Analysis of Changes over Time of the Costs of Hydrogen Infrastructure for Vehicle Refuelling in London

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\textbf{ABSTRACT:}

The cost of building a hydrogen ($H_2$) infrastructure is often said to be a major obstacle to the introduction of hydrogen vehicles to the current mix of road vehicles. But there are a number of ways of producing and distributing hydrogen, each with different associated costs. In addition, changes in key factors, such as technology development and level of demand for hydrogen, will affect costs. This paper looks at factors affecting the costs of hydrogen infrastructure over time for a small, but growing demand from fleet vehicles (e.g. buses or other vehicles) in London. The effects of changes in three key factors, namely $H_2$ demand, technology development, and energy prices (electricity and gas) over time, on the unit of cost of hydrogen are analysed. The analysis and results discussed here have been taken from a PhD project in progress at Imperial College. It is found that the level of demand (for $H_2$) and its rate of growth is the main factor affecting the unit cost of hydrogen over time, as well as the relative costs of the various production-delivery options.

\textbf{KEYWORDS:} hydrogen, infrastructure, costs, modelling, London

\section{1 Introduction}

Several publications \cite{1,2,3,4} have suggested that the cost of hydrogen infrastructure per unit of hydrogen output is relatively high for low levels of demand. As the demand for hydrogen increases and the scale of the infrastructure expands, this unit cost falls. It has been estimated that vehicle populations on the order of a thousand cars or several hundred buses are required for these costs to fall to a level that results in hydrogen prices that are competitive with petrol and diesel prices \cite{1}.

The cost of hydrogen production and delivery infrastructure at a scale suitable for a small number of vehicles is, therefore, seen as a barrier to the introduction and uptake of hydrogen vehicles. Hence it is important to investigate the costs of the possible production-delivery pathways for the first stages of development of a hydrogen infrastructure.

This paper analyses the costs of these pathways and examines the factors that influence them over an initial phase (2007-2025) of the development of a hypothetical infrastructure. It summarises part of the results from a PhD research project at Imperial College London. The research was funded by the UK Engineering & Physical Sciences Research Council as part of a bigger project on the development of a hydrogen infrastructure in London (grant reference GR/R50790/01). The analysis, which has involved the construction of a costing model, is based on the development of a hydrogen infrastructure for refuelling fleet vehicles in London. It could also, with modification, be applied to other large cities.

It is assumed that the first types of vehicles to use $H_2$ on any scale will be fleet vehicles such as buses, as their demand is more predictable, and they return to their depots for refuelling. Furthermore, their large size means that they can carry enough $H_2$ on-board for their round trip \cite{4}.

The PhD project analyses and compares the costs of a number of different combinations of production technologies and modes of transportation (hereafter ‘production-delivery pathways’). It has been found that only five of the pathways investigated could qualify as least-cost. The others are significantly more costly over a wide range of levels of demand. The results of these analyses, as well as others, are the subject of a
soon to be published paper in the Journal of Power Sources [5]. The five production-delivery pathways identified as potentially least-cost are therefore the only pathways examined in this paper.

The analysis discussed here considers several scenarios, to analyse the effects of varying rates of growth in hydrogen demand, varying energy prices, and different rates of technology development. In addition a number of key assumptions have been identified and the effect of changing their values on the results of the analyses are analysed.

2 Methodology

2.1 Outline of Modelling Methodology

For the PhD project described above, two models were built in Excel corresponding to two main types of hydrogen infrastructure, on-site (i.e. both the H₂ production and other refuelling processes are on the same site), and off-site infrastructure (where the H₂ production site is separate from the refuelling site). The models were built to represent various technologies and types of infrastructure. The choice of technologies included was based on technologies that are commercially available and in use (albeit mostly in pilot plants). The technologies include:

- three different types of H₂ production technologies: steam methane reforming (SMR), alkaline electrolysis, and PEM electrolysis
- two forms of H₂ storage: as compressed H₂ (hereafter CH₂) in cylinders and as liquid H₂ (hereafter LH₂) in tanks (or dewars)
- three methods of H₂ transportation: CH₂ by pipeline, CH₂ by road and LH₂ by road
- three methods of H₂ dispensing: LH₂ dispensing, CH₂ dispensing (booster method with buffer storage), and LH₂ vapourised to produce CH₂

