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Analysis of the cost of hydrogen infrastructure for buses in London

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Abstract

The use of hydrogen (H_2) as transport fuel is often said to suffer from the 'chicken and egg' problem: vehicles that depend on H_2 cannot go on the roads due to the lack of an adequate infrastructure, and the almost non-existent fleet of H_2 vehicles on the roads makes it economically unsound to build a H_2 infrastructure.

Although both hydrogen vehicles (fuel cell and internal combustion engine) and the related infrastructure have been (and are being) developed and some are commercially available, cost is seen as a major barrier. With today's technologies, H_2 only becomes competitive with petrol and diesel when produced at large quantities, suitable for supplying e.g. thousands of H_2 buses. The question is, how might this point be reached, and are there least cost infrastructural pathways to reach it. This paper tries to address the latter question, using the early development of a H_2 infrastructure for buses in London as a case study.

The paper presents some of the analyses and results from a Ph.D. project (in progress) being undertaken at Imperial College London, funded by EPSRC (Grant GR/R50790/01). The results presented here illustrate that cost of hydrogen production and delivery vary mainly with levels of hydrogen demand and delivery distances, as well as other logistic criteria; least cost production–delivery pathways have been identified for various hydrogen demand scenarios and refuelling station set-ups. Another important conclusion is that the pattern of converting a group of refuelling stations to hydrogen (e.g. a group of refuelling stations for buses in London) has a significant effect on the unit cost of hydrogen.

Keywords: Hydrogen; Infrastructure; Costs; Modelling; London; Buses

1. Introduction

The use of hydrogen (hereafter H_2) as a transport fuel has been investigated for a few decades, but in the past 10 years the number of research and pilot projects (such as the Clean Urban Transport for Europe (CUTE) project) has escalated. This increased interest and investment has been stimulated by a perceived need to replace fossil fuels for environmental and/or security of supply reasons. The recent hikes in the price of oil have also added impetus to the movement towards H_2, and other alternative fuels.

It has been shown elsewhere that, given the current state of technology, H_2 could only be competitive with petrol and diesel when produced in sufficiently large quantities (which lead to lower unit costs). Hence, there would need to be a sufficiently large fleet of vehicles to create the necessary levels of demand. [1].

An important step towards switching to H_2 (as fuel for road transportation) is to make a transition to the point where H_2 is competitive with more conventional fuels. As well as technological developments, government policy (e.g. tax incentives) can speed up the large-scale penetration of H_2. In addition, it is important that least cost pathways for the production and delivery of H_2 are identified in order to lessen any financial burdens for this transitional phase.

The Ph.D. project, from which the results presented and discussed here are drawn, focuses on the production and delivery pathways for the initial stages of development of a H_2 infrastructure. The study focuses on London, so all local parameters, such as feedstock and land prices considered relate to this city. It is assumed that the first types of vehicles to use H_2 on any scale

Abbreviations: Buff., buffer; Boost., booster; CH_2, compressed H_2; Comp., compressor; Disp., dispenser; Elec., electrolyser; LH_2, liquid H_2; Pipe., pipeline transportation; Transp., transportation

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will be fleet vehicles such as buses, as their demand is more predictable, and they can go back to their depots for refuelling. Furthermore, their large size means that they can carry enough H_2 on-board for their round trip [2].

The key aim of this paper is to compare and discuss the relative costs of H_2 associated with various production–delivery pathways.[1] The analyses presented explore the unit costs of H_2 produced and delivered at a particular point in time. It has been assumed that costs remain constant over any period considered and are not affected by technological development or feedstock price changes.[2] The paper is structured in the following way: Section 2 explains the methodology; Section 3 includes the analysis and discussion; Section 4 the conclusions.

A spreadsheet modelling methodology has been used for the analysis presented here. This type of methodology has been used by other studies looking at hydrogen infrastructure costs [3,4], but none have been specifically focused on London.

2. Methodology

2.1. Modelling the costs of H_2 infrastructure: structure and scope

An Excel-based model was first developed for an onsite H_2 infrastructure (i.e. both the H_2 production and other refuelling processes are on the same site), and then expanded for an off-site infrastructure (where the H_2 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 both commercially available and widely used (albeit mostly in pilot plants). The technologies include:

- *Three different types of H_2 production technologies:* Steam methane reforming (SMR), alkaline electrolysis and PEM electrolysis.
- *Two forms of H_2 storage:* As compressed H_2 (hereafter CH_2) in cylinders and as liquid H_2 (hereafter LH_2) in tanks (or dewars).
- *Three methods of H_2 transportation:* CH_2 by pipeline, CH_2 by road and LH_2 by road.
- *Three methods of H_2 dispensing:* LH_2 dispensing, CH_2 dispensing (booster method with buffer storage), and LH_2 vaporised to produce CH_2.

In addition, the models include compressors and liquefiers wherever required. Although currently there are two main types of H_2 compressors on the market, reciprocating and diaphragm, the reciprocating one was modelled, both because it currently has lower capital costs, and because fuller commercial information was obtainable. The commercial and technical data required for modelling the equipment were obtained, as far as possible, from industry sources.

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 LH_2 or CH_2). Combined with the three possible production technology options (SMR, alkaline and PEM electrolysis), this means that the model can explore 12 theoretically possible *production–delivery pathways*. Similarly, for each production technology, the off-site model can analyse six theoretically possible combinations of transportation and dispensing methods. This makes a total of 18 possible pathways for the off-site model. The term *theoretically* here emphasises the fact that in practice some combinations may not be possible or plausible, e.g. due to lack of availability of a technology above a certain flow rate.

2.2. Important calculations and assumptions within models

The models were used to calculate the 'total' unit cost of H_2 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 costs of this equipment consist of capital costs, O&M costs and feedstock costs (natural gas, electricity and water). There are also 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.

2.2.1. Cost calculations

All capital costs are annualised by being discounted over the lifetime of each piece of equipment; this is done by multiplying the capital cost by the capital recovery factor (CRF), represented by the expression:

$$\mathrm{CRF} = \frac{d(1+d)^n}{(1+d)^n - 1} \tag{1}$$

where d is the discount rate, and n is the lifetime of the equipment.

In the case of most pieces of equipment included in the models, the unit capital cost is related to the size, or output of that equipment, i.e. there are some *economies of scale*. For example for liquefiers, this relationship is represented as:

$$\mathrm{CC} = 5.263 \times (\text{capacity})^{-0.4114} \tag{2}$$

where CC is the unit capital cost in £m per tonne H_2 per day, and *capacity* is in tonnes H_2 per day (hereafter $\mathrm{t\,d^{-1}}$) [5].

