Modelling pathways for a hydrogen fuel Infrastructure system

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1. Abstract

Hydrogen may act as one potential alternative to reducing current fossil fuel demand but only if the correct systems are in place. The work considers a variety of options using a ‘bottom-up’ perspective incorporating the production phase, the ‘delivery method’ (road tankers versus pipeline) and the final local conversion phase (gas or liquid use for end consumers). It is assumed that the ‘fuel’ (or more precisely energy carrier) produced will be for a fleet of ground vehicles and the default size is set at 100 buses which need to be fuelled daily. The model calculates both overall CO_2 emissions, as well as an overall cost of production and delivery based on distance travelled. Results are compared to a baseline case, based on a conventional diesel bus system. Input variables include fleet size; fuel demand and economy, gas and electricity feedstock data, capital and operation costs for production equipment and transport, fuel delivery distance and pipeline installation cost as a function of terrain (urban or rural).

Thus the main model steps can be summarised as: centralised or localised production; production output (gas or liquid); delivery method (‘tankers or pipeline’) and local conversion ‘method’ employed (again gas or liquid). For example one pathway might be centralised production via electrolysis to produce gaseous hydrogen, delivered by tanker (as gas) and used as gas at the filling station. Another different approach would be via Steam Methane Reforming (SMR) at the local level to produce gas which would be used in that state. The localised production methods do not involve any form of ‘delivery’ phase as they create the energy carrier at point of use, and some economic and emission savings might be expected. Initial results show these paths to be relatively more expensive when compared to other pathways.

Hydrogen production is calculated via three main methods offering the user a choice of SMR, biomass or electrolysis by centralised production (i.e. large scale) or localised methods (i.e. small scale). Certain pathways are not modelled due to physical constraints or infrastructure systems which are construed to be energy ‘illogical’ (e.g. produce as liquid but then transport as gas causing large overall energy increases in the supply process). The total number of pathways considered is 22, although there are many more, with a core of 11-13 being investigated in depth (including the diesel baseline case) as these are felt to have the highest potential in the marketplace. Although this work is designed to identify the best pathway for a very limited and specific set of circumstances it is flexible in that input variables include electricity generation costs and potential future emissions reduction techniques such as carbon sequestration and storage as well as using fuel cell powered trucks to deliver the hydrogen. It can also be expanded to cope with larger fleets or mixed vehicle fleets. Future work could investigate the potential to incorporate solid hydrogen pathways, or production at the lowest local scale using household generation systems.

2. Introduction

This paper follows on from the paper submitted by the author at UTSG 2008, entitled Pathway options for a hydrogen fuel infrastructure system (Berridge, 2007) In that study, various pathways were considered for a transition from hydrocarbons to hydrogen to power bus fleets. In this paper the author reviews the preliminary results of the modelling which is currently carried out (Berridge 2009, forthcoming thesis).

There are a number of reasons why a transition away from dependence on hydrocarbon based fuels towards potentially renewable options such as hydrogen may be desirable. Amongst the most common are:- cost, energy efficiency, energy security, environmental concerns and energy shortage.

Presently, hydrogen appears to be more expensive than the hydrocarbon competition, but with volatility of oil prices, this may not be the case indefinitely. There is a significant variation in both the cost of producing and the cost of transporting hydrogen depending on the pathway chosen. The term “pathway” is used to define the boundaries of a hydrogen supply system which includes the following steps - production, compression, transportation, storage and loading on board vehicles.

Hydrogen, as an energy carrier rather than combusted as a fuel has to be converted from another source, such as oil, coal, gas, electricity, biomass etc. Due to inefficiencies in conversion processes, it is unlikely that energy efficiency would be a reasonable justification for a change to hydrogen. It would be more logical in terms of an overall energy balance, to use the initial energy source directly. It is therefore not considered further in this paper.

Energy security is a relatively new driver for change which has developed due to recent world events causing instability in oil prices. Also, newly discovered hydrocarbon reserves are increasingly located in politically sensitive and / or geographically remote regions. Hydrogen is almost unique as a source of energy in that it can be produced in a variety of ways, and from a variety of energy sources. Consequently, hydrogen offers the potential for countries and regions to become independent in terms of energy needs regardless of oil and gas reserves. Thus, this term is sometimes referred to as energy dependence or ‘energy independence’.

Environmental concerns have been a topical issue for a number of years now, with conventions such as Kyoto attempting to address global climate change issues. Whilst hydrogen is emissions free at the point of use, the production process and distribution system may actually produce more CO_2 emissions than conventional fuels such as diesel, petrol, CNG and LPG etc. Consequently, the complete pathway needs to be considered when measuring the CO_2 emissions reduction potential of hydrogen. The study takes a bounded, or limited, life cycle approach since fuel cell buses are not yet in series production. This could be considered a gate to tail pipe approach.

Energy shortage concerns can quite subjective, depending on timescale chosen. According to a review by BP, world reserves of oil have actually increased from 761.6 thousand million barrels in 1984 to 1188.6 thousand million barrels in 2004 (BP, 2005). Whilst it is true that there are still significant reserves of oil and potential for further discoveries in the future, it is also true that we are using hydrocarbon reserves faster than they are replenished by nature. It is logical, that at some point in time the world will experience either short term shortages or a major decline of oil and gas supplies.

Both energy shortage and environmental concerns may prove to be long term reasons for change. Many advocates see hydrogen as a long term solution. A common timescale for a transition to a hydrogen economy is the year 2050. For example, Dutton and colleagues in, *The hydrogen energy economy: it’s long term role in greenhouse gas emissions,* considers the year 2050 in their assessments (Dutton et al, 2005).