In addition, the models include compressors and liquefiers wherever required. In the on-site version of the model, for each production technology, there are four different combinations of storage and dispensing options (as both storage and dispensing can be in the form of LH₂ or CH₂). Combined with the three possible production technology options (SMR and alkaline and PEM electrolysis), the model can explore 12 theoretically possible ‘production-delivery pathways’. Similarly, for each production technology, the off-site model can analyse 6 theoretically possible combinations of transportation and dispensing methods, making a total of 18 possible pathways. The term theoretically here emphasises that in practice some combinations may not be plausible or even possible, e.g. due to lack of availability of a technology at a certain scale.

The models were used to estimate the ‘total’ unit cost of H₂ by aggregating unit costs from the various pieces of equipment employed in the infrastructure modelled, i.e. production, storage, compression, liquefaction, transportation and dispensing. The equipment costs consist of capital costs, O&M costs, and feedstock costs (natural gas, electricity and water). Also included are costs of land, and ‘other’ costs, which include project costs related to both the production and refuelling sites, most of which are expressed as a percentage of the capital costs of the equipment on these sites. They include installation costs, shipping costs, engineering, planning and permitting, safety and contingency.

2.2 Methodology for Time-Related Analysis

Several factors related to the derivation of the unit cost of hydrogen can change with time. Some relate to technology and market development, including capital costs of equipment, efficiencies of equipment, and demand for hydrogen. Others relate to feedstock, i.e. the cost of natural gas, electricity and water. Further factors whose values could change over time include price of land, discount rate, footprint of equipment, and maintenance costs. Some factors are, however, more likely to change more than others.

Through conducting sensitivity analyses, it was found that change in the following factors could potentially have a significant effect on the unit cost of hydrogen in the time interval considered (2007- 2025):

- The level and rate of growth of demand for hydrogen
- Energy prices (electricity, gas and diesel)
- The rate of technology development
How these factors, and hence associated input parameters in the models, will change over time is uncertain, therefore scenarios with high and low levels of change (in each case) were considered.

The most important assumption about demand was, that over the time interval considered, only buses would be using hydrogen in London. The high level scenario of demand for hydrogen (from buses) was based on H₂ demand modelling work at Imperial College [6]. This modelling assumed that the maximum number of hydrogen buses (first hybrid-electric internal combustion engine buses and then hybrid-electric fuel cell buses) entering service is set at 5% of the fleet per year, approximately equal to the annual rate of bus replacement. This scenario includes policy parameters that provide sufficient subsidy for the hydrogen bus fleet to grow at that maximum rate, after an initial period of slower growth. For the low level or pessimistic scenario it is assumed that the support for hydrogen buses is lower and until 2015 only thirty percent of the buses replaced use hydrogen, and thereafter (when FC buses become cost-competitive) the percentage increases gradually.

Two different sets of energy prices were also assumed: ‘low’ and ‘high’ levels, based on estimated projections in a parallel study at Imperial College [8]. Price changes over time were considered for three types of fuel/energy sources: natural gas (NG), electricity, and diesel. The low and high cases are based on differing assumptions for oil prices. The low energy price projections are based on the EU Energy Outlook from 2001, where it is assumed that the price of oil starts at 27.5 $/bbl, and falls gradually to 20.1 $/bbl in 2010, and then rises to 25.85 $/bbl in 2025. In the high price scenario it is assumed that the price of oil is 53.05 $/bbl in 2007, and rises by 3% in real terms per year to 90.31 $/bbl in 2025. Wholesale natural gas prices are linked to oil prices using a 50% indexation, which is common in European natural gas contracts. A further linkage is included between the natural gas price and the cost of electricity generation, indexed according to projections of the proportion of natural gas-fired power generation in the UK.

