Cambridge Peterhouse Kelvin Science Prize
Essay Title 4

Nicolas Weninger
St Paul's School

The Hydrogen Economy: A Brief Feasibility Analysis

1. Introduction

1.1 What is "The Hydrogen Economy"?

The term "Hydrogen Economy" was first coined by electrochemist John Bockris in 1970 [1]. It refers to the use of hydrogen in place of our current oil-based fossil fuels for use as an energy storage medium in the powering of motorised transportation in order to reduce the negative environmental impacts of the extraction and combustion of fossil fuels. Hydrogen can be combusted or passed through a hydrogen fuel cell, producing only water and energy. At first glance, the concept is a fascinating one and appears to be promising. As with any large-scale infrastructure endeavour, the solutions, and how these may be implemented, are not straightforward. Conflicting interests, evolving technologies and the relative benefits of such solutions must all be considered when attempting to evaluate such an ambitious concept.

Opinions on its feasibility differ. Proponents argue that the hydrogen (H_2) supply-chain pathway would release significantly less carbon dioxide (CO_2) than is currently released by existing systems [2], and given the abundance of hydrogen in organic and inorganic compounds [3], it is in effect a renewable resource. Opponents claim that the capital costs of implementing a hydrogen infrastructure and development of efficient storage and energy extraction systems will ultimately deter the wide-spread use of hydrogen [4], given the challenging physical properties of elemental hydrogen, such as its low energy per unit volume and gaseous state at standard conditions.

People have considered the sustainability of the Earth's energy-producing capacity from easily exploitable methods for a long time, since Jules Verne himself contributed to the discussion in his "The Mysterious Island" [5]*: "I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will [be] an inexhaustible source of heat and light".* Although such a world is still remote, work has already begun. With the introduction and implementation of new technologies, we can question the relative benefits a hydrogen economy brings, and the challenges that must be overcome in order for a successful widespread implementation.

1.2 The Need for Alternative Energy Generation and Storage

The presently predominant fuels are derived from the non-renewable sources of natural gas and crude oil. Globally ~81% of electricity production is from fossil fuels [6]. Combustion of these detrimentally affects the global climate, possibly resulting in sudden non-linear changes in the biosphere. Continued use of such fuels narrows the window of opportunity in the search for more sustainable energy sources [7]. An alternative solution must satisfy several criteria, for example, as aircraft jets make direct use of combusted fuel exhaust gases, the alternative must emulate its combustion properties to avoid significant jet design overhauls. Hydrogen, through the processes described below, has this potential.

The geopolitical circumstances arising through continued fossil-fuel extraction is another factor to be considered. Oil extraction follows Hubbert's Curve [8], and given that there is seemingly no consensus on where the human population currently lies on it [9], it is uncertain how long oil reserves will last for. Over 70% of all oil reserves are located in politically volatile areas: such as Iran or Iraq, both *Organisation of the Petroleum Exporting Countries* (OPEC) members [10]. Instability in these areas could suddenly decrease oil supply, such as during the 1980 Iran-Iraq war, when the combined loss amounted to 6% of global production at the time [11]. With the increasing industrialisation of nations such as China and India (Fig. 1), global energy use will increase, placing more demand on resources, potentially increasing the oil equilibrium price, leading to energy scarcity if alternative infrastructures are not in place.

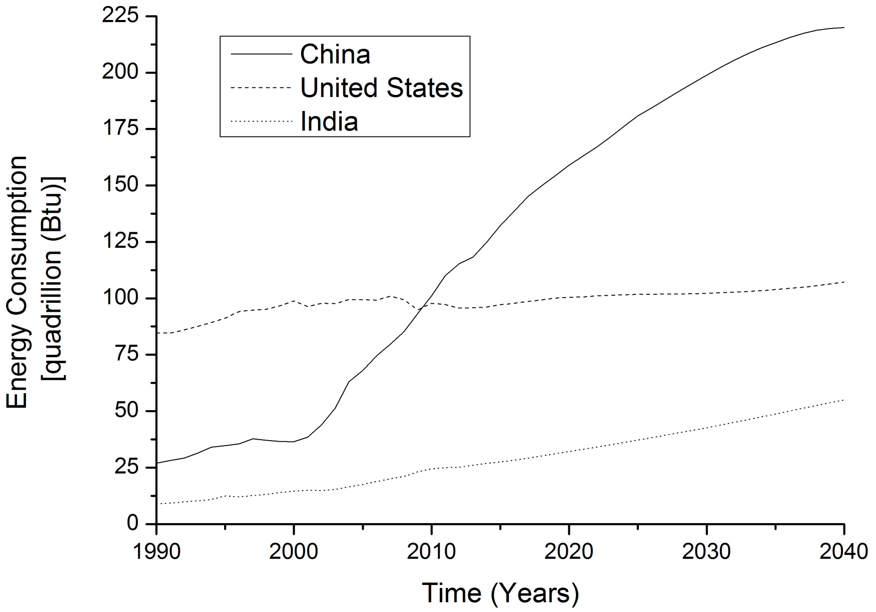

Fig 1: Projected Energy Consumption of China, US and India [12]

2. Hydrogen Production

2.1 Current Production Methods and Prerequisites for Continued Production

The initial challenge to be overcome relates to hydrogen production. Molecular hydrogen itself is not an energy source, but rather a storage medium. It cannot be found in significant, easily accessible quantities, or be easily separated from a mixture. Its production requires an energy input. The challenge therefore is to establish a production pathway that is able to produce large enough quantities of hydrogen in an environmentally and energetically favourable manner.