The cost and environmental impact of any transition will be two key factors in the decision making process to determine whether a hydrogen economy is viable. The benefits of energy security are also related to cost, and modelling of pathways would also be beneficial. Energy efficiency, whilst clearly desirable would perhaps be less of an obstacle if the source of energy to produce hydrogen was considered limitless (eg: wind or solar power). Consequently, the choice of energy source is another reason to measure the different pathways as some paths are still largely hydrocarbon dependent.

3. Modelling approach

Since cost and environmental impact are two of the key factors which may justify the transition to a hydrogen economy, the model needs to be defined in terms of the H_2 system, along with it’s boundaries and a base case for comparison.

The system is based on a bus fleet, chosen to minimise the requirements of a large distribution chain. Typically, buses travel a limited distance from the depot and return at the end of their journey, making only one filling station necessary per fleet. This is also means that a single point distribution model is appropriate, rather than a more complicated distribution network model which is typical of a large city wide bus fleet. This simple approach enables a detailed analysis of a wider range of pathways in greater depth. More complex distribution network models are likely to be appropriate for further study, once the pathways options have been reduced.

The boundaries of the system can be defined as starting from the point of hydrogen production and includes all the necessary steps through to the point of loading onto the buses, including fuel use. Each pathway will include some or all of the following steps, in some 'linear' series:-

Production > Purification > Liquefaction > Compression > Transportation > Storage > Vaporisation > loading (on to the buses).

The base case for comparison uses a diesel buses powered with an internal combustion engine. The hydrogen bus uses a Proton Exchange Membrane (PEM) fuel cell to power the buses.

The capital costs of both types of buses, as well as associated maintenance costs have been considered as outside the boundary of the model. This is justified on the basis that, at present, the hydrogen powered FCV buses used in the CUTE project can best be described as prototype vehicles rather than mass produced production line products. This would make the hydrogen pathways uncompetitive due to the purchase and maintenance costs.

The comparisons are made in terms of £ (cost) or kg CO_2 (emissions), per 100 km of bus travel. It is not appropriate to just consider the cost per kg of fuel loaded on to the buses for the following two reasons:-

- Hydrogen and diesel have significantly different energy values in terms of the LHV (Lower Heating Value). Hydrogen has approximately three times the energy value by mass at 120 MJ/kg compared with diesel at 45 MJ/kg.
- Fuel cell vehicles (FCV's) are claimed to be more than twice as efficient as an internal combustion engine, with typical values of >60% for an FCV compared with 30% for diesel.

4. Hydrogen pathways selected

This research is partly based on the recent Clean Urban Transport for Europe Project (CUTE), which involved the trial and demonstration of twenty seven Fuel Cell powered buses in nine European cities. The CUTE project ended in 2006 and a number of reports were disseminated to the public. In total the buses travelled in excess of a million kilometres over a two year period (Anon, 2005).

A total of twenty two pathways have been identified, see Table 1 below. Some of these were quickly eliminated (refer to exclusion notes below). This reduced the number of likely pathways down to a total of eleven, of which nine are produced via centralised production and two are localised production. Only four of these pathways were demonstrated in the recent CUTE project.

The most common methods of hydrogen production presently are:-

- Steam Methane Reforming (SMR) of natural gas
- Biomass gasification of various types of feedstock, which is then converted to hydrogen using a reforming process.
- Electrolysis.

Pathway	Production Method	Produced as	Transport method	To be modelled	Reasons for exclusion
C1	SMR	GAS	ROAD	**Yes**	
C2	SMR	GAS	PIPELINE	**Yes**	
C3	SMR	GAS	RAIL	No	1
C4	SMR	LIQUID	ROAD	**Yes**	
C5	SMR	LIQUID	PIPELINE	No	2
C6	SMR	LIQUID	RAIL	No	1
C7	Biomass	GAS	ROAD	**Yes**	
C8	Biomass	GAS	PIPELINE	**Yes**	
C9	Biomass	GAS	RAIL	No	1
C10	Biomass	LIQUID	ROAD	**Yes**	
C11	Biomass	LIQUID	PIPELINE	No	2
C12	Biomass	LIQUID	RAIL	No	1
C13	Electrolysis	GAS	ROAD	**Yes**	
C14	Electrolysis	GAS	PIPELINE	**Yes**	
C15	Electrolysis	GAS	RAIL	No	1
C16	Electrolysis	LIQUID	ROAD	**Yes**	
C17	Electrolysis	LIQUID	PIPELINE	No	2
C18	Electrolysis	LIQUID	RAIL	No	1
L1	SMR	GAS	-	**Yes**	
L2	SMR	LIQUID	-	No	3
L3	Electrolysis	GAS	-	**Yes**	
L4	Electrolysis	LIQUID	-	No	3