As well as liquefiers, this type of relationship also exists in the cases of SMRs, electrolysers and liquid H_2 storage tanks. For other pieces of equipment, including pumps, vaporisers, dispensers, LH_2 tankers and CH_2 tube trailers, a capital cost for each unit was used. CH_2 storage cylinders do not lie in any of these categories. Their capital costs vary with capacity and

[1] Although effort has been made to derive realistic values for unit cost of H_2 as far as possible: (a) a number of assumptions have had to be made to arrive at these values (see Appendix A); (b) the aim has not been to try to derive *exact* values for the unit cost of H_2.

[2] All capital costs have been inflation adjusted to 2004, and feedstock costs are based on values at the first quarter of 2005.

with pressure of H_2. However, because these relationships are disordered and cannot be expressed as an equation, costs for a number of different storage cylinders, with varying pressures and capacities were obtained (both from industry and literature), and in each case the models pick the least cost from a list of these cylinders. As the choice is cost-based, the cylinder pressures may be higher than required, e.g. for a pressure requirement of 29 MPa the chosen cylinder could have a pressure of 35 MPa.

Pipeline installation cost is also a special case, since it depends on a number of different parameters. An equation that relates the unit cost of pipelines to their diameter and length has been derived from the costs of a large number of natural gas pipelines, and then adjusted for H_2 pipelines [6]:

$$CC = \left(3.70 \times D^2\right) + (19.00 \times D) + \left(\frac{161.7}{L}\right) \tag{3}$$

where CC is unit capital cost (US\$ m^{-1}), D the pipeline diameter (cm) and L is the length of the pipeline (m). (The currency conversion assumed is: £1 = US\$ 1.6.) A further cost per unit length of pipeline has also been added—this includes costs specific to London, as well as general ones for large cities (industry source and [7]).

Annual O&M costs are expressed as a percentage of capital costs. Feedstock costs are calculated from the unit consumption and unit cost of the feedstock (e.g. price of electricity). For some pieces of equipment, it has been found that the feedstock consumption is also related to their output. In these cases, the relevant equation is used in the model. Cost of land is estimated by multiplying the estimated footprint of a piece of equipment by the average unit cost of land. Footprints are calculated from an estimated area per unit output, for each piece of equipment (e.g. $m^2\ kg^{-1}$ of H_2 stored). In some cases the footprint of a piece of equipment is related to its size. In these cases an equation is used in the models. (The estimated price of land (in London) is, however, twice as high for a refuelling site as for a production site (Table A.2, Appendix A). This is because a refuelling site is likely to be located in more central areas of London than a H_2 production site.)

2.2.2. Other important assumptions

The costs of compression and storage depend on the assumptions about the number of storage days, and levels of pressure for storage, transportation and dispensing. The assumptions regarding number of storage days and pressures for the various processes are given in Appendix A. These values, as well as other technical data, are based on private communications with experts within industrial gas companies, as well as H_2 refuelling station operators and recent literatures [8–10], and [11]. In some cases, the availability of cost data for CH_2 storage cylinders (see Section 2.2.1) affected the assumed storage pressure.

The method of storage on the refuelling site depends to a great extent on the mode of hydrogen transportation. In the case of road transportation of CH_2 by tube trailer, the H_2 is stored in the tube trailer cylinders themselves on the refuelling site (this is sometimes called the 'drop and swap' method).

As stated, there are certain limitations for certain production–delivery pathways due to technical or logistic factors. In the case of both CH_2 and LH_2 road transportation, there is a limit to the number of deliveries per day, depending on the loading/unloading times and time taken for delivery journeys.

2.3. Outline and aims of analysis

The first part of the analysis in this paper focuses on the main factors, which affect the overall unit cost of H_2, for a particular production–delivery pathway. These are:

- costs of various production technologies;
- costs of storing and dispensing H_2 in different states (liquid or compressed);
- costs of various methods of H_2 transportation in combination with varying states of hydrogen dispensed;
- effect of the set-up of refueling points relative to the production site, as well as pipeline structure, on the cost of hydrogen.

The aim is to compare the different options and find those with the least cost at varying ranges of flow rates, delivery distances and other key factors. The second part of the analysis asks what are the least cost production–delivery pathways for both on-site and off-site infrastructures. The third and final part of the analysis here compares on-site and off-site H_2 production–delivery pathways (in terms of costs), by using possible infrastructural scenarios for buses in London. The aim of this final analysis is to deduce which are the least cost delivery pathways, and what are the key factors, which affect them.

In the case of each analysis, baseline values are assumed for all parameters, except those that are being investigated. Examples of these baseline values are given in Appendix A.

3. Analysis and discussion

3.1. Part I: effects of varying key cost parameters

3.1.1. Comparing costs of H_2 production technologies

As noted, three different production technologies are compared here: steam methane reforming (SMR), alkaline electrolysis and proton exchange membrane (PEM) electrolysis. The cost-related differences between them relate to their unit capital costs, feedstock consumption (electricity, gas and water), O&M costs, installation and shipment costs and footprint. The on-site model is used to compare these technologies (the off-site model has also been used and produces similar trends). The results for three different flow rates are shown in Table 1. All input parameters are kept constant (at baseline values) apart from type of production technology and flow rates. In each case the delivery pathway is also the same: because H_2 is stored and dispensed on-site in compressed form, a buffer storage and a booster compressor are included.[3]

[3] Cost of compression following production is slightly lower for PEM electrolysis, as the assumed pressure of the H_2 following production is higher (1.4 MPa as opposed to 1 MPa).

Table 1
Unit cost of H_2 for different production technologies

	Flow rate ($t\,d^{-1}$)								
	0.1			0.4			0.8		
	SMR[a]	Alkaline elec.[a]	PEM elec.[a]	SMR[a]	Alkaline elec.[a]	PEM elec.[a]	SMR[a]	Alkaline elec.[a]	PEM elec.[a]
Production	3.53	4.51	4.12	1.84	3.22	3.64	1.42	2.88	3.63
compression	0.44	0.44	0.42	0.24	0.24	0.23	0.18	0.18	0.17
Storage	0.21	0.21	0.21	0.18	0.18	0.18	0.18	0.18	0.18
Booster compressor	0.17	0.17	0.17	0.09	0.09	0.09	0.06	0.06	0.06
Buffer storage	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06
Dispensing	1.97	1.97	1.97	0.49	0.49	0.49	0.26	0.26	0.26
Land	1.26	0.93	0.90	0.46	0.33	0.32	0.3	0.22	0.21
Other	2.06	1.62	1.12	0.86	0.67	0.58	0.59	0.46	0.51
Total	9.71	9.92	8.98	4.22	5.27	5.59	3.04	4.30	5.09

[a] Unit cost (£ kg^{-1} of H_2).