Current hydrogen production serves two main applications [13] (Fig.2): the production of alkenes, used to manufacture plastics, and for the Haber process to create ammonia, a key component in fertilisers.

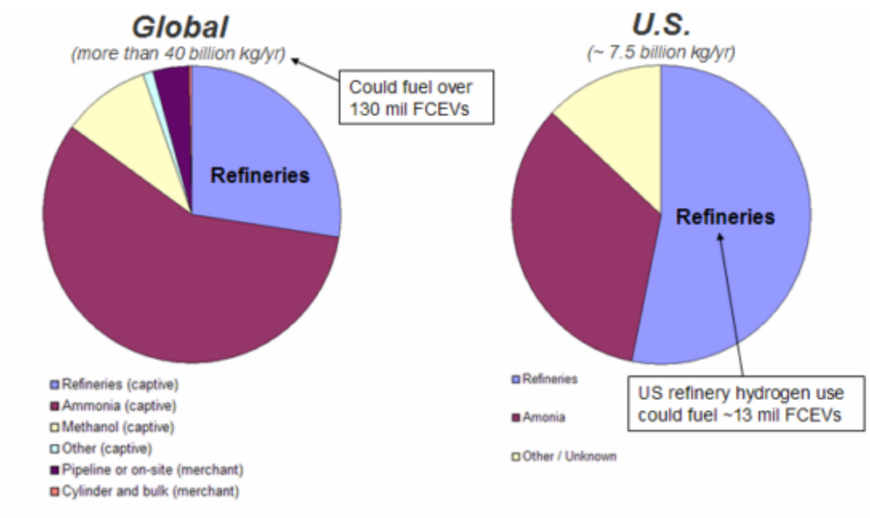

Fig. 2: Global and US hydrogen use as of 2007 [13]

For hydrogen to become a more widely available commodity, it would need to be offered at competitive prices and in large enough quantities in order to supply the estimated 600MT/year required in a fully implemented hydrogen economy [14].

There are many proposed hydrogen production processes documented, the most relevant of which are covered in this section. Current industrial-scale methods require a fossil fuel input, negating the benefits of a hydrogen economy. Currently, 95% of the hydrogen available in the U.S. is produced by the direct extraction of hydrogen from fossil fuels, or use of energy supplied by them [15]. Of the alternative methods, most require an electricity input. Thus in order to achieve carbon neutrality, the accompanying electricity infrastructure must be supplied entirely by electricity from renewable sources.

2.2 Electro-chemical Water Electrolysis

Electro-chemical Electrolysis processes use electricity and non-depleted chemical inputs to separate water into hydrogen and oxygen. There are three main electrolysis cell designs:

1. Solid Oxide Electrolysis cells (SOEC)
2. Polymer Electrolyte Membrane (PEM) cells
3. Alkaline Electrolysis cells

M. Carmo et al (2013) provided a comprehensive review of these three differing electrolysis cells in their paper “*A comprehensive review on PEM water electrolysis*” [16]. To summarise, alkaline cells are a well-established technology and widely used, resulting in its current low cost, but the hydrogen purity is lower than with other solutions. SOECs can operate at high pressures and temperatures, increasing production rates; however, its high component cost and non-standard manufacturing methods result in a comparatively high hydrogen cost. PEM cells exhibit efficiencies of up to 80% [17], and compact physical designs, potentially beneficial in a distributed production network. It is also able to accept a range of input voltages. Taking these and other factors into account, PEM electrolysis appears to be the best solution in the case of distributed production, given its ability to accept a wide range of input voltages [18], the lack thereof often being a limitation of the use of renewable electricity sources.

2.3 Photocatalytic Water Electrolysis and Nanotechnology Considerations

Light can supply the energy for an electrolysis process to decrease electricity use. This process is relatively novel [19]. Photons strike a semi-conductor nanostructure, such as TiO_2, creating an electron-hole pair. A potential difference maintains the separation of the electron and hole. Water molecules adsorb to the semiconductor surface, creating a H^+ and OH^- ion, forming hydrogen and oxygen. Efficiencies of only 10% have been observed [20], and new catalysts need to be developed in order to lower the semiconductor band-gap. Two disadvantages that are as yet unresolved are the requirements of a large reaction surface area – posing further research challenges – and access to a continuous light source [14], both reducing the process’s practicality. There are advances in nanostructured materials substrates for increasing surface area; however, their high cost and difficult scalability may limit implementation in the immediate future.