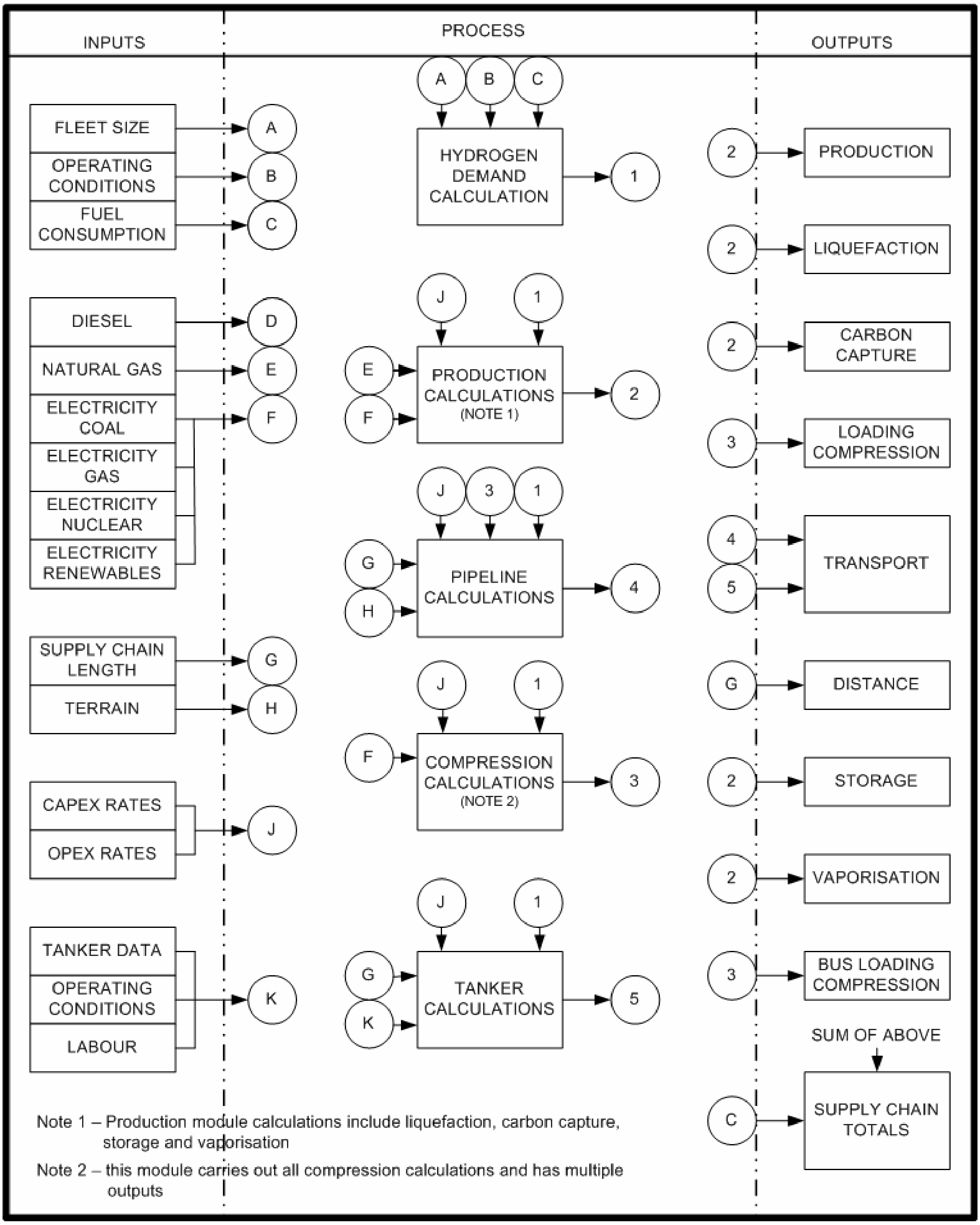
Table 1 – 22 Potential hydrogen pathways to be modelled

Exclusion Notes

1. Transportation of hydrogen by rail has been excluded at this stage for simplicity. Transport technology is similar to road transport for both gas and liquid state. The choice of road or rail is largely dependent on locality to a suitable rail network. Even then, it is difficult to foresee that it would be economic, except in the rare case when the fleet refueling depot was located adjacent to a rail terminus. Whilst this may be a solution for an integrated hydrogen network these six pathways are not considered further here.
2. This option has been excluded because it is technically difficult to transfer liquid hydrogen long distances by pipeline due to heat gain in the cryogenic fluid. It would vaporize unless excessive sub-cooling is carried out, which is energy intensive and hence expensive. This reason eliminates the three liquid pipeline pathways.
3. As the current bus fleet on board storage medium is gaseous hydrogen, producing liquid fuel at the point of use and the vaporizing it, is energy inefficient and unnecessary. Two pathways are discounted on this basis.

5. The model in detail

The model uses a spreadsheet to enable the user to input variables, and extract results for the chosen pathways for a given set of conditions. It can be considered as three separate stages, inputs, calculation modules and outputs as shown in Figure 1, below.



Note 1 – Production module calculations include liquefaction, carbon capture, storage and vaporisation

Note 2 – this module carries out all compression calculations and has multiple outputs

Figure 1 - Block diagram of the model

Hydrogen Demand calculation module

This module is used to calculate the hydrogen demand in kg / day, based on fleet size, operating hours / days, average speed, fuel consumption etc. The output is used in all the other calculation modules.

Production calculation module

The production calculation module determines the cost and emissions of hydrogen "at the factory gate" which includes any liquefaction or carbon capture where appropriate. It also calculates the on-site storage and vaporisation results.

Pipeline calculation module

There are several elements to the pipeline calculation module. Firstly, an optimum pipe diameter is selected from look up tables correcting for demand and allowable pressure drop (due to gas velocities). There can be significant variations in the estimated cost of pipelines. This is partly due to variations in terrain, but it can also be "country specific" depending on issues such as labour costs and planning constraints.