Similarly, two levels (‘low’ and ‘high’) were assumed for rates of technology development. Capital costs of all equipment and their efficiencies are the parameters affected by technology development in the models. Several factors were considered when estimating the high and low reductions in capital costs and improvements in efficiencies:

- Near-term technology developments
- Increases in production volumes
- Increases in cost of raw materials
- Level of market development for product in question

Information on these factors was obtained mainly from industry experts. Where insufficient information was available, effects on similar types of equipment were considered.

The combinations of the high and low levels assumed for the three factors yields eight different scenarios, as shown in figure A.

*Figure A: Time-Related Scenarios*
These time-related scenarios are referred to by three letters, e.g. HHL (H=high, L=low). The first letter relates to the level of demand growth, the second energy prices, and the third the rate of technology development. The time-related scenarios were applied to a number of different pathways for the production and delivery of hydrogen. As mentioned, previous analysis (described in a soon to be published report [5]) has shown that five of these pathways are potentially least-cost, two on-site and three off-site:

1- On-site SMR + CH$_2$ storage and dispensing
2- On-site Electrolysis + CH$_2$ storage and dispensing
3- Off-site SMR + pipeline transportation of CH$_2$ + dispensing as CH$_2$
4- Off-site SMR + transportation as LH$_2$ by road + storage as LH$_2$ + dispensing as CH$_2$\(^1\)
5- Off-site SMR + transportation as CH$_2$ + storage as CH2 + dispensing as CH$_2$

For the second pathway, there are two electrolysis options, alkaline and PEM. Alkaline electrolysis becomes the least cost option for flow rates higher than around 0.3 t/d, but even below this flow rate the unit costs from both types of electrolysis are very close. Alkaline electrolysis is the technology used in the analyses discussed in this paper, as most flow rates are higher than 0.3 t/d.

In the case of the fifth pathway, transportation of CH$_2$ by road is only possible for refuelling sites with flow rates below 0.35t/d, because of practical considerations such as loading/unloading time. For higher flow rates it is assumed that pathway 4 (listed above) is followed.

Both the on-site and off-site models were adjusted to accommodate for annual changes to the various parameters mentioned above (energy prices, capital costs, process efficiencies, and levels of demand) for the time period between 2007 and 2025. The models were then run to generate values for the different time-related scenarios for all the least-cost pathways. The results of these runs are discussed in section 3.

A number of key assumptions had to be made with regard to the formation and structure of the hydrogen network. These included the commissioning period (time between commissioning the infrastructure and its full operation), the number (and so size) of the refuelling stations built at each commissioning interval, and the distance hydrogen has to be transported between production and refuelling sites. These assumptions and the sensitivity of the analyses results to them are discussed in section 3.4.

3 Analysis Results: The Effect of Key Factors Over Time on the Unit Cost of Hydrogen

The models were run to generate costs for all eight time-related scenarios for each of the least-cost pathways. In all cases a similar trend was observed.

It was found that unit hydrogen costs generally fell into two main categories, those of the high demand growth scenarios and those of the low demand growth scenarios (this distinction becomes less clear over time). Unsurprisingly, within these two groups, the ones with low energy prices cost less than those with high energy prices. In turn, within these four groups the scenarios where the technology development was assumed to be optimistic were less costly, albeit very slightly. This is shown in figure B, which shows the unit costs for the eight scenarios for one of the on-site least-cost pathways.

The grouping of the results into two categories based on demand growth suggests that the rate of demand growth has the greatest effect on unit cost of hydrogen over these parameter ranges. It is followed in importance by energy prices and then technology development. This deduction is not conclusive as it depends on the assumptions made about future energy prices, the rate of hydrogen infrastructure technology development and the rate of demand growth for hydrogen.

Although it is interesting to know to which of the factors (under analysis) the cost of hydrogen is most sensitive, this is not a crucial question when comparing the different production-delivery pathways. More important are:

- how does the relative unit cost of hydrogen change for the 5 different pathways under the 8 time-related scenarios?
- how does this affect the pattern of least-cost pathways?

\(^1\) For this pathway if the hydrogen was dispensed as LH$_2$, the cost would be almost the same, but as the scenarios here are considering fuelling buses that use CH$_2$, only the latter is considered.
These questions are investigated in the sub-sections that follow.