2.4 Thermo-Chemical Water Splitting Cycles

Production cycles that use a chemical cycle and heat can serve as alternative solutions. The main advantage of this is that the chemical inputs are not depleted. In the literature, three such cycles are proposed as promising solutions:

1. Sulfur-Iodine (S-I)
2. Copper-Chlorine (CuCl)
3. Westinghouse Sulfur Process (WSP)

The S-I and WSP cycles are similar. The differences arise with regards to a step in the processes: a high-temperature step in S-I is replaced by a low-temperature electrolysis in WSP [16]. However, WSP exhibits issues that are intrinsic to the reactions employed: comparatively high temperatures and pressures are required to achieve comparable efficiencies to the CuCl cycle, and the acid component may present further challenges in inventory. Further, the materials required for the electrolysis reaction results in cost uncertainties in its long-term implementation. By contrast, the scale-up of the CuCl cycle, would appear to be more economical, as the process is based on low-temperature reactions [16], with a yield of close to 100% in certain conditions and a heat-to-electricity efficiency of 54% [21]. Thus the CuCl cycle seems like the most viable solution. This process is able to use “low-grade waste heat” [14]. An EU consortium project used the sun as the heat source [22]. Heat from future generation-IV nuclear reactors could be used for both thermochemical cycles and high-temperature water electrolysis processes [23] in adjacent hydrogen production plants. Co-production of electricity and hydrogen then becomes possible, altering their relative quantities based on current demand: when there is a surplus of electricity on the grid, the power stations can redirect their heat output to a hydrogen plant, eliminating the need for grid-scale energy storage solutions, currently required for intermittent renewable sources.

2.5 Biological Hydrogen Production Methods

Biological batch processes have been in use for a long time to create compounds like ethanol; however, batch processes are not suitable for the large-scale production of hydrogen, due to the time and labour required to repurpose a reaction vessel and the low purity of the product. There has been some research into continuous biological hydrogen production routes, such as an enzymatic pathway (SyPaB) to convert 1 mole of glucose to 12 moles of hydrogen in excess water [24]. Modified algae have also demonstrated an ability to produce hydrogen under certain conditions [25]; however, more work is needed to create a continuous process out of this.

Despite the promising prospects of these pathways, the costs to synthesise the enzymes required is still prohibitively expensive for large scale implementation; however, with ever decreasing synthesis costs, such pathways may be used. Pilot-scale systems are being evaluated [26]. Biological methods, however, may have further uses in hydrogen transportation and storage, rather than production.

2.6. Conclusions

There appear to be two attainable solutions to large-scale, long-term hydrogen production for the immediate future. For centralised production, given the plant size required, the CuCl cycle seems very promising. This assumes that the heat required for the cycle is available without combustion of carbon-containing fuels, potentially from Generation-IV nuclear reactors; however, it will be several years before such reactors come online. For distributed production, PEM electrolysis appears favourable, given the possible compact size of an electrolysis unit, and its inputs, water and electricity, being readily available through existing infrastructure. The relative split of centralised and distributed production will dictate the predominance of these and future hydrogen production methods.

3. Infrastructure Considerations

3.1 Centralised and Distributed

The question of whether to produce hydrogen at point locations in a centralised manner, as current fuels are, or in a non-centralised distributed manner, represents a key facet in the concept of the hydrogen economy, due to the potential for increased personal energy security. The relative efficiencies of each option and associated cost of supporting infrastructure construction must be considered when evaluating the two options.

The production of hydrogen at point locations is an attractive solution: certain pathways must be incorporated into a centralised production system, as they require inputs only available in such conditions, such as a heat source for the CuCl cycle. Higher efficiences and economies of scale would also arise in a centralised system, further reducing the price of hydrogen [27].

Centralised production may not be the most viable system on its own. Following production, the hydrogen would need to be transmitted, most likely across the natural gas network (Fig.3). In many cases, these high-pressure pipes have not been treated to avoid embrittlement [28], a change in the material's mechanical properties due to small hydrogen molecules leaching through the material. Thus a large capital investment would be required to adapt the grid to carry hydrogen; as a transition to a hydrogen economy has very little immediate monetary gain for private organisations – hydrogen transmission over long distances costs ~4.5 times more than for natural gas [17] – governments would need to fund the project.

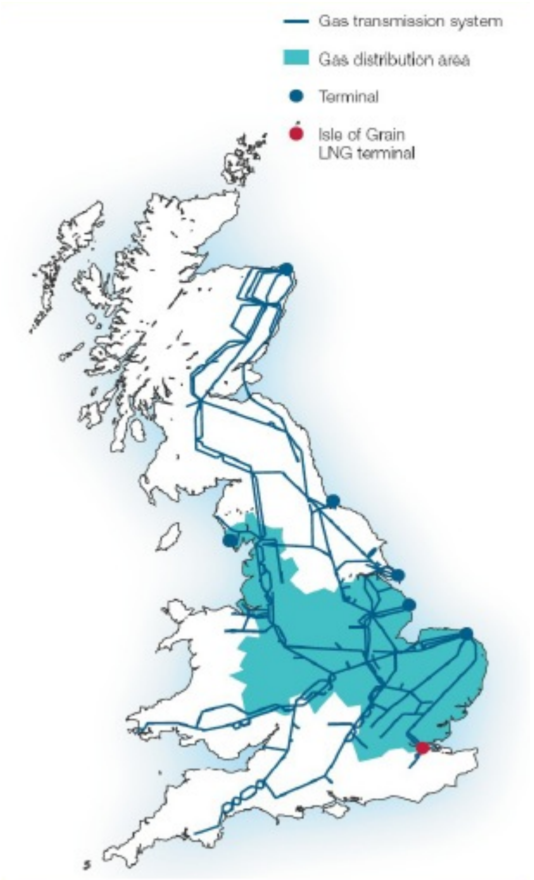

Fig. 3: National Grid operated natural gas transmission lines [29]

Distributed systems are beneficial to nations with a limited existing natural gas infrastructure. Similar to how these nations are forgoing the construction of copper telecom lines [30], distributed hydrogen production does not require the construction of a new network, as, in many cases, the existing ones can be used to deliver the raw material, electricity and water, needed for PEM electrolysis, with little modification [28]. For example, in India, electrolysis cells are being used to power mobile phone towers [31].