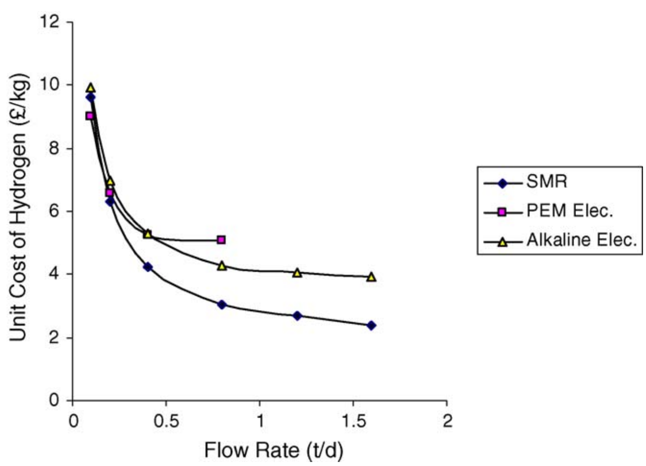

Fig. 1. Unit cost of H_2 for different production technologies.

As the unit cost of production is highly dependant on the capacity of equipment, which is related to flow rate, this relationship was analysed for all three technologies. Table 1 shows how costs change for three different flow rates. It can also be seen that three sets of costs (production costs, cost of land and *other* costs) change notably from one type of production technology to another. Unsurprisingly, the production and *other* costs also change, because they depend on the capital costs of the production equipment. Land costs depend on the footprint of the different pieces of equipment, which also changes with types of production technology. Although unit production cost for SMR is lower than for both alkaline and PEM electrolysis, the higher cost of land and *other* costs for SMR brings its overall unit cost closer to the others.

From Fig. 1, it can be seen that for flow rates below 0.2 $t\,d^{-1}$ the total unit cost of H_2 does not change very much between production technologies. Above this flow rate SMR is clearly the least costly. Between 0.2 and 0.4 $t\,d^{-1}$ alkaline and PEM electrolysis are very close, but above 0.4 $t\,d^{-1}$, alkaline electrolysis becomes the cheaper technology of the two. The trends shown in Fig. 1 depend to a great extent on the values assumed for parameters which affect production costs; the principal influences are capital costs, electricity and gas prices, discount rate and load factor. Other factors, such as energy efficiency, water consumption and O&M costs also affect unit production costs, but to a much lesser extent.

Below the threshold flow rates mentioned above, unit costs of two or more of the production technologies are very close. For such flow rates, changing the key parameters mentioned above (energy costs, discount rate and load factor) is likely to change the costs of the technologies relative to each other. This means that only approximate threshold values can be given for flow rates, i.e. for example, it can be said that above *around* 0.4 $t\,d^{-1}$,[4] alkaline electrolysis becomes less costly than PEM electrolysis.

As stated the costs of natural gas and electricity are likely to affect the relative costs of the different production technologies. This is because the electrolysis process uses electricity while SMR uses mainly natural gas (a small amount of electricity is also used in the SMR process). Furthermore, energy costs make up a significant percentage of overall production costs: for a flow rate of 0.15 $t\,d^{-1}$, for example, cost of natural gas makes up about 20% of total cost of hydrogen production from SMR, and cost of electricity makes up as much as 50–60% of the production cost of hydrogen from electrolysis. The effects of electricity and gas prices on the relative costs of hydrogen production technologies need further investigation (work in progress).

3.1.2. Analysis of costs of on-site storage-dispensing options

At a refuelling station with on-site H_2 production, in addition to a choice between production technologies, there are also choices about storage and dispensing. H_2 must be stored on site, either in liquid or compressed form, before dispensing. Furthermore, the H_2 can be dispensed as a gas or liquid, yielding four alternatives:

[4] In future work, sensitivity analysis will be undertaken to give a tighter approximation of threshold values and the extent to which they could fluctuate in different conditions.

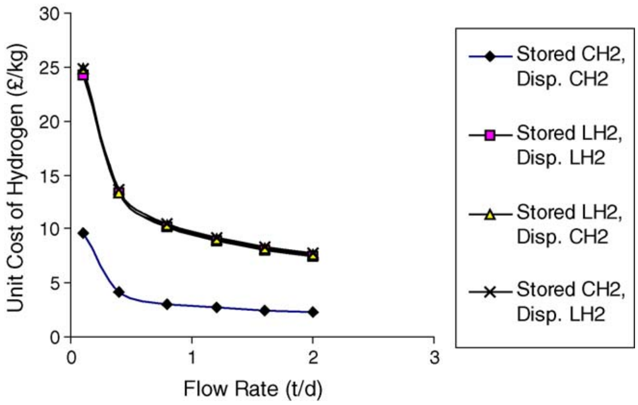

Fig. 2. Unit cost of H_2 for various on-site storage–delivery options.

(1) storage as CH_2 followed by dispensing as CH_2;
(2) storage as LH_2 followed by dispensing as LH_2;
(3) storage as LH_2 followed by dispensing as CH_2;
(4) storage as CH_2 followed by dispensing as LH_2.

In order to compare costs, the model was run for all four options, at different flow rates (Fig. 2). (Although option 4 is not considered in practice, it is included here for completeness.) The results show that apart from option 1, all other storage–delivery options are very close to each other, and all are more costly than option 1. (Option 2 costs slightly less than option 3 which costs slightly less than option 4.)

Options 2–4 are more costly than option 1 because they all include a liquefaction process, either before or after storage. Liquefaction, particularly at the flow rates considered, is a very costly process, making up as much as 50% of total unit cost of hydrogen.

As with production technologies, certain (baseline) assumptions about key parameters underlie the trends in Fig. 2. They include assumptions about flow rate of dispensers, and the option of having a buffer storage (for some dispensing schedules it may not be necessary). It is unlikely that changing these parameters within reasonable limits would make option 1 more expensive than any of the others, but the relative costs of options 2–4 are likely to change.

Apart from cost, there are other factors that could influence the type of storage and/or method of dispensing. For example, if space is very limited, liquid H_2 storage could be preferable to compressed H_2 storage (as the latter has a higher footprint). Furthermore, if H_2 is required in both compressed gaseous and liquid forms then a combination of options 2 and 3 would be preferred.

3.1.3. Analysis of off-site H_2 delivery options

In theory 6 different H_2 delivery pathways exist between the point of production and point of delivery in the off-site refuelling mode:

(1) CH_2 transported by pipeline and dispensed as CH_2 at refuelling site;
(2) CH_2 transported by pipeline and dispensed as LH_2 at refuelling site;
(3) CH_2 transported by road and dispensed as CH_2 at refuelling site;
(4) CH_2 transported by road and dispensed as LH_2 at refuelling site;
(5) LH_2 transported by road and dispensed as LH_2 at refuelling site;
(6) LH_2 transported by road and dispensed as CH_2 at refuelling site.