A pipeline cost estimating tool (Penspen, 2005) is used to determine costs per km based on two typical types of terrain, urban and rural. These are adjustable in the model. It should be noted that the accuracy of using such a tool on "generic" terrains is considered to be in the range of +/- 25%. It is also necessary to apply some boundary conditions to model, due to limitations of the estimating tool :-

- For distances >10km the equation approximates to the straight line formula

  Equation 1 $y = mx + C$

  where y = cost and x = distance. Short pipeline projects have administrative, design and management costs which are a disproportionately high percentage of the overall cost, which renders the results less accurate. Therefore supply chain lengths <10km should be modelled with great care.
- The estimating tool is based on natural gas pipelines and materials suitable for natural gas. Due to the physical properties of hydrogen, it was necessary to limit the pipeline maximum pressures to approximately 60 Barg. For higher pressures it is likely that more exotic (and expensive) materials may be required and the calculation tool then becomes less accurate.
- Although the estimating tool allows for cost calculation of varying line sizes, it was found that for all reasonable hydrogen demands, a maximum line size of 6" diameter was sufficient. For line sizes in the range of 2" to 6", costs of the pipe do not significantly affect the overall costs. Consequently, the costs shown in. can be considered as independent of pipe diameter within these boundary conditions.

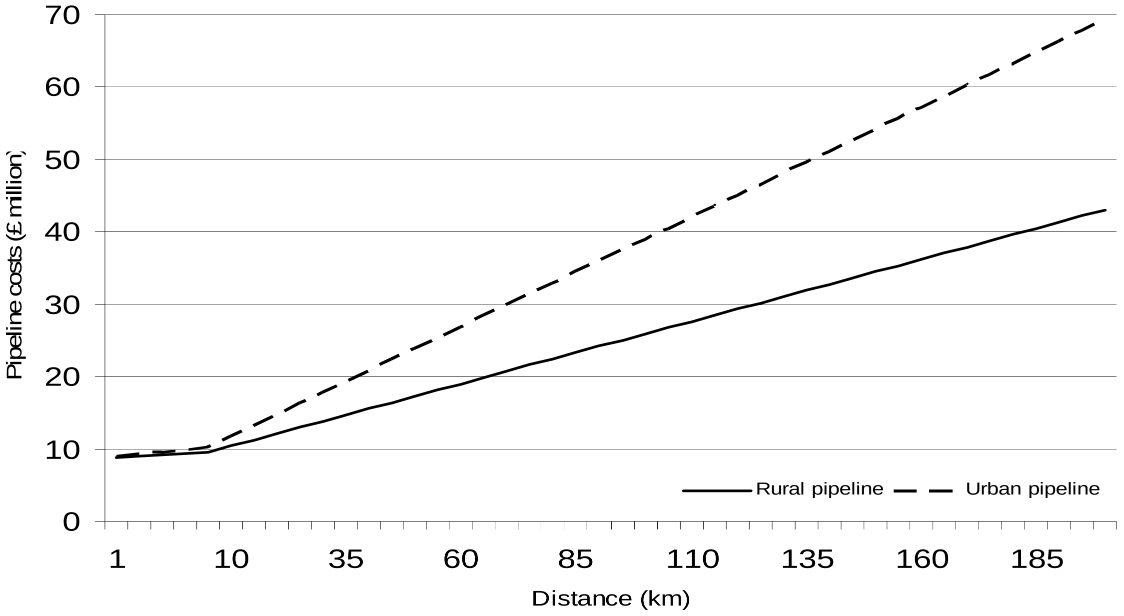


Figure 2 – Results of the pipeline calculation tool

Finally, these costs are then combined with compressor power requirements to deliver the hydrogen, based on demand and distance, which then produce cost and emissions results.

Compression calculation module

This module calculates all compression data required for the various components of the model. It includes loading on to tankers for transportation, fleet vehicles, pipelines as well as liquefaction compression requirements. It uses a basic compressor power equation:-

Equation 2 Power = Mass flow * R * T * (LN(Pin/Pout)) / e)

Where:-

R = Specific gas constant (kJ/kg K)

Pin = -suction pressure (bar absolute)

T = temperature (K)

Pout = discharge pressure (bar absolute)

e = efficiency (typical 0.67 for a reciprocating compressor)

Once the compressor power requirements have been calculated, it uses look up tables to determine optimum compressor sizes and energy input data, assuming that an electric motor driven compressor is used. This gives output costs and emissions which are used elsewhere as shown in the diagram.

Tanker calculation module

This module is intended to calculate the requirements of delivering the hydrogen from the central production facility to the point of end use, either in liquid or gaseous form. It takes into account the hydrogen supply chain length allowing the user to input parameters such as capital cost of equipment, labour rates, average tanker speeds, loading and unloading times etc. It uses this data to calculate the cost and emission to deliver hydrogen per kg.

6. Modelling results

The results in this section were produced using the hydrogen pathways model described earlier. The results show costs and emissions of the selected pathways from Table 1. There are a significant number of input variables in the model, which have been fixed for all results reported in this paper. For simplicity in reporting, only the key default values are listed below :-

Bus fleet size	100	**Gas costs**	£0.0357 / kW hr
Distance travelled	22,000 km / day	**Electricity costs**	£0.074 / kW hr
Hydrogen demand	5,381 kg H_2 / day	**Electricity mix**	Coal = 35%
Supply chain length	200km		Gas = 40%
Terrain	50% urban / 50% rural		Nuclear = 21%
Diesel cost	£1.10 per litre (forecourt price)		Renewable = 4%
Diesel fuel consumption	0.37 kg / km	**Hydrogen fuel consumption**	0.25 kg / km

The variables which are modified to produce the various results graphs are:-

- Diesel costs
- Changes in electricity generation basis between UK average mix to renewable.
- The use of carbon sequestration and delivery by FCV trucks for hydrogen / diesel, rather than conventional diesel powered trucks.