**Figure B**

*Time-Related Scenarios: On-site SMR Pathway*

3.1 *Effect of Technology Development on Least Cost Pathways*

To find out whether changing the rate of technology development (while keeping other assumptions constant) affects the costs of the five different production delivery pathways relative to each other, scenarios LLH and LLL were compared for all the production-delivery pathways. (This comparison could also have been made between HHL and HHH, or LHL and LHH, etc.).

**Figure C**

*LLL Scenario for 5 Production-Delivery Pathways*
Figures C and D show the unit hydrogen costs for these two time-related scenarios. These graphs look almost identical. It is clear that for both scenarios trends remain the same irrespective of the rate of technology development.

The effect of varying technology development on the unit cost of hydrogen was found to be minimal. The effect did increase over time, but even at the end of the period of investigation, in 2025, the difference between the unit cost of hydrogen under the LLL scenario and LLH scenario was only 2-6%, depending on the production-delivery pathway (the LLH scenario having lower unit costs than the LLL scenario of course).

**Figure D**

![Graph showing unit cost of hydrogen for various delivery pathways from 2007 to 2025.](image)

3.2 Effect of Energy Price Scenarios on Least Cost Pathways

The effect of the high and low energy price scenarios on the relative costs of the production delivery pathways are analysed here by comparing the HLH and the HHH scenarios. These scenarios are identical except for the assumptions about energy prices.

Figures E and F show that there is very little change in the relative costs of the production delivery pathways between scenarios HLH and HHH. These figures also show that the difference between the pathways with hydrogen production via SMR and that producing it via electrolysis is very slightly less under the HHH scenario.

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This analysis could also be done by comparing other scenarios such as LLL and LHL, or LLH and LHH, etc.
3.3 Effect of Rate of Demand Growth on Least Cost Pathways

Figures G and H show the unit costs of hydrogen for scenarios HLH and LLH. These scenarios are identical except with regard to level and rate of growth in demand for hydrogen. For both of these scenarios the off-

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3 This analysis could also have been done by comparing other scenarios such as LLL and HLL, or LHL and HHL, etc.
site production-delivery pathways cost more than the on-site at first but after the first four years the reverse becomes the case- except for the 5th pathway (off-site CH2/LH2 by road), which costs less than the on-site ones under the LLH scenario. It must be noted that under the HLH scenario (as well as all other high demand growth scenarios) CH2 transportation by road can not happen due to the higher flow rates which would require more frequent deliveries in one day.

Slight trend differences between unit hydrogen costs under HLH and LLH can be observed (see figures G and H). In the case of both scenarios unit costs under all pathways get closer and closer with time. Under the HLH scenario the convergence of costs happens faster than under the LLH scenario.

**Figure G**

![HLH Scenario Graph](image1)

**Figure H**

![LLH Scenario Graph](image2)
It can also be seen that under the high demand growth scenario (HLH) the unit costs of the off-site pathways are much closer to each other than under the LLH scenario. The on-site pathways have notably different unit costs under both scenarios after 2010 (on-site SMR is less costly than on-site alkaline electrolysis).

As mentioned in section 2.2, the level and rate of demand growth are affected by assumptions about the commissioning interval and number and size of refuelling stations. Section 3.4 investigates whether changing these assumptions will produce different trends compared to those seen in this section.

3.4 Effect of Changing Key Baseline Assumptions

As well as assumptions about the values for the three time-related parameters mentioned above, other factors that could have a significant effect on the unit cost of hydrogen include:

1- The commissioning interval
2- The number of refuelling stations
3- The distances from production to refuelling sites

The commissioning interval (CI) is the period of time in the future for which infrastructure is constructed. For example to meet a predicted demand of 12 t/d of hydrogen in 2010, if the commissioning interval is 4 years, that means a capacity of 12t/d, minus the existing capacity, has to be commissioned in 2006.

The commissioning interval affects both the capacities of the production and refuelling site equipment as well as the load factor. The longer the commissioning interval, the higher the capacities of both the production and refuelling site equipment will be relative to the level of demand. In addition, a longer commissioning interval will lower the average load factor, as the difference between the capacity and level of hydrogen demand will be higher. Although low load factors will increase the unit cost of hydrogen, larger capacities will lower this cost (due to economies of scale).