With regard to finding the least costly options, pathways 2 and 4 can be discounted immediately, as they both include a liquefaction step at the refuelling site, which would be very costly, and would dwarf any other costs at the refuelling sites (as discussed in Section 3.1.2). Therefore, here, only the costs of pathways 1, 3, 5 and 6 need to be analysed and compared in order to find the least costly pathway(s). Pathways 5 and 6 also include a liquefaction step, but since this is at the production site, a much larger and hence less costly liquefier would be required.

Costs of H_2 transportation are likely to change with the delivery distance, and the flow rate of H_2 transported. The effect of these factors on the relative costs of the different delivery pathways are analysed in the sub-sections that follow. The effects of distribution of refuelling sites and pipeline structures are also discussed here (Fig. 3).

3.1.3.1. Effect of flow rates on off-site H_2 delivery pathways. To analyse the effect of changing flow rates on the relative costs of the different H_2 delivery methods (1, 3, 5 and 6, as mentioned above), a hypothetical scenario, 'scenario a' has been considered and is illustrated in Fig. 3. It is assumed that four refuelling stations of the same size are being supplied by one production site, which is at the same distance from them all. The flow rates of these four stations are varied between 0.4 and 4 t d^{-1}, while the delivery distances (between production and refuelling sites) are kept constant at 30 km. The production method is assumed to be SMR in each case, and baseline values are used for all

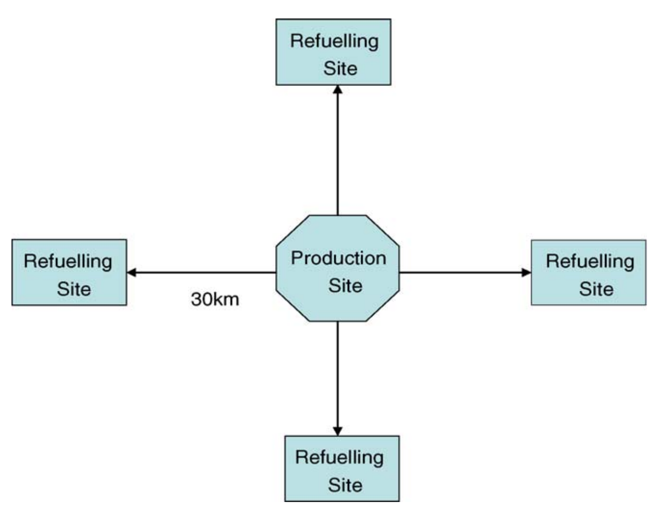

Fig. 3. Production and refuelling site set-up for scenario a.

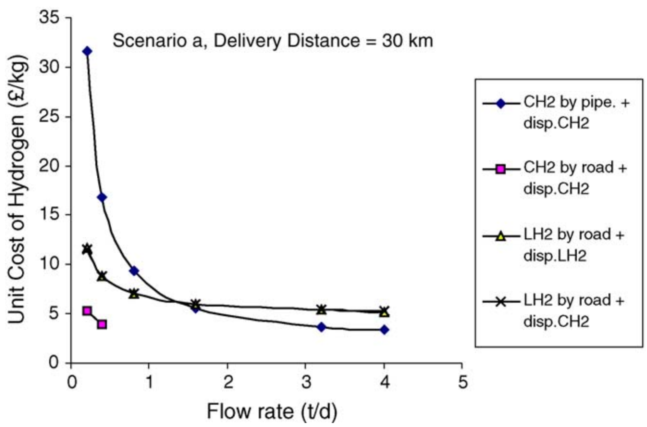

Fig. 4. Unit cost of H_2 for various delivery pathways for off-site refuelling stations: changing flow rates.

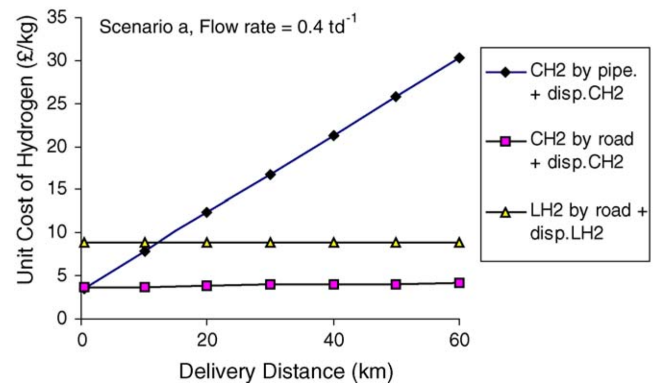

Fig. 5. Unit cost of H_2 for varying delivery pathways for off-site refuelling stations: changing delivery distances.

other input parameters. As the refuelling stations are all the same size, the unit cost of H_2 is the same for all of them for a particular flow rate. These costs are derived using the off-site model.

The results (Fig. 4) indicate that for all delivery pathways, the unit cost of H_2 decreases with increasing flow rate. Compressed H_2 transported by pipeline and dispensed as CH_2, is the least cost pathway, but only for flow rates less than $0.4\,t\,d^{-1}$; it is not possible to deliver H_2 by this method for higher flow rates due to the low capacity of the tube trailers and time taken for loading/unloading.

For the delivery distance considered, LH_2 delivered by road becomes the least cost option for flow rates between around 0.4 and $1.2\,t\,d^{-1}$. This is the case for H_2 dispensed as CH_2 and as LH_2—the costs are almost identical. This is because although a pump and vapourizer are required for dispensing the delivered LH_2 in compressed form, a CH_2 dispenser is then used, which is almost half the cost of an LH_2 dispenser.

In the scenario analysed, pipeline delivery of CH_2 only becomes less costly than road delivery of LH_2 at flow rates higher than $1.2\,t\,d^{-1}$. (And even for hypothetically very high station flow rates of $25\,t\,d^{-1}$, pipeline delivery remains the least cost pathway.)

Fig. 4 also shows that the unit cost of the pipeline delivery pathway falls more rapidly with increasing flow rates. The choice of least cost pathway is clearly greatly affected by refuelling site flow rates, while pipeline transportation is more sensitive to flow rates than road transportation of H_2.

3.1.3.2. Effect of delivery distance on off-site H_2 delivery pathways. To examine the effect of changing the delivery distances (the distance between production and refuelling sties), the off-site model was run for the *scenario a* refuelling structure (see Fig. 3), for various delivery distances. The flow rate was kept constant this time (at $0.4\,t\,d^{-1}$), and the delivery distance was changed from 0.5 to 60 km. The results of this analysis are shown in Fig. 5. They show that, as with flow rates, the cost of H_2 delivered by pipeline is far more sensitive to delivery distance.