To ensure equal comparisons, where cost results are shown as £ / 100km in the following graphs, they are based on pre-tax diesel prices. This ensures that both diesel and hydrogen are treated equally in terms of taxation for comparison purposes. The diesel costs shown, in Figure 4 and quoted here are based on actual forecourt prices and hence inclusive of all taxes.

Current costs and emissions

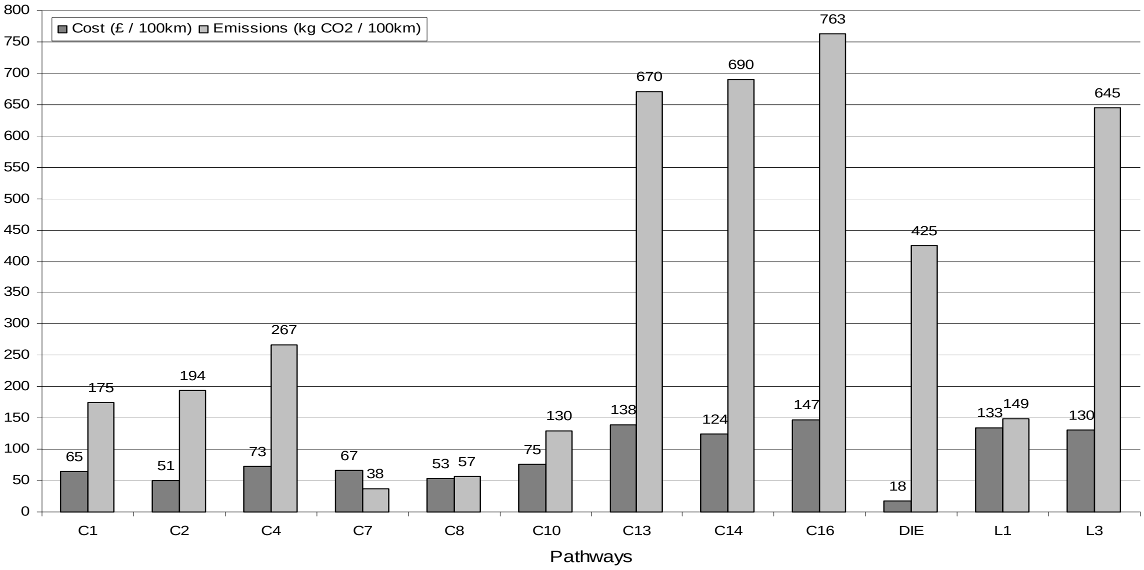


Figure 3 - Current cost and emissions of the selected pathways

Figure 3 shows costs and emissions for the selected pathways based on the default values, compared with a base case of diesel. Costs are calculated using pre-tax prices for both diesel and hydrogen. It is clear from the chart, that currently, not only is hydrogen more expensive than diesel for powering a bus fleet, but depending on the pathways chosen, there may be little or no environmental benefit either.

It should be noted that the diesel case allows for CO_2 equivalent values of other engine emissions such as NOX etc. and hence could be considered "worst case". Pathways C13, C14, C16 & L3 are based on electrolysis, which is heavily dependent on the method of electricity generation. This explains the relatively high emissions levels, as a UK average mix of electricity generation was used.