A 2007 report from General Motors analysed the relative costs of a distributed and centralised system. They concluded that for a densely populated area centralised production is best, as the benefits of a mobile hydrogen production unit become less prominent when compared to the greater efficiencies of centralised production [13]. Distributed production would benefit areas of low population density and nations that do not currently have an integrated natural gas grid. A more distributed system, however, is inevitable in the gradual transition from an oil-based economy, as production plant operators and vehicle purchasers slowly scale up supply and demand, rather than invest heavily in a new, unproven technology. This is commonly termed "The Chicken and Egg Problem".

3.2 Storage and End-Use States

In both distribution cases, hydrogen will need to be stored at the end-use site. A good hydrogen storage medium in mobile applications must satisfy certain criteria to be viable. It must:

- Have a high mass and volumetric energy density
- Be carbon-neutral
- Integrate well with a hydrogen distribution network
- Be at an equivalent cost to current fuel equivalents

3.2.1 Gaseous Hydrogen

Storing hydrogen in a gaseous state requires the repurposing of the natural gas infrastructure. In an interview with a National Grid systems engineer, it was mentioned that the UK's natural gas transmission network is being repurposed to allow it to store gas under high pressure within the transmission lines. Such a concept could apply to hydrogen; however, the standard enthalpy of combustion of hydrogen is ~-285.8 kJMol^{-1}, whereas for methane its ~-890.4 kJMol^{-1} [32], giving hydrogen gas a lower volumetric energy. Given the large volume and masses – both a premium in mobile applications - of the storage cylinders, gaseous storage is unlikely to be viable.

3.2.2 Liquefied Hydrogen and Liquid Storage Compounds

Condensed hydrogen has a higher energy density per unit mass; however, the energy required to condense hydrogen would equate to ~15% of its energy content [28] and the continuous boiling of the liquid limit liquid hydrogen's possible uses, especially given the limitations of high-pressure storage mentioned above. Natural gas, formed by carbon dioxide and hydrogen could be used, but adding Carbon Capture and Storage (CCS) capability to capture the carbon dioxide and maintain carbon neutrality to vehicles seems unreasonable.

There has been some research into using aqueous carbohydrates as a storage medium through the use of a bioreformer. One example exhibited 14.8% hydrogen by mass, exceeding the US Department of Energy's (DOE) target of 9% [28]. However, a number of issues are still present with such a storage method, many of which are similar to those associated with biological hydrogen production pathways, such as regeneration of used enzymes in the bioreactor. As such, this storage medium is unlikely to be used in the immediate transition to a hydrogen economy. If these challenges are overcome, it may become a viable option in the future.

3.2.3 Solid-state Hydrogen Storage

Hydrogen can also be stored in a solid compound through physisorption, where the hydrogen molecule interacts with the surface of a substrate in part through dispersive van der Waals forces or chemically bonded hydrogen in metal hydrides, where the hydrogen atoms are stored through covalent or ionic bonds. In the former, the amount of hydrogen that can be adsorbed is proportional to the surface area of the material (Fig.4). Nano-structuring material would increase this, but as the hydrogen is bonded relatively weakly, impractically high pressures and low temperatures are required to achieve a storage density acceptable for mobile applications, as has been established by multiple analysis of such materials [33].

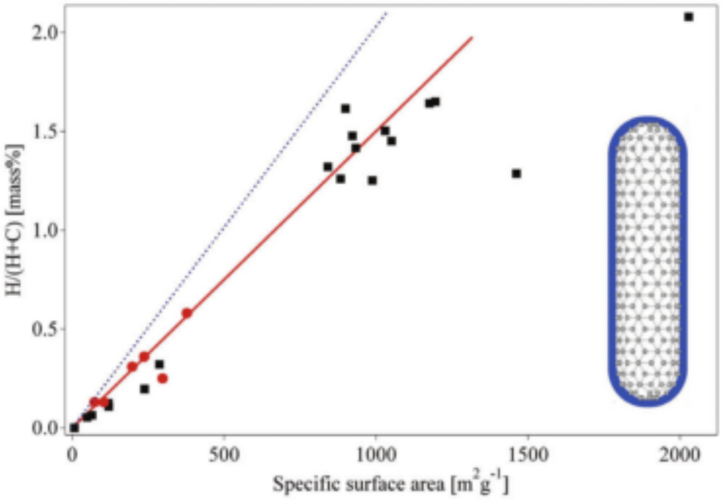

Fig. 4: Reversible amount of hydrogen adsorbed versus the surface area of carbon nanotube samples. Graph from [33]

The latter method has been a topic of much interest recently, due to the high hydrogen storage density possible with such materials. However, an analysis on a selection of promising materials concludes that there are still many material-science orientated challenges to overcome [33]. Regardless, such technologies are becoming commercialised. In a correspondence with Dr Arthur Lovell of *Cella Energy*, he detailed their ammonia borane (AB) composite, manufactured in pellet form, which can be pumped in and out of cars in a manner similar to liquid fuels [34].