This is not a surprising outcome, as the transportation cost is the only cost that changes with delivery distance. The cost of pipeline transportation, as mentioned above, is almost proportional to distance, while that of road transportation changes very little. In the case of road transportation, as transportation distance increases, it is mainly the cost of fuel that increases, while in the case of pipelines, the extra cost of installation (which is proportional to the length of the pipeline—see equation (3)) is added.

Fig. 5 shows that CH_2 transported by road and delivered as CH_2, is the least cost pathway for a flow rate of $0.4\,t\,d^{-1}$; this is the case for all delivery distances, except very short ones (below around 500 m). At these short distances and low flow rates, CH_2 delivered by pipeline and dispensed as CH_2 is the cheapest option. For flow rates above $0.4\,t\,d^{-1}$, CH_2 road delivery becomes impractical due to the low capacity of the tube trailers and delivery time. For these higher flow rates, CH_2 transported by pipeline and delivered as CH_2 is the least cost option for longer distances, followed by LH_2 transported by road and delivered as LH_2 (or CH_2; see Section 3.1.3.1). The threshold distance at which CH_2 by pipeline becomes more expensive than LH_2 by road depends on flow rate. As can be seen in Fig. 5, for a flow rate of $0.4\,t\,d^{-1}$ this delivery distance is around 12 km.

It must be pointed out that, as for threshold values of flow rates, those for delivery distance are only approximate as they depend on the baseline assumptions made for parameters such as installation cost of pipelines, and costs of transportation vehicles.

This analysis shows that the least cost pathway depends on delivery distance as well as flow rate, and that pipeline delivery is very sensitive to distance, while road transportation of H_2 is not.

3.1.3.3. Effects of changing refuelling station distribution and pipeline structure. There are other logistical factors as well as flow rates and delivery distances that could be different for an off-site refuelling infrastructure. These are also likely to affect the relative costs of the various delivery options. One such factor is the distribution of refuelling stations. For example, instead of four stations, as in *scenario a*, there could be eight stations with half the output – as in *scenario b*, shown in Fig. 6. The overall

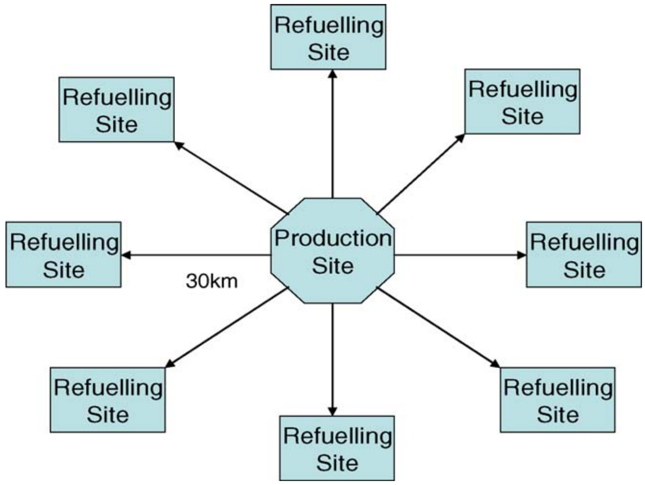

Fig. 6. Production and refuelling site set-up for scenario b.

level of H_2 distributed would be the same, but more refuelling points would be covered.

Fig. 7 shows unit costs of H_2 at refuelling points for both *scenario a* and *scenario b*: for all delivery pathways *scenario a* is less costly than *scenario b*. The cost difference between the two scenarios is greater for the pipeline transportation pathway – because in this latter pathway the cost of transportation makes up a much larger percentage of overall costs, and this falls significantly with increasing flow rate (see Fig. 8).

Fig. 8 also shows that pipeline transportation costs are very sensitive to the number of refuelling stations changing, as between scenarios a and b.

Looking at the diagram of *scenario b* (Fig. 6), and the results shown in Fig. 8, we can ask whether the costs of pipeline transportation might be reduced by changing the network structure of the pipelines. An alternative pipeline network structure could be like that in Fig. 9, for a *scenario c*.

The number and sizes of the refuelling stations are assumed to be the same for *scenario c* as that for *scenario b*. A primary pipeline takes H_2 to two refuelling stations, which then splits into two secondary pipelines. It is assumed that the primary and

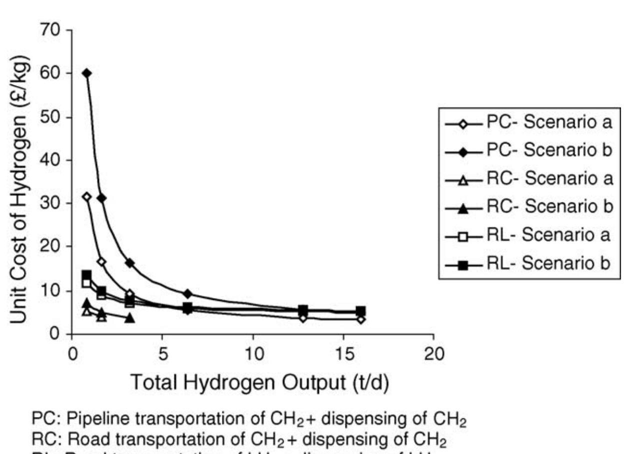

Fig. 7. Unit H_2 cost for scenarios a and b for different delivery pathways.

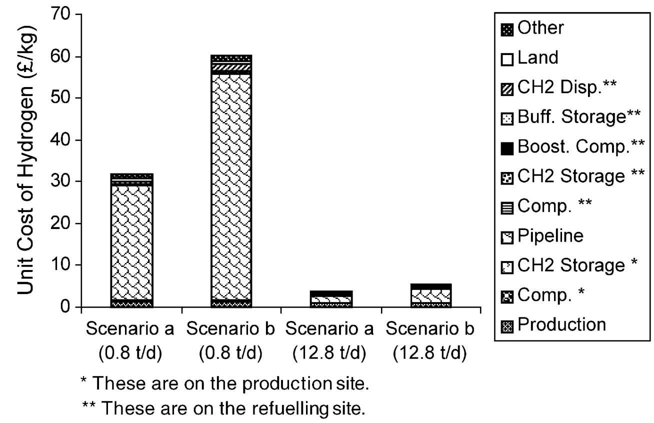

Fig. 8. Unit H_2 cost for scenarios a and b for pipeline transportation Pathway.