Cost and emissions targets

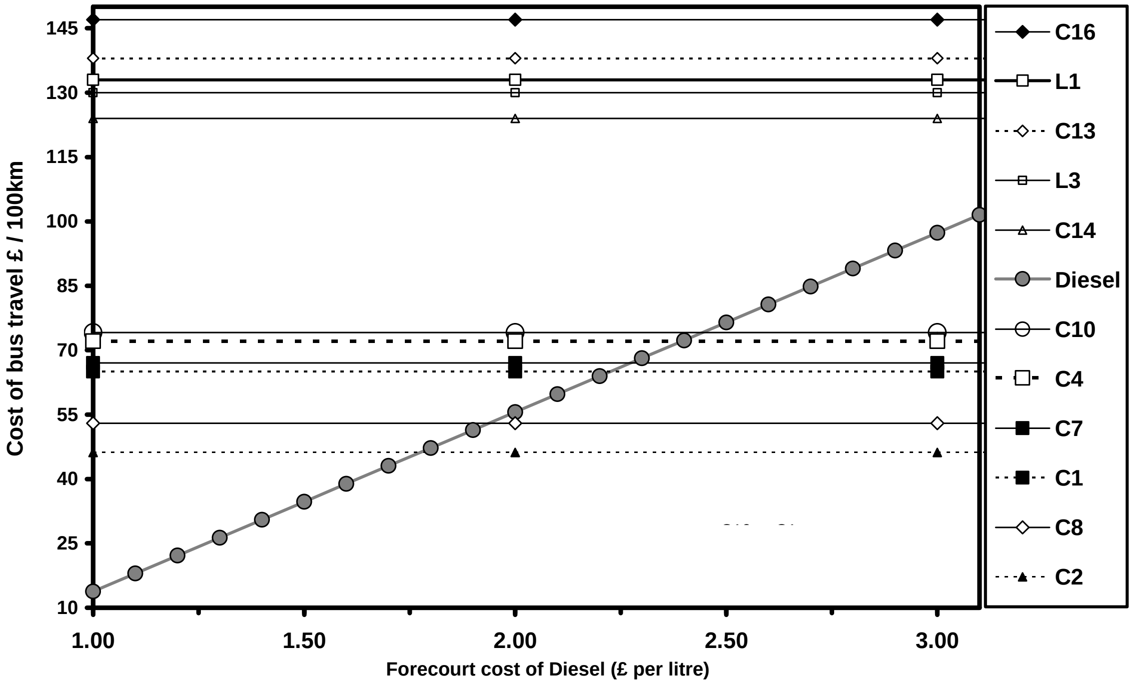


Figure 4 - Hydrogen pathways versus diesel costs

Figure 4 shows the “break even” points for diesel, compared with the various selected hydrogen pathways. Diesel costs shown here are “forecourt prices”, ie: they include all UK taxes. Cost of bus travel shown here are “pre-tax” as explained previously. Even the cheapest option would require diesel to reach £1.80 per litre to break even. At the time of writing, diesel forecourt prices are approximately £1.10 per litre. It would appear that diesel forecourt prices would need to rise 66% to reach the break even point of the cheapest hydrogen pathway. Five pathways are not cost competitive with diesel costs of more than £3.00 per litre.

Two of these are the localised production pathways. It is generally recognised that small scale production costs are less competitive compared with large scale centralised production due to savings in economies of scale. Currently they tend to be small scale bespoke designs, but if significant demand allowed mass production techniques, these localised pathways could become more competitive.

The other three are the centralised electrolysis pathways. Electrolysis is heavily dependent on electricity generation costs and partly explains the lack of apparent competitiveness. Potential to reduce electricity generation costs are likely to be limited, however there is a greater potential to reduce emissions using electrolysis pathways (refer to Figure 5 below).

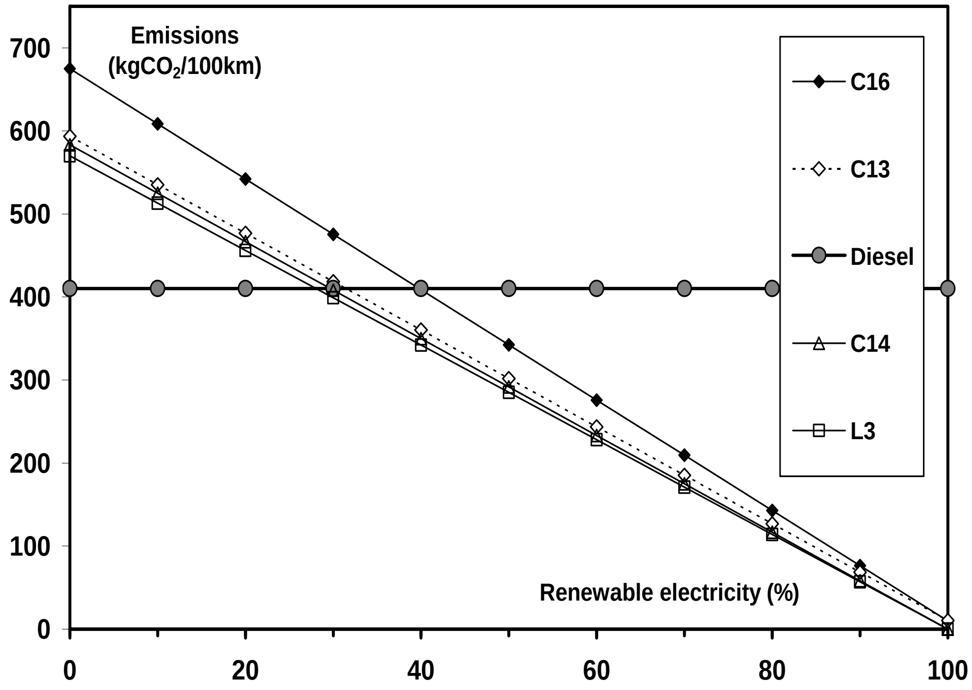


Figure 5 - Emissions reduction potential as a function of renewable electricity increases[1]

Whilst the electrolysis pathways in Figure 4 do not show any potential cost benefits, they do have potential for emissions reductions if renewable electricity is used as an emissions reduction technique. Figure 5 shows the electrolysis pathways against the base diesel case for an increasing percentage of electricity generated from renewable energy sources.

The diagram shows, that at a mix of between 30 to 40% of electricity generation using renewable sources, environmental benefits can start to be achieved from the electrolysis pathways. With current levels of UK average mix at approximately 4%, it would appear to require a significant increase in UK electricity generation to achieve the necessary levels for emissions reduction in the hydrogen pathways. Even the current government targets for increasing the percentage of electricity generated from renewable sources do not meet the break even point for years to come.

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[1] It has been assumed that the “non renewable” element of electricity generation is based on natural gas. If a typical UK mix was used for the “non renewable element” this would have the effect of reducing the percentage of renewable electricity required.

Two of the pathways do not quite reach “zero emissions”, even at 100% use of renewable electricity. This is explained by the fact that these pathways use road tankers as a delivery mode and consequently there is still some residual emission due to the use of diesel trucks to deliver the hydrogen.

However there is no specific requirement to use “grid” electricity for hydrogen production. It could just as easily be generated by wind turbine, making hydrogen when climate conditions allow and storing the “excess” energy in the form of hydrogen. Hydrogen is potentially more efficient than electricity as an energy carrier for both transportation and storage of energy.

Other selected pathways (eg: SMR and biomass) are not particularly dependent on electricity generation and have limited emissions reduction potential. They have been excluded from Figure 5 for clarity. The relevant CO_2 emissions levels of these pathways would largely remain at levels shown in Figure 3.