Another analysis [35] suggests that AB is a promising material, as it has a high hydrogen capacity – 19.6% by mass – and releases hydrogen under thermal decomposition at moderate temperatures (423-523 K), but faces efficiency challenges in the regeneration step, significantly reducing its Well-To-Tank (WTT) efficiency in comparison to other materials (Fig.5).

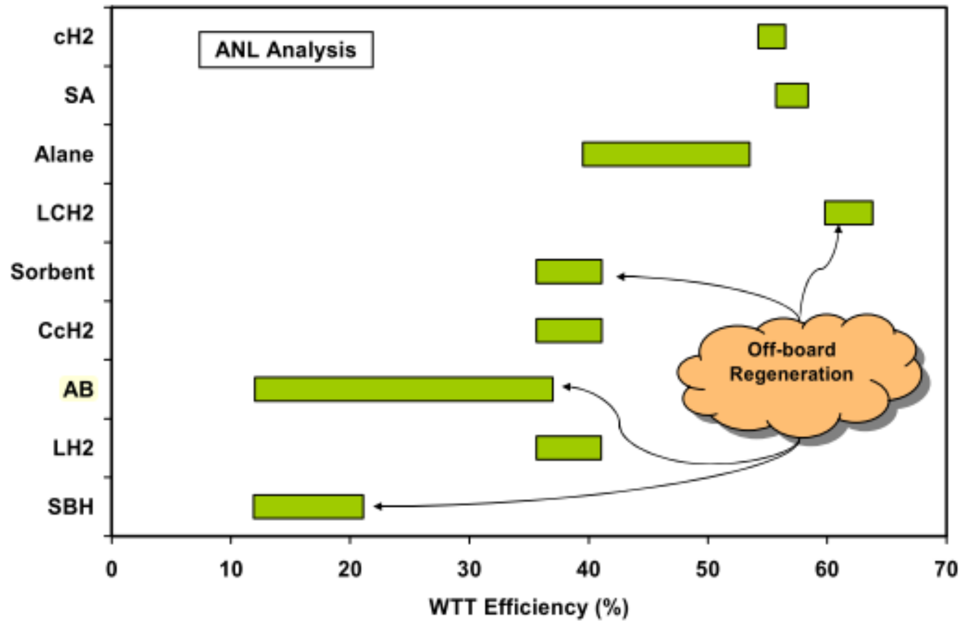

Fig. 5: Well-to-tank efficiencies – the compound efficiency of all processes from source to end-use – of the hydrogen storage options (abbreviated on the y-axis). The results are shown as a range to allow for variations in the assumptions made in assessing the off-board regeneration performance – the efficiency of 'refuelling' the compounds with hydrogen. Graph from [35]

A solid-state hydrogen storage system based on AB appears promising, due to the pellet nature of the fuel requiring only minor modifications to existing refuelling station infrastructures. This is provided that processes and economies of scale are developed for the regeneration step to increase its WTT efficiency and allow for on-site regeneration, removing the additional process of transporting used pellets for regeneration. If this can be achieved, solid-state storage presents itself as a viable solution.

4. Implementation and Case Studies

4.1 Hydrogen Fuel Cell and Internal Combustion Engine Vehicles

a) $2H_2 + O_2 \rightarrow 2H_2O$

b) $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

c) $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

d) $(2n+1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O$

Fig. 6: a) ICE and HFC reaction. b) Sabatier reaction. c) Combustion of methane. d) Fisher-Tropsch reaction.

The energy in the stored hydrogen can be directly extracted through two methods in mobile applications: a Hydrogen Fuel Cell (HFC) and an Internal Combustion Engine (ICE). They both allow for the same reaction to take place in terms of molar ratios (Fig.6a). As hydrogen is not explosive in pure form [36], it needs to be mixed with hydrocarbons or oxygen in specific ratios in order for ICE applications to be efficient. Such control systems may be too temperamental and potentially dangerous if a fault results in incorrect hydrogen to oxygen ratios. Instead, natural gas (CH_4) could be used, produced via the Sabatier reaction (Fig.6b).

Several issues could arise when assessing the suitability of this. To achieve carbon neutrality, the carbon dioxide released with combustion (Fig.6c) would need to be captured and transported back to a methane generation plant. If it is to be generated on-board, one has to consider the additional weight and volume of the reaction chamber, as well as the ICE and hydrogen storage medium.

HFCs seem more viable, as they replace the need for an ICE and associated reaction or mixing chambers. There are many types of HFCs, but the US Department of energy deems Polymer Electrode Membrane (PEM) (Fig.7) HFCs suitable in transportation [37], due the solid electrode, low operating temperatures, quick start-up times and high efficiency (~60%). Some manufacturers exhibited HFC road vehicles at the 2014 Consumer Electronics Show [38], indicating the strong support manufacturers have for the technology.