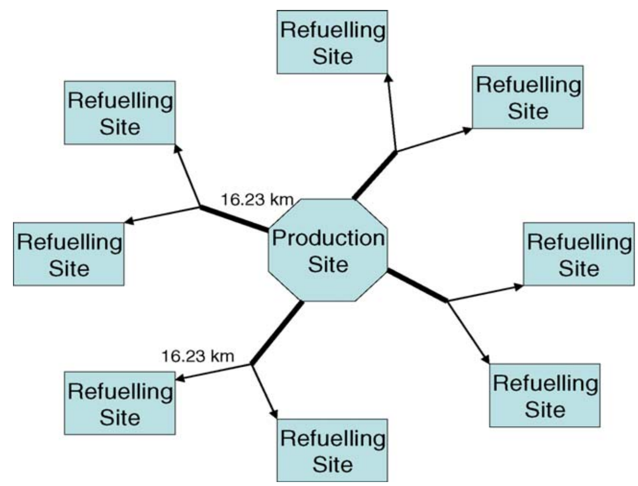

Fig. 9. Production and refuelling site set-up for scenario c.

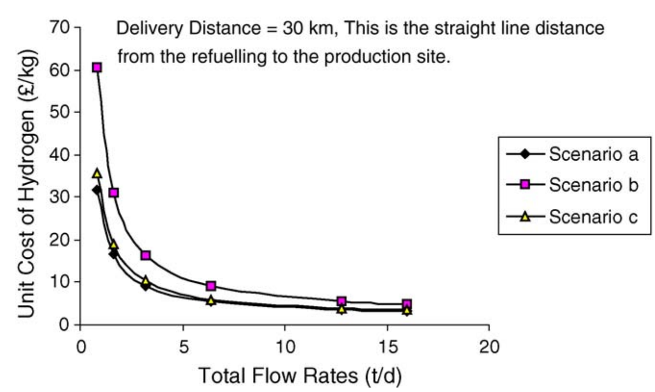

Fig. 10. Unit cost of H_2 delivered by pipeline for various scenarios.

secondary pipelines are of the same length.[5] Fig. 10 gives the costs of scenarios a–c for various total flow rates, for pipeline delivery of CH_2. This graph shows that the unit costs of H_2 for *scenario c* is significantly lower than that for *scenario b*, and is

[5] If it is assumed that the straight line distance from the production site to the refuellingr sites is 30 km, and that the eight stations are all evenly distributed along the radius around the production site, the length of the pipelines is 16.23 km.

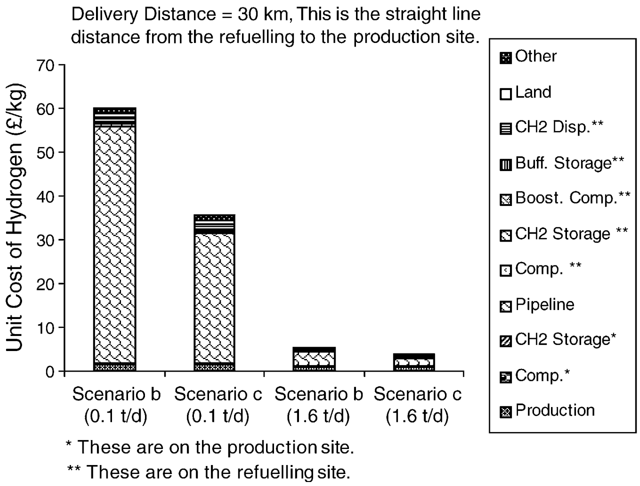

Fig. 11. Unit cost of H_2 delivered by pipeline for scenarios b and c.

very close to *scenario a*, where half as many refuelling stations are being supplied.

The cost difference between scenarios b and c arises from the difference in transportation costs, as Fig. 11 indicates. This suggests, therefore, that wherever possible, a scenario c type pipeline structure, consisting of primary and secondary pipelines, is likely to cost notably less than a scenario b type pipeline structure.

From the analyses in Section 3.1.2, regarding on-site H_2 refuelling stations, it can be seen that costs of the various options depend strongly on the flow rate. However, while production technologies can be different, there is only one least cost storage–delivery option—that of CH_2 storage and dispensing.

3.2. Part II: least cost H_2 delivery pathways

For on-site hydrogen production and delivery, it has been shown in the previous sections, that the least cost pathway is production of hydrogen via SMR, followed by storage and dispensing in compressed form, except for flow rates lower than around 0.2 t d^{-1}. For the latter flow rates, production of hydrogen via electrolysis also becomes a least cost option (see Section 3.1.1).

In the case of off-site H_2 delivery pathways, it has been shown that the relative costs of the various off-site delivery pathways change not only with flow rates and delivery distances but with the set-up of refuelling stations and pipeline structure (in the case of pipeline delivery). This is demonstrated graphically in Figs. 12–14, which show least cost pathways for scenarios a–c. In these charts each shaded square represents a particular flow rate and delivery distance.

The pattern of least cost pathways is evidently different for the different refuelling station set-ups/scenarios. However, as Figs. 12–14 indicate, in general the following trends hold for all of them:

- For low flow rates (<0.4 t d^{-1}) CH_2 by road + CH_2 delivery is the least cost pathway for all the delivery distances analysed.

Flow rate* (t/d)	0.5	10	20	30	40	50	60	70
6 (24)	p	p	p	p	p	p	p	p[l]
4 (16)	p	p	p	p	p	p	p	l
3.2 (12.8)	p	p	p	p	p	p	p[l]	l
1.6 (6.4)	p	p	p	p[l]	l	l	l	l
0.8 (3.2)	p	p	p[l]	l	l	l	l	l
0.4 (1.6)	p	l	l	l	l	l	l	l
0.2 (0.8)	c[p]	c	c	c	c	c	c	c

Distance (km)

p: CH_2 by pipeline + CH_2 delivery
c: CH_2 by road + CH_2 delivery
l: LH_2 by road + LH_2 delivery
[l]: letters in brackets mean that this delivery option is very close in cost to the one shown in the chart
* The flow rates in brackets are the total flow rates, as there are 4 or 8 of each station.

Fig. 12. Least cost delivery pathways: scenario a.

Flow rate (t/d)	0.5	10	20	30	40	50	60	70
3 (24)	p	p	p	p	p	l [p]	l	l
2 (16)	p	p	p	p	l [p]	l	l	l
1.6 (12.8)	p	p	p	l [p]	l	l	l	l
0.8 (6.4)	p	p	l [p]	l	l	l	l	l
0.4 (3.2)	p	p [l]	l	l	l	l	l	l
0.2 (1.6)	c[p]	c	c	c	c	c	c	c
0.1 (0.8)	c	c	c	c	c	c	c	c

Distance (km)

p: CH_2 by pipeline + CH_2 delivery
c: CH_2 by road + CH_2 delivery
l: LH_2 by road + LH_2 delivery
[l]: letters in brackets mean that this delivery option is very close in cost to the one shown in the chart
* The flow rates in brackets are the total flow rates, as there are 4 or 8 of each station.

Fig. 13. Least cost delivery pathways: scenario b.