Similarly changing the number of refuelling stations (for the same level of total demand) will affect their capacity, and hence the unit cost of hydrogen from them.

Another set of key assumptions investigated here are the distances hydrogen is transported from production site to refuelling sites. It has been shown previously [5] that in the case of the off-site scenarios, the distance between the production site and the refuelling stations will affect the unit cost of hydrogen, to different extents for pipeline and road transportation.

This section discusses the effect of changing the values of the key assumptions (listed above) on the analysis results. Table A shows the baseline values and the range of values considered for the key parameters.

Table A: Key Assumptions for Time-Related Scenario Analyses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline value(s)</th>
<th>Range of values considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commissioning Interval for on-site infrastructure</td>
<td>1 year</td>
<td>1 to 2 years</td>
</tr>
<tr>
<td>Commissioning Interval for off-site infrastructure</td>
<td>4 years</td>
<td>2 to 8 years</td>
</tr>
<tr>
<td>Number of refuelling stations commissioned within the commissioning period</td>
<td>3 for on-site, 10 for off-site</td>
<td>2 to 6 for on-site, and 5 to 20 for off-site</td>
</tr>
<tr>
<td>Distance between production site and refuelling stations</td>
<td>2 x 10km, 2 x 20km, 2 x 25km, 2 x 30km, 2 x 40km</td>
<td>5 to 40km</td>
</tr>
</tbody>
</table>
In choosing a baseline value for the commissioning interval, considerations are different for on-site and off-site refuelling infrastructure. For both types of infrastructure, advance planning would be required. For on-site refuelling stations, long-term planning is less of a consideration as they will be meeting demand on the site itself and can be built as and when required. The off-site production sites, on the other hand, are much larger and will be supplying a number of refuelling sites, and so will need to consider requirements further into the future- hence the longer commissioning intervals.

The numbers of refuelling stations chosen for both off-site and on-site stations are based on level of demand, and the likely sizes of bus depots (this corresponds to refuelling capacities of around 8 to 104 buses per day, which is a reasonable assumption judging by current bus depot sizes [7]. In addition the sizes of stations for both on-site and off-site are kept as close as possible (limitations of the model allowing) so that a like with like comparison can be made.

The effects of changing the key assumptions on the relative costs of the five least cost pathways under the various scenarios were investigated. The following observations were made:

**Changing the length of the commissioning interval:**

- for all CI values, the off-site pathways become cheaper than those on-site between 2009 and 2013. When CI (for off-site pathways) is 2 years; however, the CH\textsubscript{2} / LH\textsubscript{2} off-site pathway is cheaper than the on-site pathways in the first two years of the analysis period as well. This was the case for both high and low demand growth scenarios.

- It can, therefore, be concluded that the lower the CI value for the CH\textsubscript{2} / LH\textsubscript{2} off-site pathway, the more likely it is that this will be the least-cost pathway at the beginning of the analysis period for all the time-related scenarios. Apart from the above observation, increasing and decreasing the CI did not affect the least cost pathway trends under any of the scenarios.

**Changing number and size of refuelling stations:**

- It was found that doubling the number of off-site refuelling stations (which is the same as halving the capacity of the stations), does very little to the relative costs of the various production-delivery pathways. In fact, although the unit costs of the off-site pipeline pathway increase significantly (as the number of pipelines installed is doubled), the trends in terms of least cost pathways are the same for the different scenarios.

- Increasing the size of off-site refuelling stations was, however, found to have a small effect on the relative unit costs of the various pathways. The off-site pathways, particularly the pipeline pathway, have lower unit costs compared to the base case scenarios, which means that they become the least-cost options 3 to 4 years earlier.

- The effect of decreasing refuelling station sizes in the case of on-site pathways has also been analysed. Decreasing the size of the on-site refuelling stations increases their unit cost, which results in the off-site refuelling stations becoming a relatively cheaper option sooner (as early as 2008). In addition, compared to the base case scenarios, the on-site pathways become significantly more costly than those off-site from 2009 onwards.