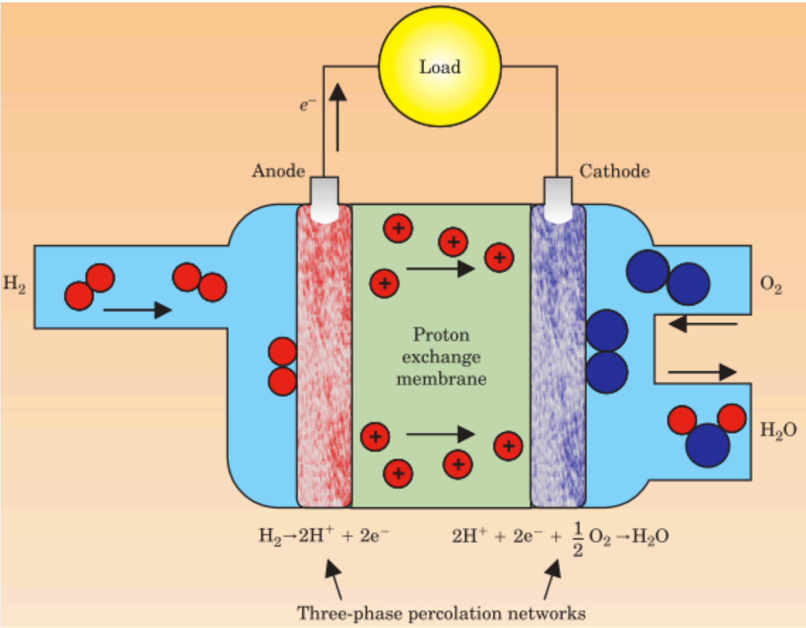

Fig. 7: PEM HFC. At the anode, hydrogen molecules dissociate and electrons are directed to an external circuit; protons are handed off to the ion-exchange membrane and pass through to the cathode. There, oxygen combines with protons from the ion-exchange membrane and electrons from the external circuit to form water. Graphic from [7]

4.2 Consideration of Competing Battery Technologies

As HFCs output electricity, this raises the question of the usefulness of a hydrogen economy, considering that Battery Electric Vehicles (BEVs) are currently commercially available and comparatively little infrastructure needs to be built for them. Further, the precious metal catalysts, such as platinum, needed in PEM HFCs, increase overall cost of Fuel Cell Vehicles (FCVs) independently of economies of scale, requiring further research to find alternatives or limit the need for them. Contrarily, battery technology is already well developed and widespread, requiring comparatively little research to widely implement them.

A 2011 analysis of this comparison, published in *The International Journal of Hydrogen Energy* [39], suggested that either configuration could be shown to be superior: The FCV weighs less, requires less fuel volume, costs less in terms of vehicle and life cycle costs and takes less time to refuel; however, BEVs have a lower fuel cost per kilometre, higher well-to-wheels efficiency per kilometre and can employ existing infrastructure.

The analysis concludes that, due to a lack of priority in vehicle configurations, such as cost, range and weight, both BEVs and FCVs are evenly matched in the light duty vehicle market. However, recent developments in battery technology – such as the “all-electron” battery developed by the Rapid Prototyping Laboratory at Stanford University – may deliver both higher power and energy density and exhibit a longer lifetime than the current lithium-polymer batteries [40]. Even so, current battery manufacturing processes are resource and energy intensive, and the rare-earth metals required are becoming limited resources [41]. Conversely, the same argument can be made for the platinum in PEM HFCs. Thus, it is hard to conclude which is the superior solution in vehicles at the present time. It may be the case that FCVs are used for longer-distance travel, and BEVs within cities, in part due to their relative fuelling times and range; however, this depends on future developments in both battery and fuel cell technologies.

4.3 Consideration of the Fischer-Tropsch Process for Aviation and Shipping

Aviation and shipping contribute to carbon dioxide emissions and fossil fuel depletion alongside automobiles: the fifteen largest ships pollute as much as all cars worldwide [42]. Consideration of alternative fuel sources for these is thus important. For aviation, current jet technology relies on the combustion exhaust gases and – given the design constraints – a high fuel density per unit mass and volume. A larger fuel storage volume is required for hydrogen – a lower volumetric density fuel – so hydrogen fuel cell systems cannot be implemented without significant jet and aircraft design overhauls. Hydrogen can, however, be used to form alkanes for use in aviation via the Fischer-Tropsch reaction (Fig.6d) [43]:

The question of carbon neutrality arises here, given that combustion of alkanes leads to production of carbon dioxide. This is less of a problem on ships, as volume and mass for CCS systems are less constrained than on aircraft. However, ships could use electrolysis cells with wind or solar energy to produce hydrogen from desalinated seawater, as demonstrated aboard *The Hydrogen Challenger* [44], leading to a fully sustainable industry. In both the case of aviation and shipping, design overhaul-timescales are longer than for automobiles, meaning that the relative successes of different technologies in the consumer vehicle industry will affect the design of future ships and aircraft. Implementing a chosen solution will thus have further impacts on other industries in the future.

5. Geopolitical Considerations

5.1 Hydrogen Competitiveness and Legislation

Governments will have to also consider the economic and legislative viability of hydrogen for the consumer in choosing solutions to the various challenges above. According to the DOE, legislation has been repeatedly identified as an institutional barrier to deploying hydrogen technologies: should hydrogen be made available for public consumption, the price of hydrocarbon fuel, now a direct competitor, would need to be kept artificially high in order to prevent the latter from having a price advantage as its consumption decreases.

5.2 Water Scarcity

Governments will further have to manage new resource constraints in a hydrogen economy. As all of the sustainable hydrogen production methods discussed above require clean water as an input, increased water use due to the hydrogen economy could worsen the issue of water scarcity. 1.1 billion people currently lack access to safe drinking water [45], and an analysis in the journal *Agricultural water management* suggests that, with an increasing world population and agricultural activity, this number will increase independently of a hydrogen economy [46]. Saltwater desalination is not an option for countries with no sea border.