Flow rate (t/d)	0.5	10	20	30	40	50	60	70
3 (24)	p	p	p	p	p	p	p	p [l]
2 (16)	p	p	p	p	p	p	p [l]	l [p]
1.6 (12.8)	p	p	p	p	p	p [l]	l [p]	l
0.8 (6.4)	p	p	p	p [l]	l	l	l	l
0.4 (3.2)	p	p	l [p]	l	l	l	l	l
0.2 (1.6)	c[p]	c	c	c	c	c	c	c
0.1 (0.8)	c	c	c	c	c	c	c	c

Distance (km)

p: CH_2 by pipeline + CH_2 delivery
c: CH_2 by road + CH_2 delivery
l: LH_2 by road + LH_2 delivery
[l]: letters in brackets mean that this delivery option is very close in cost to the one shown in the chart
* The flow rates in brackets are the total flow rates, as there are 4 or 8 of each station.

Fig. 14. Least cost delivery pathways: scenario c.

- For higher flow rates, either CH_2 by pipeline + CH_2 dispensing or LH_2 by road + LH_2 dispensing are cheaper: pipeline delivery costs less for high flow rates and relatively short distances and LH_2 by road costs less for lower flow rates and longer delivery distances.

Other parameters could also affect the pattern of least cost pathways; they include various assumptions such as those related to unit pipeline installation costs, capacities, load factor and costs of H_2-carrying vehicles, as well as local factors such as discount rate, cost of diesel and many others. A sensitivity analysis (in progress) is needed in order to assess the overall effect of all these parameters on the least cost pathway patterns. It is likely that if some or all of these other parameters are varied, the least cost pattern will change at the borderlines—particularly where the costs for two different pathways are very close, such as those shown in Figs. 12–14 by the square brackets. (In these boxes the difference between the cost for the two H_2 delivery pathways is less than 10%.)

3.3. Part III: comparing costs of on-site and off-site H_2 refuelling options

In the analyses so far it has been shown that both for on-site and off-site refuelling some production–delivery options cost less than others, depending on logistic circumstances (i.e. distribution and flow rate at refuelling stations, delivery distances and pipeline structures). This section tries to answer the question: when do on-site refuelling stations cost less than off-site ones, and vice versa? The assumptions about flow rates and distances in the scenarios analysed here, attempt to mirror an early infrastructure in London for H_2 buses.

As well as the size of each refuelling station and their distance from the production site (if production is off-site), the way in which an infrastructure will develop over the first few years is likely to affect unit costs of H_2. Load factors are likely to change in the first few years of the development of a H_2 infrastructure as they are affected by demand and rate of growth of demand. These changes and their effects on the costs of H_2 from both on-site and off-site infrastructures are also explored in this section.

3.3.1. Effects of flow rate and delivery distance

It is assumed that five refuelling stations (at depots) supply buses in an area in e.g. North East London. In the off-site scenario, a separate production site supplies them with H_2 (see Fig. 15), and in the on-site scenario each has its own H_2 production facility. It is assumed that in the case of off-site scenarios the method of H_2 production is SMR, as this is the least cost method of production for flow rates of higher than 1 t d^{-1} (see Section 3.1.1). In the case of on-site scenarios, all production technologies are considered, and the cheapest one is chosen.

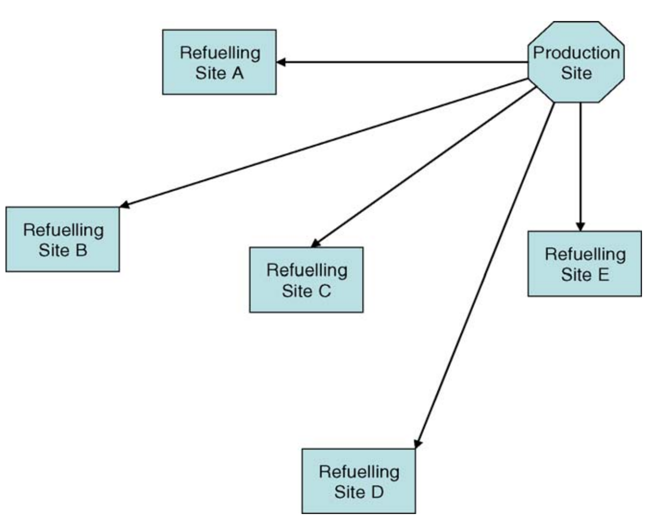

Fig. 15. Off-site refuelling scenario for buses.

Table 2
Flow rates for analysis of on-site and off-site scenarios

Refuelling site	Low flow rates (t d^{-1})	Medium flow rates (t d^{-1})	High flow rates (t d^{-1})
A	0.2	0.4	0.8
B	0.25	0.5	1.0
C	0.3	0.6	1.2
D	0.2	0.4	0.8
E	0.15	0.3	0.6
Average flow rate	0.22	0.44	0.88
Average no. of buses fuelled at each station[a]	6–15	12–30	24–60

[a]This depends both on the flow rate at each refuelling station, and on the fuel requirement of the buses. Here it is assumed that the fuel requirement ranges from 20 to 25 kg of H_2 per bus [10].

For the on-site scenario it is also assumed that the H_2 is stored as CH_2 and dispensed as CH_2, as this has been found to be the least cost method of delivery. For the off-site scenario the least cost pathway in each case has been chosen (since these depend on flow rate and delivery distance). As the scenarios are for refuelling buses, it is assumed that in all cases H_2 is dispensed as CH_2. Both the effects of changing flow rates and changing delivery distances are investigated. Using the on-site and off-site models, the unit costs of H_2 are derived for three sets of flow rates, as shown in Table 2 and three sets of distances, as shown in Table 3. The results are shown in Fig. 16.

As can be seen from Fig. 16, in all cases on-site refuelling is the least cost option, except in the case of low flow rates, where off-site is cheaper. This is mainly because the method of transportation for low flow rates is CH_2 by road, a relatively low cost option. For higher flow rates (medium and high) on-site SMR followed by CH_2 storage and dispensing was the least cost pathway, for all delivery distances. (Higher flow rates were considered, 1.2–2 t d^{-1}, but even then on-site refuelling stations were found to be cheaper.)

There are other important limitations, as well as costs, that can influence the choice between on-site and off-site infrastructure, including the availability of space and planning permission; both could present difficulties for an on-site H_2 refuelling station in the central areas of London.