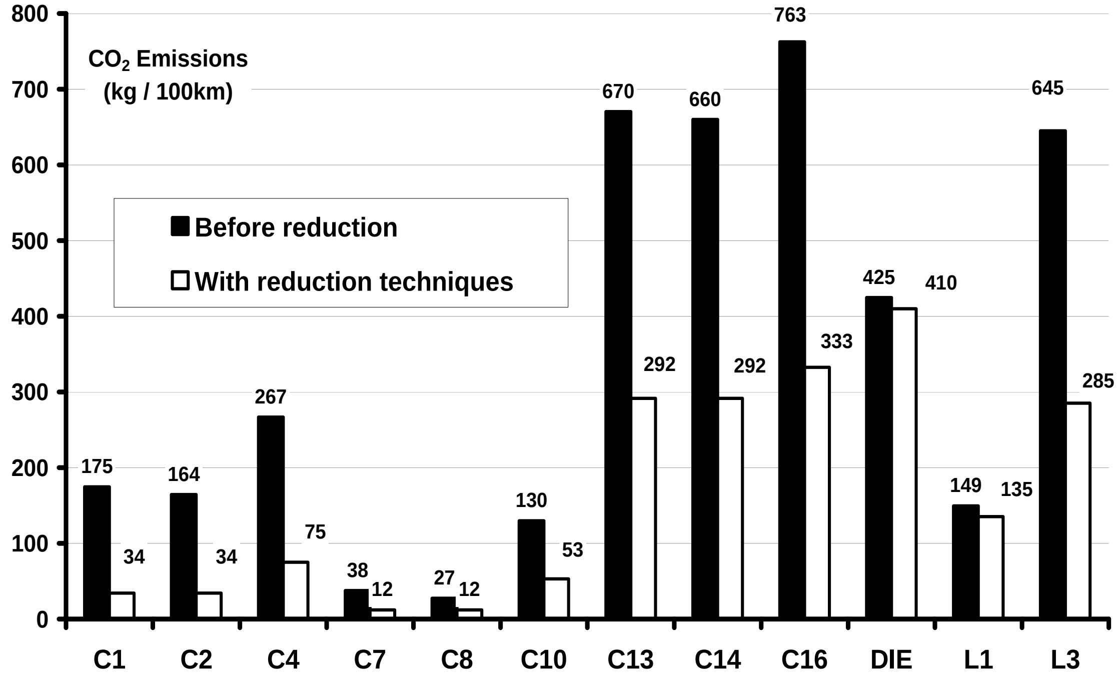

Figure 6 - Hydrogen pathway emissions (using emissions reductions techniques)

Figure 6 shows the potential reductions in emissions if 50% of electricity is generated from renewable sources, carbon sequestration is used (where appropriate) and delivery is by fuel cell truck. These emissions reduction techniques are combined together to show the total reduction in emissions. Each technique contributes to the reduction by varying amounts depending on the pathways, and can be summarised as follows:-

- Centralised SMR pathways (C1, C2 & C4) benefits are based largely due to the use of carbon sequestration.
- Centralised Biomass pathways (C7, C8 & C10) benefits are mixed. C7 & C8 are largely as a result of delivery by FCV truck. C10 is mainly due to the increased use of renewable electricity for the liquefaction stage of the process (which is energy intensive). There are some minor benefits due to delivery by FCV trucks.
- Centralised Electrolysis pathways (C13, C14 & C16) benefits are mainly due to the increased use of renewable electricity. With some minor benefit due to delivery by FCV trucks.
- The Diesel base case (DIE) shows limited benefit. This is entirely due to the use of FCV trucks for delivery of the diesel.
- Localised SMR pathway (L1) shows minimal benefit. It is not suitable for carbon sequestration, and has no delivery chain, so cannot benefit form the use of FCV trucks. It also has limited

benefit in the increased use of renewable electricity as it is mainly used for compression in the SMR process which is a heavy user of natural gas.

- Localised Electrolysis pathway (L3) benefits are almost entirely due to the use of increased renewable element in the electricity generation.