A second facet to this is the unequal distribution of water sources: if the hydrogen economy is to be marketed as way to democratise energy production, then the global water distribution would favour wet over dry areas. Seeing as many of the affected countries are facing shortage problems as it stands, a hydrogen economy may cause further demographic and economic difficulties for them. A solution to this problem is not straightforward, and collaboration between governments and non-governmental organisations is required in order to bring about an effective one.

6. Conclusion

Governments are beginning to recognise the need for a change in energy markets, and have invested in technologies for a hydrogen economy. The Canadian government has funded research into various hydrogen production pathways [27] and Iceland has transitioned Reykjavik's public transportation system to hydrogen, which has been well received by the public [47], indicating the potential for widespread administrative and public approval of a hydrogen economy.

However, a global hydrogen economy still appears remote, due the prerequisites required for one. Investment in hydrogen production plants for centralised distribution requires the presence of sufficient demand, which requires availability of hydrogen applications, such as HFC vehicles. Further research needs to be conducted to reduce the need for precious metal catalysts in PEM electrolysis and fuel cells, while transitioning the global electricity grid to an entirely renewably supplied one, a challenge already facing many developed nations. The associated geopolitical issues would require settling if a hydrogen economy – being more complex to implement than the previous oil-based one – were to become widespread.

Such a transition will not happen on any short timescale. Intermediate solutions to the challenges above, such as the use of a consumer vehicle technology that can employ existing energy infrastructures, for example battery or hybrid-electric vehicles, will be required alongside strong international support for the growth of a hydrogen economy. Research efforts must ensure the continued development of hydrogen-related processes to maintain its viability as an energy storage solution. However, whatever future developments present, finding an alternative to fossil fuels is a necessity.

Body text word count: 4000

Bibliography

[1] National Hydrogen Association, “History of Hydrogen Timeline.” pp. 1–2, 2010.

[2] C. on Alternatives, S. for Future Hydrogen Production, and N. A. of E. Use National Research Council, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. The National Academies Press, 2004.

[3] M. Q. Wang and H. S. Huang, “A full fuel-cycle analysis of energy and emissions impacts of transportation fuels produced from natural gas,” Argonne, IL, Jan. 2000.

[4] “Hobbled by High Cost, Hydrogen Fuel Cells Will Be a Modest $3 Billion Market in 2030.” [Online]. Available: http://www.luxresearchinc.com/news-and-events/press-releases/143.html. [Accessed: 02-Feb-2014].

[5] J. Verne, *The Mysterious Island*. Grosset & Dunlap, 1956, p. 500.

[6] “US Energy Supply and Fossil Fuels Use | The Energy Collective.” [Online]. Available: http://theenergycollective.com/matstc/228791/our-energy-use-numbers. [Accessed: 02-Feb-2014].

[7] G. W. Crabtree, M. S. Dresselhaus, and M. V Buchanan, “The Hydrogen Economy,” *Phys. Today*, no. December, pp. 39–45, 2004.

[8] S. H. Mohr and G. M. Evans, “Peak Oil: Testing Hubbert’s Curve via Theoretical Modeling,” *Natural Resources Research*, vol. 17. pp. 1–11, 2008.

[9] S. Dunn, “Hydrogen futures: toward a sustainable energy system,” *Int. J. Hydrogen Energy*, vol. 27, pp. 235–264, 2002.

[10] J. Rifkin, *The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth*. J.P. Tarcher/Penguin, 2003, p. 294.

[11] J. Hamilton, “Historical oil shocks,” pp. 1–51, 2011.

[12] US Energy Information Administration, “International Energy Outlook 2013,” 2013. [Online]. Available: http://www.eia.gov/forecasts/ieo/world.cfm. [Accessed: 08-Feb-2014].

[13] B. K. Gross, I. A. N. J. Sutherland, and I. J. Sutherland, “General Motors Corporation Infrastructure Assessment,” 2007.

[14] G. Crabtree and M. Dresselhaus, “The hydrogen fuel alternative,” *Mrs Bull.*, vol. 33, no. April, pp. 421–429, 2008.

[15] “Looking at Hydrogen to Replace Gasoline in Our Cars: Scientific American,” *Scientific American*, 2008. [Online]. Available: http://www.scientificamerican.com/article.cfm?id=can-hydrogen-replace-gas.

[16] M. Carmo, D. Fritz, J. Mergel, and D. Stolten, “A comprehensive review on PEM water electrolysis,” *Int. J. Hydrog. …*, vol. 8, no. 1, 2013.

[17] “Hydrogen Production and Distribution,” *IEA Energy Technol. Essentials*, pp. 1–4, 2007.

[18] A. Hauch, S. D. Ebbesen, S. H. Jensen, and M. Mogensen, “Highly efficient high temperature electrolysis,” *J. Mater. Chem.*, vol. 18, no. 20, p. 2331, May 2008.

[19] L. Amirav and a. P. Alivisatos, “Photocatalytic Hydrogen Production with Tunable Nanorod Heterostructures,” *J. Phys. Chem. Lett.*, vol. 1, no. 7, pp. 1051–1054, Apr. 2010.

[20] S. U. M. Khan, M. Al-Shahry, and W. B. Ingler, “Efficient Photochemical Water Splitting by a Chemically Modified n-TiO2,” *Science (80-.).*, vol. 297, no. 5590, pp. 2243–2245, 2002.

