.2 billion tons of carbon dioxide will be recycled back into chemical fuels globally by 2050.[5] Based on the discussion above, it is speculated that LHCs can be well-matched with emerging technologies such as Power-to-X, Carbon Capture Utilization Storage (CCUS), and Artificial Photosynthesis. The eventual success of these emerging technologies will undoubtedly promote the linkage of renewable energies to all economic sectors *e.g.* chemical industry, traffic, agriculture, metallurgy, and residence via the medium of liquid hydrogen carriers. It is also beneficial for alleviating the atmospheric CO_2 concentration, thus accelerating the arrival of carbon neutrality. Despite the grand promise, it remains a huge challenge for the direct synthesis of green LHCs with the renewable feedstocks e.g. CO_2, H_2O, N_2, and sunlight, which is substantially associated with the chemical inertness of the feedstock molecules. Thus far, there has been a lack of efficient and durable catalytic systems to break the energy efficiency bottleneck of renewable energies-to-chemical conversion with cost competitiveness. There is still a long way to go.

In a broad sense, liquid hydrogen carriers are not only energy carriers but also important feedstock for various economic sectors. For instance, CH_3OH is a key chemical feedstock for producing various liquid fuels and value-added chemicals via the well-known Fischer-Tropsch process. NH_3, a mature product of the Haber-Bosch Process ($N_2 + 3H_2 = 2NH_3$), has been massively produced from N_2 hydrogenation with the use of H_2 from fossil fuels. It is an important feedstock for producing fertilizer, which is critical for securing the food supply. What is more, as a carbon-neutral fuel, ammonia has also attracted growing research interest in the heavy-duty and long-distance power sector.

Since LHCs can be in principle produced from renewable resources powered by renewable energies, the widespread application of liquid hydrogen carriers will undoubtedly facilitate the elimination of environmental pollution e.g. water pollution, air pollution, and plastic pollution. However, it is worth noting that there is a global shortage of fresh water, especially in the districts that possess abundant solar and wind. The distribution mismatch between renewable energies and freshwater resources needs to be considered, to avoid the dilemma of producing green hydrogen at the cost of fresh water, especially in the water-scarce area. Considering the virtual unlimited seawater, sunshine, wind, and tidal energy in the ocean, seawater splitting may provide a more viable solution for the massive supply of green hydrogen in the future.

In short, LHCs show great potential in linking renewable energies to various economic sectors. The exploration of revolutionary tools, materials, and methods to advance this field is urgently demanded. Although many technological and economic challenges need to be resolved, joint efforts from the broad community of academia, industry, finance, and governance will accelerate the arrival of carbon neutrality and liquid hydrogen carriers will play an increasingly important role in this process. By that time, the issues arising from fossil fuels including climate change, energy crisis, and environmental pollution will be addressed in a sustainable manner.

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DECLARATION OF INTERESTS

The author declares no competing interests.