Hydrogen: Overview

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September 10, 2022

1 Production:

- Blue hydrogen is produced via steam methane reformation (SMR). Methane reacts with water to produce carbon dioxide and hydrogen. The greenhouse gas (GHG) emissions of this process can be largely mitigated using carbon capture and sequestration (CCS). Recent advancements in carbon capture have enabled greater than 95% capture rates at the reactor. Life cycle assessment (LCA) of blue hydrogen provides an estimated emission of 60 kg $CO_{2,\,e}/MWh_{H2}$ [2, 3]. Emissions associated with this process come from uncaptured reactor emissions ($\approx$ 45%), methane extraction and transportation ($\approx$ 45%), and plant construction ($\approx$ 10%). The current market price is US$ 2/kg_{H2}[2].

- Green hydrogen is produced using electrolysis, wherein water is split into hydrogen and oxygen. The carbon footprint of electrolysis is dominated by the emissions from electricity generation. LCA studies have estimated emissions of green hydrogen to be 20 kg $CO_{2,\,e}/MWh_{H2}$ when the electricity is sourced from renewable methods [3]. It is important to note that there are still some emissions associated with production of green hydrogen. These emissions arise from the production and installation of wind turbines, solar panels, batteries, and electrolyzers. The current market price is US$ 8/kg_{H2}.

Choosing a production method for hydrogen has to take into account two important factors: costs, and emissions. Blue hydrogen is far superior when it comes to cost competitiveness, and is expected to remain cheaper in the near future. In addition, we see that carbon capture, if employed successfully, can significantly curb emissions from blue hydrogen. Thus, we expect similar GHG emissions from blue and green hydrogen generation. During emission analysis, we need to consider the opportunity cost of using renewable electricity to generate hydrogen, which could otherwise be used to decarbonize the national electricity grid. This was recently studied by Dowell et al [3], and they concluded that for most nations/regions including USA, China, UK and the EU, we can achieve a larger GHG reduction if renewable electricity is used for grid decarbonization over hydrogen production. This result can be explained by the following reasons: "dirty" grids as they greatly rely on fossil fuels (coal, natural gas, etc.) for electricity generation, and blue hydrogen being relatively clean. Given the cost and minimal emissions benefit of green hydrogen, it is clear that SMR with CCS (blue hydrogen) is the better method to produce hydrogen in the short-term .Eventually, when grids are cleaner and the price of renewable energy is lower, we expect a transition to green hydrogen.

2 Storage and Distribution:

Distribution and storage are real pain points when it comes to hydrogen. It has a high propensity to leak as it is a small molecule. Hydrogen is also a greenhouse gas, and it can lead to global warming. Therefore, hydrogen leaks are particularly concerning, especially for large scale applications such as long-haul trucking. Hydrogen is primarily transported as a high-pressure gas (700 bar) or a cryogenic liquid (20 K). This is not synergistic with the existing fuel distribution infrastructure that is optimized to handle room temperature liquid fuels. We are unable to use existing gas pipelines, and hydrogen distribution is largely reliant on specialized trucks which are unsuitable for large scale applications and have higher costs [1, 4]. Cost of hydrogen delivery with trucks grows non-linearly to distribution distance. Therefore, current hydrogen distribution cannot compete with pipelines over long-distances. This has limited hydrogen to local networks and prevented the development of global supply chains. Another major concern with existing distribution is the compression and boil-off losses associated with compressed gas and cryogenic liquid distribution respectively. Studies estimate losses to be roughly 20% of the hydrogen's energy content [2, 4]. Costs associated with the storage of hydrogen under non-ambient conditions have prohibited distribution centers (gas stations) from having sufficient inventories. Therefore, the supply chain suffers from poor robustness which is particularly critical when considering a commercial application such as long-haul trucking.

An alternate option is to store and distribute hydrogen via solid or liquid carriers. A hydrogen carrier is any chemical compound that can be broken down to release hydrogen. There are various chemicals, both solids and liquids, that can be considered as effective carriers such as ammonia, methylcyclohexane, and ammonium formate to name a few. They all have the same key benefit: converting hydrogen in a form that is convenient to store and transport. This addresses a significant portion of the drawbacks of compressed and liquid hydrogen. However, there is a cost associated with all hydrogen carriers. Regeneration of hydrogen is an energy intensive process, and can account upwards of 30% of the stored hydrogen's energy. In addition, there is often a need for additional purification of the released hydrogen which further adds to the energy requirements.

