CHEMICAL ECONOMICS - THE HYDROGEN ECONOMY?

In the community and politics there is a tendency to conflate technically demonstrated projects with economically viable projects. There are many technologies that can technically be demonstrated, especially if money is no object, but will always remain not commercially viable. The hydrogen economy is a good example.

Across the research and development community there is a fascination for the use of hydrogen as a transport fuel, especially for driving cars fitted with fuel cells. The attraction comes from two drivers, the first is that hydrogen combustion does not emit carbon and thus the use of hydrogen is an alternative to battery powered vehicles for decarbonising the transport fleet. The second is that internal combustion engines are not very thermally efficient whilst in theory at least fuel cells have a much higher efficiency. Today there are many examples of demonstration programs, many supported by the vehicle manufacturers, for hydrogen fuel cells and the required infrastructure. A small demonstration program has recently been announced by the ACT government supported by Hyundai and Siemens and others associated with the renewable fuels industry.

There are three steps required for the effective use of hydrogen fuelled vehicles, each requiring significant innovation before practical use can come to fruition: 1. hydrogen production at a competitive cost, 2. hydrogen distribution to filling points, 3. operation and storage of hydrogen at the filing point and in the vehicle.

Hydrogen is widely used in the hydrocarbon processing industry including oil refining. Here it is produced as a by-product of dehydrogenation processes, such as naphtha reforming to produce aromatics for fuels and chemicals. These processes are supplemented by steam reforming of natural gas (or partial oxidation of natural gas). The co-produced carbon monoxide is converted to more hydrogen by the water-gas-shift process and the co-produced carbon dioxide extracted by an absorption process. Nowadays, many plants separate pure hydrogen from this product stream using membrane or PSA separators. The natural gas route is considered the most efficient and cheapest method for producing hydrogen.

One concept for hydrogen distribution is to have a large centrally placed production facility which distributes the hydrogen to retail forecourt sites. Such a central facility would produce about 400kt/y of hydrogen, enough to provide over 2 million vehicle fills. The large facility would maximise the benefits from economies of scale and my estimates for the production cost from such a facility is shown in Figure 1 (data extracted for US National Academy of Science reports). Gas priced below US$4/GJ (HHV basis on which gas is usually sold) would produce hydrogen below $7/GJ (LHV basis which is the way the hydrogen is used).

How this stacks up against gasoline (petrol) prices is shown in Figure 2 which illustrates the change in the traded price of gasoline expressed in energy units (US$/GJ, LHV basis) on the Singapore market as the price of crude oil (Tapis blend) changes. If we assume that a vehicle fuel cell has an efficiency of 55% and gasoline (petrol) engine of 30% then the price equivalent cost of hydrogen is shown on the top line. Thus with prevailing oil prices at $60/bbl, the gasoline price is US$12.50/GJ and the hydrogen equivalent price is US$23/GJ which is achieved with gas prices below US$14/GJ (Figure1).

Since gas prices (even in Australia) are well below this all seems well and good. Unfortunately there are a couple of issues which spoil this rather rosy picture.

One is the basic assumption that a fuel cell vehicle will operate in practice at significantly higher efficiency than a modern gasoline or diesel hybrid vehicles. In practice when losses from the fuel cell to the electric drive and drive chain are taken into account there may not be much difference. This would reduce the target production cost for hydrogen to a similar order for gasoline or diesel unless at the end of the day the consumer is happy, or forced, to pay more for the privilege of a hydrogen vehicle.

Because of its innate properties, for a reasonable operational mileage, hydrogen has to be stored on-board the vehicle at very high pressure, typically 350bar or even 700bar. This is seriously high pressure for an application as common as vehicle refuelling.

Hydrogen at this sort of pressure is very dangerous. Leaks can spontaneously ignite. The flame is over 2000^{o}C which melts metal structures holding the pipeline or storage facility together. I once worked on a hydrogen plant which operated at over 200bar and was built in 1936. All the pipe-work was extremely thick; it was made by the Woolwich Arsenal which had the specialist equipment to manufacture it. To prevent destruction from hydrogen leaks the whole plant was clad in over 4 inches of blue asbestos and stood behind a thick brick wall to further protect operators. Only senior qualified graduate engineers where allowed to tackle leaks behind the wall, much to the fear of the tradesmen, because often the engineers would feign ignorance of which way to turn the 6" diameter bolts to tighten gaskets. I would hope the mechanical engineering design as improved since then.

Hydrogen production facilities tend to operate at about 30bar for steam methane reforming (and 100 bar for partial oxidation). A rough estimate is that to intensify the pressure from 30 bar to 350 bar in a central facility producing hydrogen would require 85MW and to compress to 700 bar somewhere in the region of 125MW. This would represent a serious cost penalty, especially if the power was from wind or solar generators.

What about different approaches. The marginal (no capital considered) cost of production of hydrogen by electrolysis is illustrated in Figure 3. Wind and solar generation costs are generally in excess of $100/MWh (unsubsidised basis) and production by this route is clearly very costly compared to conventional fuels. This is further exacerbated by electrolysis generally occurring at or near atmospheric pressure, which will incur vast compression costs to bring the product to a 350bar filling pressure. This issue has been addressed by some developers trying to use electrolysis at high pressure (Honda).

In the research stage are several routes to produce hydrogen by solar irradiation, missing out the photovoltaic and electrolysis steps. This is very much a research activity and as yet well away from a demonstration facility let alone commercialisation.

There are also developments in using small scale PV for distributed hydrogen generation (household make-your own hydrogen). How proponents solve the problem of providing homes with 350bar hydrogen compressors is somewhat unclear.