[21] J. Masin, M. Lewis, and R. Vilim, “Development of the low temperature hybrid Cu-Cl thermochemical cycle,” *AIChE Annu. Meet. Conf. …*, vol. 2, no. l, 2006.

[22] A. G. Konstandopoulos, “Solar Hydrogen: The Hydrosol Technology and its Implications.”

[23] “Nuclear’s new generation - physicsworld.com.”

[24] Y.-H. P. Zhang, B. R. Evans, J. R. Mielenz, R. C. Hopkins, and M. W. W. Adams, “High-yield hydrogen production from starch and water by a synthetic enzymatic pathway.,” *PLoS One*, vol. 2, no. 5, p. e456, Jan. 2007.

[25] I. Hargittai, *Candid Science: Conversations with Famous Chemists*. Imperial College Press, 2000, p. 516.

[26] N. Ren, J. Li, B. Li, Y. Wang, and S. Liu, “Biohydrogen production from molasses by anaerobic fermentation with a pilot-scale bioreactor system,” *Int. J. Hydrogen Energy*, vol. 31, no. 15, pp. 2147–2157, Dec. 2006.

[27] G. F. Naterer, S. Suppiah, L. Stolberg, M. Lewis, Z. Wang, V. Daggupati, K. Gabriel, I. Dincer, M. a. Rosen, and P. Spekkens, “Canada’s program on nuclear hydrogen production and the thermochemical Cu–Cl cycle,” *Int. J. Hydrogen Energy*, vol. 35, no. 20, pp. 10905–10926, Oct. 2010.

[28] Y.-H. P. Zhang, “A sweet out-of-the-box solution to the hydrogen economy: is the sugar-powered car science fiction?,” *Energy Environ. Sci.*, vol. 2, no. 3, p. 272, 2009.

[29] National Grid UK, “National Grid Overview Presentation,” 2014. .

[30] F. Olsen, *Bellona rapport nr. 6 - 2002*, no. 6. 2002.

[31] “Hydrogen fuel cells for India’s mobile phone masts - E & T Magazine.” [Online]. Available: http://eandt.theiet.org/news/2014/jan/fuel-cells-mobile.cfm. [Accessed: 23-Feb-2014].

[32] J. G. Stark, *Chemistry Data Book*. Hodder Education, 1982.

[33] A. Züttel, “Materials for hydrogen storage,” *Mater. today*, no. September, pp. 24–33, 2003.

[34] “Our materials | Hydrogen storage materials development since 2011.” [Online]. Available: http://cellaenergy.com/our-materials/. [Accessed: 25-Feb-2014].

[35] R. K. Ahluwalia, T. Q. Hua, and J. K. Peng, “On-board and Off-board performance of hydrogen storage options for light-duty vehicles,” *Int. J. Hydrogen Energy*, vol. 37, no. 3, pp. 2891–2910, Feb. 2012.

[36] V. Molkov, “Hydrogen Safety Engineering: The State-of-the-Art and Future Progress,” *Compr. Renew. Energy*, vol. 4, pp. 77–110, 2012.

[37] US Department of Energy, “FCT Fuel Cells: Types of Fuel Cells.” [Online]. Available: http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html. [Accessed: 26-Feb-2014].

[38] “Toyota Shows Off Fuel Cell Vehicle Powered by Hydrogen, Air.” [Online]. Available: http://mashable.com/2014/01/06/toyota-fuel-cell-vehicle/#:eyJzIjoidCIsImkiOiJfaTlqamVtbHZubzUzNzdvcHI5a2MyeGF4eGJfIn0.

[39] A. Veziroglu and R. Macario, “Fuel cell vehicles: State of the art with economic and environmental concerns,” *Int. J. Hydrogen Energy*, vol. 36, no. 1, pp. 25–43, Jan. 2011.

[40] “Mechanical Engineering - Army High Performance Computing Research Center.” [Online]. Available: http://me.stanford.edu/research/centers/ahpcrc/Project1_6.html.

[41] T. Letcher, A. Väyrynen, and J. Salminen, “Lithium ion battery production,” *J. Chem. Thermodyn.*, vol. 46, pp. 80–85, 2012.

[42] “Rose George: Inside the secret shipping industry | Video on TED.com.” [Online]. Available: http://www.ted.com/talks/rose_george_inside_the_secret_shipping_industry.html.

[43] C. Windle, “Artificial Photosynthesis,” *Chemistry Review*, pp. 7–9, Sep-2013.

[44] “Hydrogen Challenger Wind Wasserstoff-Produktionsschiff [Translated].” [Online]. Available: http://www.diebrennstoffzelle.de/h2projekte/mobil/hydrogen_challenger.shtml. [Accessed: 01-Mar-2014].

[45] “WHO | Water supply, sanitation and hygiene development.” [Online]. Available: http://www.who.int/water_sanitation_health/hygiene/en/. [Accessed: 01-Mar-2014].

[46] F. Rijsberman, “Water scarcity: Fact or fiction?,” *Agric. water Manag.*, vol. 80, no. 1–3, pp. 5–22, 2006.

[47] J. Ritter, A. Ebner, J. Wang, and R. Zidan, “Implementing a hydrogen economy,” *Mater. Today*, vol. 14, pp. 52–64, 2003.