Unlike hydrogen production, there is no clear winner when it comes to the best method to store and transport hydrogen. The transportation distance and duration of storage must be considered, as each method excels for different instances. Our group has extensively analyzed liquid and compressed hydrogen delivery methods, and we are currently working on liquid carriers.

3 Price at the gas-station

The make or break for any alternative fuel is its cost at the gas station. Our analysis shows that hydrogen price must be at US$4/Kg to out-compete diesel. The metric used for this calculation is the total cost to society (TCS). TCS includes the private cost (eg. price of fuel) and the social cost (cost of carbon). Our calculations are based on the social cost of carbon reported by Biden administration, and focus on the US trucking market. We evaluated various combinations of production and delivery schemes to identify the optimal option considering both costs and emissions. Presented in Figure 1 and Figure 2 are graphs that shows the costs for present day (2020) and the long-term future (2050), respectively.

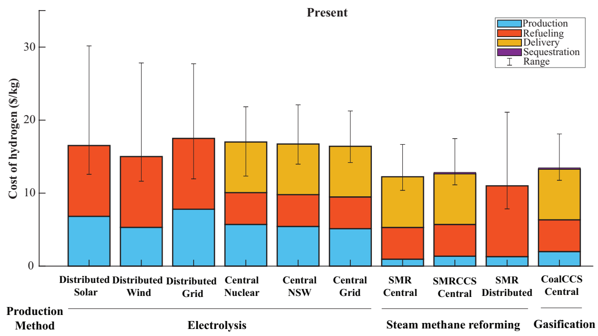

Figure 1: Predicted price per kg hydrogen in 2020 for different production and distribution methods for the US market

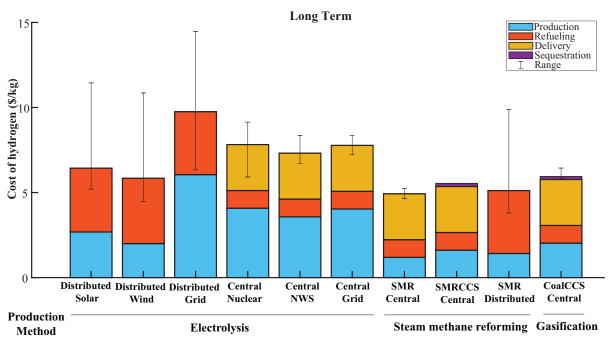

Figure 2: Predicted price per kg hydrogen in 2050 for different production and distribution methods for the US market

It is evident that hydrogen prices are egregiously high for the present day scenario for both steam methane reformation and electrolysis production schemes. An important takeaway from the analysis is the large contribution of delivery and refuelling to the total cost, arising from compression and liquefaction requirements. In the distributed production schemes we are able to completely avoid the delivery cost, but still have to pressurize the hydrogen before it can be used as fuel on the truck. The lack of economies of scale lead to higher refuelling and production costs which nearly offset all benefits from the saved delivery cost. It is also clear that current electricity prices make the electrolytic production of hydrogen much more expensive than SMR. We see that centralized and distributed SMR have similar price ranges, however centralized scheme has major benefits when carbon capture is considered. Therefore, centralized SMR with CCS is currently the optimal scheme.

The price forecast for hydrogen shows a reduction in price across all schemes. The expected reductions in 2050 arises from two major sources: a larger hydrogen market allowing economies of scale, and technological maturity which makes processes more efficient. Unfortunately, the forecasted hydrogen prices for 2050 are greater than $4/Kg, thus hydrogen is unable to out-compete diesel. This analysis should not be understood as the inability of hydrogen to replace diesel as fuel, but as the inability of existing hydrogen technologies to out-compete diesel.

4 Conclusion

The above analysis clarifies that hydrogen is severely limited by the lack of efficient distribution and refuelling methods, as both liquid and compressed methods are too expensive. This has motivated our group to work towards liquid organic hydrogen carriers (LOHCs) as means of transporting and storing hydrogen. We aim to modify the powertrain of trucks to allow on-board hydrogen generation using the waste heat from the engine exhaust. To learn more about the LOHC project, please read "Liquid Organic Hydrogen Carriers (LOHCs) for Long-Haul Trucking" listed **here**.

References

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