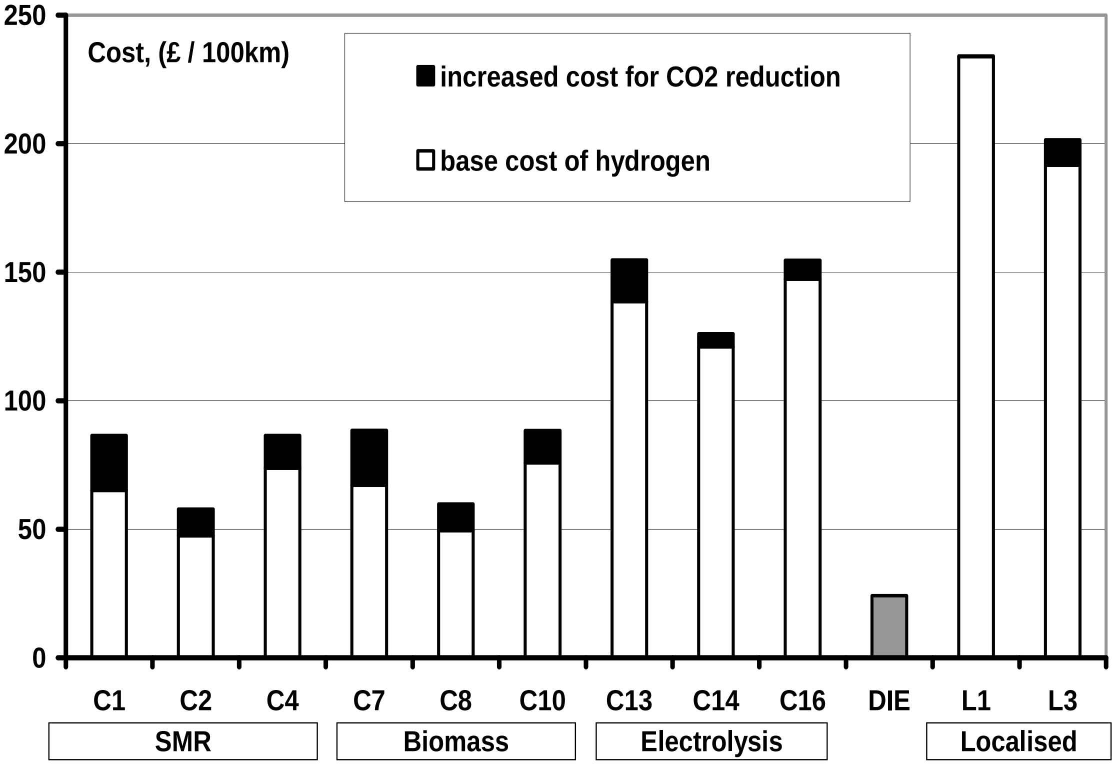

Figure 7 - Cost of emissions reduction techniques

Figure 7 shows the cost increases of the emissions reduction techniques shown in Figure 6. All figures quoted here are based on “pre-tax” fuel costs as defined earlier. The component elements of these cost increases are approximately £10 per 100km of bus travel for carbon sequestration, £11 per 100km of bus travel if FCV were trucks to deliver gaseous hydrogen and £2.50 per 100km of bus travel if FCV trucks are used to deliver liquid hydrogen. The balance of the cost increases can be attributed to the cost of renewable electricity.

The Diesel base case appears to show emissions reduction of 15kg of CO_2 per 100km (Figure 6) at no cost increase (Figure 7). This is explained by the fact that a typical tanker load of diesel contains about 20,000kg of fuel, compared with a gaseous hydrogen tanker which only contains about 360 kg of hydrogen. Thus the cost increase per kg of fuel is considerably less for diesel and hence does not show, due to the scale factor on the graph.

The localised pathway L1 also appears to show emissions reduction of 14kg of CO_2 per 100km (Figure 6) at no cost (Figure 7). This is entirely due to the use of renewable electricity, mainly for compression. There is a small cost increase of approximately £1.10 per 100km of bus travel but again this is lost in the scale factor of the graph.

When the cost of the emission reduction techniques in Figure 7 are compared with rising diesel costs in Figure 4, it would appear that these emissions reduction techniques add between 30p to 40p per litre to the forecourt price of diesel. However the localised production techniques (L1 & L3), still do not appear to be competitive even with diesel forecourt prices at £4.70 per litre.

7. Conclusion

Hydrogen is not competitive with diesel in terms of cost alone at present. Although oil price volatility which saw diesel at £1.30 per litre in 2008, may close the gap considerably. Perhaps the time when hydrogen becomes competitive is not too far away. Of course oil price increases may add to hydrogen production costs to some degree depending on feedstock (eg: natural gas for reforming), but hydrogen does have the potential to reduce this effect due to the wide variation in production technologies and feed stocks. Once the gap between the cost of diesel and hydrogen is closed, the additional cost of the emissions reductions techniques modelled in this paper, appear to show good cost benefits.

Of the five reasons for the transition given at the start of this paper, cost alone is not a viable reason. However, it may be that cost reductions, combined with another reason such as energy security or emissions reduction may be viable. Some countries may then be able to justify the additional costs of hydrogen. For example, the use of renewable sources such as geothermal energy (eg: Iceland), wind (eg: UK), sun (eg: Spain) would increase both, energy security and emissions reduction at the same time.

At present, the cost of renewable energy in the UK appears to be a barrier, but as technologies such as wind turbines become more mature, renewable electricity should become cheaper. With the relatively high taxation levels on hydrocarbon fuels (in the UK), there is potential for government to make hydrogen more competitive using tax incentive schemes.

The centralised pathways modelled in this paper are the cheapest option and initially at least, would have a role to play, although the lack of a current hydrogen supply infrastructure may limit a transition to a hydrogen economy, if the issue is not addressed in the near future.

More work needs to be done on cost reduction of local production technology, possibly using factory built production line units as suggested earlier. This would remove the not insignificant cost and technical issues associated with a hydrogen supply and distribution system required.

References

Anon (2006), CUTE detailed summary of achievements, European Union, available from http://www.fuel-cell-bus-club.com/index.php?module=pagesetter&func=viewpub&tid=1&pid=160&POSTNUKESID=56dbf282f2bdd3b708f5de49ad4d850b

Berridge C (2007), Pathway options for a hydrogen fuel infrastructure system, UTSG 2008 conference, Southampton Jan 3rd 2008, available from http://design.open.ac.uk/Berridge/index.htm

Berridge (2009), Hydrogen as a fuel source for vehicles; options for Options for a hydrogen fleet vehicle supply chain based on Economic & Environmental considerations, forthcoming, expected submission April 2009.

BP (2005), BP statistical review of world energy, British Petroleum, available from http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622

Dutton G, Bristow A, Page M, Kelly C, Watson J, Tetteh A, (2005), The hydrogen energy economy: it's long terms role in greenhouse gas reduction. The Tyndall centre, available from http://www.tyndall.ac.uk/publications/publications.shtml

Penspen (2005) Pipeline cost estimating tool, revision A, Excel spreadsheet. Penspen Ltd, 3 Water lane, Richmond, Surrey