- It can be deduced from this analysis that, not surprisingly, larger on-site refuelling stations are more likely to be cost-competitive with off-site ones. It is, therefore, better to have, e.g. four 1 t/d stations than eight 0.5 t/d stations. However, the size of the on-site (or off-site) refuelling stations is limited by the requirement of hydrogen at the bus depots and availability of land for on-site production.

**Changing Delivery Distances:**

- Compared to the base case scenarios, the only pathway whose cost is significantly affected by increasing or decreasing the delivery distance is the pathway including pipeline delivery. The effect can be significant; e.g. halving the delivery distances makes the pipeline delivery pathway become the least cost option from 2011 onwards rather than 2021 under the HLH scenario.

- However, as shown by previous analyses [5], it is not just the delivery distance that makes one off-site pathway cheaper than another; flow rate is also an important deciding parameter. For a low
demand growth scenario, such as the LLH scenario, even with short distances, the pipeline delivery option does not become the least cost pathway till 2019.

4 Conclusions

Analysis of Base Case Scenarios

- For all the eight time-related scenarios (LLH, LLL, HLH, etc.) it was found that over time, the unit costs of hydrogen from the various production-delivery pathways fall and gradually converge, such that in 2015 (or 8 years in to the analysis period) all unit costs fall within an approximate £10/kg cost band.
- Although there are differences under the various time-related scenarios in the relative costs of the various production-delivery pathways, the following holds under all the time-related scenarios:
  - For the first 1-4 years of the analysis period the on-site pathways are lower in cost than those off-site, except for when level of demand is low and delivery can be made by CH₂ trailers to off-site refuelling stations (this is the case for the first four years of the analysis period).
  - Between 2009 and 2012, the least-cost pathways alternate between on-site SMR and off-site pathways where hydrogen is transported by road (depending on the time-related scenario).
  - From 2012 onwards the off-site pathways become least-cost. Early in this period the LH₂ by road is the least-cost pathway, while later on it is the pipeline delivery pathway. For the low demand scenarios, the pipeline pathway does not become least-cost over the period of analysis.
- Technology development rates and energy prices have very little effect on the relative costs of the various production-delivery pathways. The factor which has the biggest effect on unit costs was found to be the level and rate of demand growth.
- The only effect that could be observed with regard to changing energy prices was that on the relative costs of on-site SMR and on-site electrolysis in the first two years of the analysis period, when the costs of the two pathways are very close. Under the high energy price scenario it was found that on-site electrolysis was very slightly cheaper than the on-site SMR pathway.

Changing the baseline assumptions

- The factor which had the biggest effect on the relative costs of the various production-delivery pathways was found to be the level and rate of growth of demand. Changing the assumptions which are related to the level of demand, therefore, affects the relative costs of the pathways. These assumptions include the length of the commissioning interval, and the number and capacities of the refuelling stations to be built at every interval. The analysis in section 3.4 above suggests the following:
  - Lowering the commissioning interval for the off-site pathways reduces the unit cost of hydrogen from them, and could make delivery of CH₂ by road a possible option even at high levels of demand growth. Should the latter become the case, it is likely that the least cost pathway at the beginning of the analysis period will be the CH₂ / LH₂ by road off-site pathway for all scenarios.
  - Decreasing the size of the refuelling stations (both on-site and off-site) increases their unit costs, and vice versa. This however, only has a significant effect on the unit costs of on-site pathways, because of their inclusion of production with associated economies of scale. For example, if the on-site refuelling stations built are half the size of those in the base case scenario, the on-site pathways will only be the least-cost options for the first year of the analysis period. In other words, below a certain size, on-site refuelling stations become too costly. Therefore, if a larger number of very small refuelling stations need to be supplied, some off-site pathways would be cheaper than on-site ones.
- Changing the length of the delivery distance also has an effect on the unit costs of the off-site pathways. However, the only pathway which is significantly affected is that which includes pipeline delivery. The shorter the delivery distances, the sooner the pipeline delivery pathway becomes a viable option.
5 References