The pressure problem can be overcome by moving to liquid hydrogen storage. Insulation size would restrict this to larger vehicles and does not address the compressor cost for cooling the gas to below the critical point (33K).

Across the board, the hydrogen economy is replete with research and demonstration projects pushing boundaries with innovative solutions. Unfortunately, as this analysis shows, the hydrogen economy for Australia is still a long way off. Hydrogen may be destined to be the fuel of the future but will always remain so.

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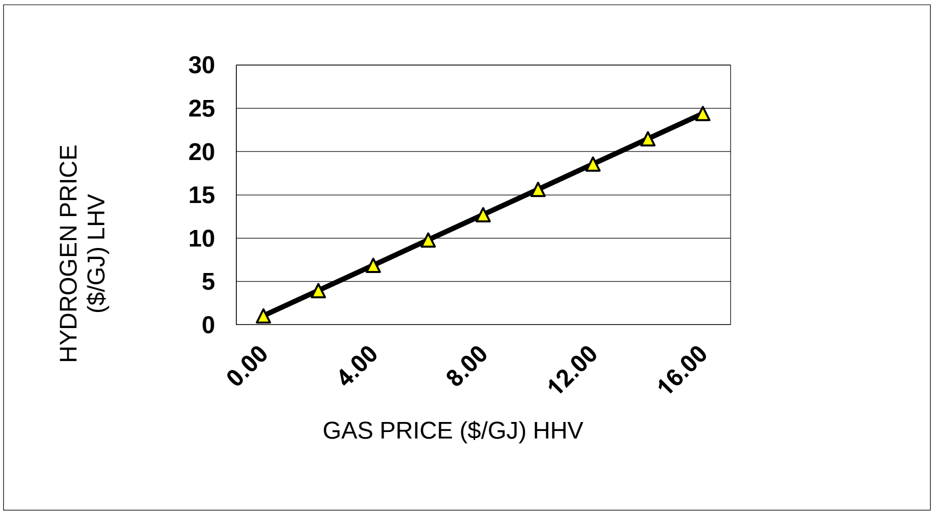

Figure 1: Estimated hydrogen production cost from gas in a large central facility

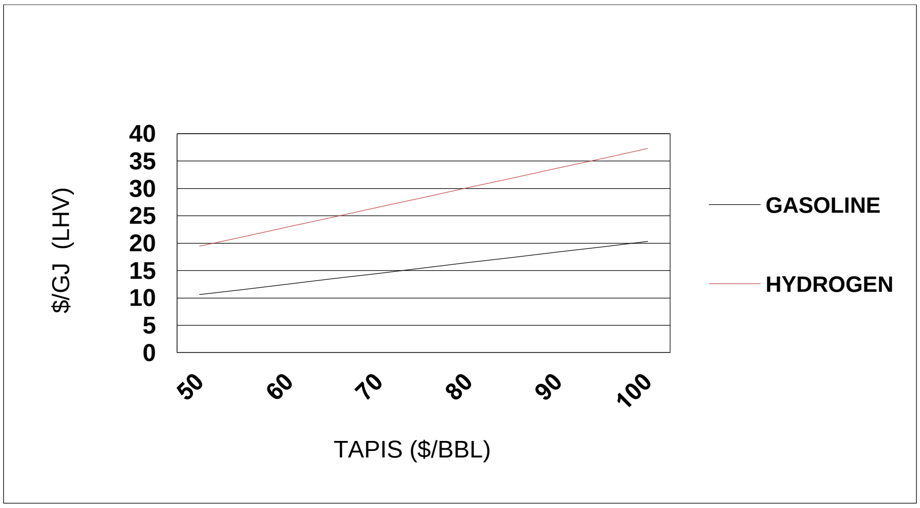

Figure 2: Equivalent values for gasoline (petrol) and hydrogen versus oil price (Tapis)

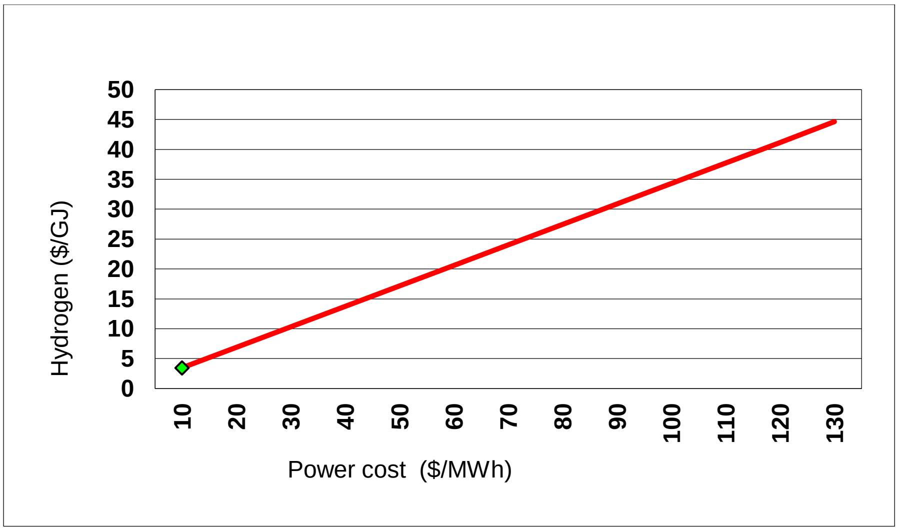

Figure 3: Marginal hydrogen production cost using electrolysis