**The Promise of Hydrogen?**

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To judge by the persistent ubiquity in the media of near frenzied promotion of hydrogen as the ideal carbon-free source of energy, the resolution of the climate change crisis may seem at hand, but a sober look behind the hype at the "hydrogen solution" reveals a landscape of physical realities and intensely difficult technological challenges, many of which have not been or may not be able to be practically overcome. The crux of the issue? Hydrogen has a serious energy efficiency problem. The basic concept at play here is hydrogen as a fuel. The accompanying assumption for this discussion is that acceptable energy solutions to the climate change problem are carbon-free (or, at least, carbon-neutral).

First, as background, what are a few of the characteristics of elemental hydrogen that fuel its apparent promise?

- High Specific Energy (energy per unit mass in megajoules per kilogram)—142 MJ/kg – highest of any fuel - compared with gasoline at 46 MJ/kg, ethanol at 27MJ/kg (Engineering ToolBox 2008), and a lithium battery at 0.5 MJ/kg (Rodrigue et al. 2020)
- Lightest element (in elemental form) and fuel
- 2/3 of every water molecule → abundant, readily acquired source
- Only combustion product is water vapor – no carbon emissions

So, high-energy, light, abundant, and zero-carbon: What more could you want?

In fact, we are left wanting due to some other, challenging characteristics of hydrogen:

- Hydrogen is a gas except at the most extreme high pressures and low temperatures
- Very low Energy Density (energy per unit volume in megajoules per liter)—0.01 MJ/L at ambient temperature and pressure, while gasoline at 31 MJ/L (College of the Desert 2001)
- Storage and transport of practical amounts requires high pressure (gas) or cryogenic temperature (liquid)
- Molecular (elemental) hydrogen, the stuff for fuel, is almost non-existent in the environment
- Bond strength between hydrogen and oxygen in water is very high while that between hydrogen and carbon (as in hydrocarbons) is relatively low (Blamire 2005).

To summarize, for a carbon-free solution, hydrogen must be extracted from water (instead of fossil hydrocarbons, which is where most of the hydrogen currently used comes from) using zero-carbon energy sources (e.g., solar), compressed or cryogenically cooled for storage, transported to local distribution or dispensing locations, and finally oxidized to extract the energy. The often-ignored bottom line in this whole process is that a significant portion of the renewable energy initially captured is lost at every step of the process (Griffith 2021). This reality points directly to a more proper way to evaluate the efficacy of fuels: round trip efficiency, which measures the amount of usable energy you get from the fuel compared to the amount used to produce the fuel i.e., energy out as a percentage of energy in. For hydrogen, round trip efficiency is a problem.

In his recent book "Electrify: An Optimist's Playbook for Our Clean Energy Future" (Griffith 2021), engineer Saul Griffith demonstrates hydrogen's round trip efficiency problem with a few quick calculations based on in/out energy efficiency at each step from fuel production to use in a vehicle. Initial hydrogen extraction by electrolysis is approximately 65% efficient, compression in a tank and decompression for use about 75%, and consumption in a fuel cell about 50%. Multiply 1 (unit of energy) by each percentage in turn, and you have a round trip efficiency of about 24% i.e., 0.24 units of energy out for each unit of electricity in. Compare this result with a similar one for an electric vehicle (EV): store initial electricity in a battery at about 90% efficiency then run the vehicle's motor at about 80% efficiency to get a round trip efficiency of 72%. The problem is clear. Griffith astutely observes that we cling to the idea of hydrogen as a fuel because we are looking to replace one fuel with another that can then be loaded into a tank as before—just because it is familiar. We need to change the 20$^{th}$ Century, fossil fuel-based way we think about energy production, storage, and use. Further, Griffith correctly points out that we do not find, drill for, and refine hydrogen because it is not a fuel, especially when produced electrolytically with renewable electricity; hydrogen is a battery and a mediocre one at that.

As a climate change solution, Griffith in "Electrify" calls for humankind to electrify everything using renewable sources of electricity but, even so, indicates that some human activities cannot be electrified given current knowledge and technology. Steelmaking, for example, involves copious and continuous amounts of high heat that cannot be practically generated with electricity. Hydrogen would be a great replacement for coking coal in the current process. At least one company has already developed a direct reduction process that uses hydrogen, to be generated by solar-pumped electrolysis in an onsite, 500MW plant (Schmies 2021). Another industry with potential for hydrogen instead of fossil fuel use is long-haul transportation, such as aviation. Although practical, small, short to medium distance electric aircraft from multiple companies are poised for commercial operations (and private use) (Public Broadcasting System 2021), larger airliners will still require fuels with good energy density. Hydrogen may, for now, be the only way to decarbonize these industries, despite the poor round trip energy efficiency of hydrogen as a fuel.

Development of new hydrogen technologies continues at an astonishing rate, especially regarding electrolysis; however, storage systems with good specific energy and with hydrogen uptake and release at reasonable temperatures and pressures and high efficiency fuel cells using less or no precious metals have been tough mountains to climb. The US Department of Energy operates large and comprehensive research programs in the latter areas focused on automotive applications.

Finally, the chemical storage, transport, and regeneration of hydrogen based on storage as ammonia ($NH_3$) has recently seen significant advances. The making of ammonia, the second most industrially used inorganic chemical in the world (Kelly-Detwiler 2020), from hydrogen and atmospheric nitrogen by the Haber-Bosch Process requires large amounts of energy. Industry has used ammonia heavily for a long time, primarily in fertilizer production, and the energy inputs come from fossil fuels. Similarly, extraction of hydrogen from ammonia typically requires large energy inputs; however, unlike for the synthetic process, extraction technology and support infrastructure are not generally implemented in the industry due to the lack of market incentive for extraction (Hirscher et al. 2020).

A considerable body of research has nonetheless accumulated for hydrogen extraction (Hirscher et al. 2020), and some entities are now prepared to commercialize their processes, generally involving newly developed low-temperature, ammonia-cracking catalysts and electrically pumped, proton-permeable membranes that hugely reduce required energy inputs to levels easily supplied by electrical energy from renewables (Gillespie 2018; McMahon 2020). These entities see an advantage for storage and transport of hydrogen as ammonia because there is already a mature and extensive system of transport and distribution of ammonia for industrial use (Hirscher 2020). Also, green ammonia synthesis has not lacked for attention (see Service 2018), so the beginning of the end for the carbon-intensive Haber-Bosch may be near, too. Even if hydrogen is likely to remain only a small part of the solution, these new ammonia technologies may significantly contribute to far more acceptable efficiencies for hydrogen as a fuel.

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