Table 3
Delivery distances for analysis of on-site and off-site scenarios

Refuelling site	Short delivery distance (km)	Medium delivery distance (km)	Long delivery distance (km)
A	10	20	40
B	20	40	80
C	15	30	60
D	20	40	80
E	5	10	20

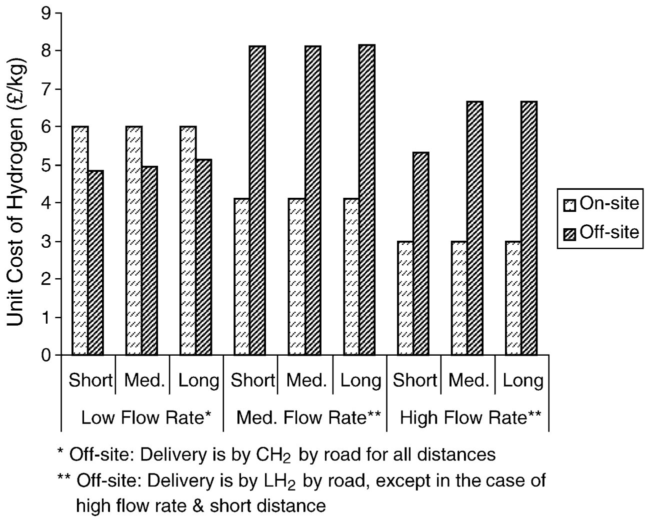

Fig. 16. Average unit cost of H_2 for on-site and off-site scenarios: varying flow rates and delivery distances.

3.3.2. *Effects of rate and pattern of demand growth*

At the beginning of the development of a H_2 infrastructure, demand is likely to grow constantly. This growth influences the appropriate capacity of the equipment on the refuelling and production sites. Although not easy to predict, in the case of bus refuelling demand growth forecasts can be based on the expected number of buses and on conversion strategies.

In the case of SMR plants, the capacity cannot be increased incrementally; therefore, for the first few years, this type of plant is likely to have relatively low load factors, depending on the rate of growth in demand. Electrolysers, on the other hand, can have units of extra capacity added on as necessary; this means that their load factor does not need to fall below the standard industry level (baseline value assumed here is 70%).

It must also be considered that once a refuelling infrastructure is in place, it would not normally be economically appropriate to replace it by another version, before the end of its lifetime. For all the analyses here it is assumed that the H_2 infrastructure has a lifetime of 15 years.

As well as the rate of demand growth, the pattern of demand could be different. Two patterns of growth considered here are:

1. *Gradual conversion scenario:* The bus depots could all gradually convert their buses to using H_2.
2. *Phased conversion scenario:* The depots could, one by one (or two by two) convert their whole fleet to H_2.

It is possible that for practical and/or strategic reasons one type of conversion might be favoured over the other. These two scenarios are described further below.

3.3.2.1. Assumptions for the gradual conversion scenario. For the gradual conversion of the depots to H_2, it is assumed that for different periods in the lifetime of the infrastructure the depots are all run at three different load factors: low (15.7%), medium (31.4%) and high (70%). Three different demand growth rates are also considered: slow, medium and fast. The number of years for which the bus depots are run at the low, medium and high load factors differs for the three different rates of demand growth; the assumptions are as follows:

- For the slower demand growth rate the lower load factor continues for the first 8 years, followed by the medium load factor for the next 4 years, and the higher load factor for the remaining 3 years.
- For the medium demand growth rate the three load factors each last for 5 years.
- For the fast growth rate the low load factor only continues for the first 3 years, the medium load factor for the next 4 years and the high load factor for the remaining 8 years.

Table 4 lists the H_2 demand (or flow rates), load factors and capacities for the different refuelling stations, for a *medium* growth rate.

It must be noted that with current technologies, if SMRs are operated below 30% loads, significant damage could be caused [12]. However, here for the sake of making comparisons, SMRs running at low load factors are also considered.

The load factors in Table 4 only apply to equipment whose capacity cannot be increased incrementally. These include SMRs, liquefiers and compressors. Equipment such as H_2 transportation vehicles, and dispensers are not in this category and, just as for electrolysers, are assumed to have a constant load factor of 70%.

3.3.2.2. Assumptions for the phased conversion scenario. In this scenario, the set-up of the bus depots is the same as the gradual conversion scenario. The main difference is that the bus

Table 4
Gradual conversion scenario: H_2 demand and load factors for a medium growth rate

Refuelling station	First 5 years		Second 5 years		Third 5 years		Required capacity ($t\,d^{-1}$)
	Demand ($t\,d^{-1}$)	Load factor (%)	Demand ($t\,d^{-1}$)	Load factor (%)	Demand ($t\,d^{-1}$)	Load factor (%)	
A	0.2	15.7	0.4	31.4	0.8	70	1.14
B	0.25	15.7	0.5	31.4	1	70	1.43
C	0.3	15.7	0.6	31.4	1.2	70	1.71
D	0.2	15.7	0.4	31.4	0.8	70	1.14
E	0.15	15.7	0.3	31.4	0.6	70	0.86
Total	1.1		2.2		4.4		7.01[a]

[a] This value is the total capacities plus any process losses of H_2 that may occur.

Table 5
Phased conversion scenario: H_2 demand and load factors for the different phases

Refuelling station	Phase 1		Phase 2		Phase 3		Required capacity ($t\,d^{-1}$)
	Demand ($t\,d^{-1}$)	Load factor (%)	Demand ($t\,d^{-1}$)	Load factor (%)	Demand ($t\,d^{-1}$)	Load factor (%)	
A	0.8	70	0.8	70	0.8	70	1.14
B					1	70	1.43
C					1.2	70	1.71
D			0.8	70	0.8	70	1.14
E	0.6	70	0.6	70	0.6	70	0.86
Total	1.4		2.2		4.4		7.01[a]

[a] This value is the total capacities plus any process losses of H_2 that may occur.

depots are converted *completely* to H_2, but in phases. As Table 5 shows, in phase 1 bus depots A and E are converted to H_2, in phase 2 bus depots A, D and E run on H_2, and in phase 3 all bus depots run their buses on H_2. The load factor for all the refuelling sites is 70% in all cases. However, the load factor at the production site using SMR technology is only 70% for phase 3, while for phase 1 it is 22.3% and for phase is 2 it is 35%. This is because the SMR at the production site has to be built with the highest capacity in mind, because its capacity cannot be increased incrementally over the 15 years, unlike that of electrolysers.

The on-site and off-site models were run for the flow rates in Table 5 and the appropriate load factors for the three phases. Both electrolysis (alkaline in this case) and SMR were considered for on-site and off-site options. For the off-site pathways, LH_2 by road and pipeline transportation were both included in the analysis. Just as for the gradual growth scenario, in order to compare the effects of slow and fast growth in demand on average unit costs, the three phases were assumed to last for varying periods, e.g. for slow growth the first phase was assumed to last for 8 years, the second for 4 years and the third for 3 years. The average unit costs of H_2 for the three different demand growth rates, and the different pathways were derived.

3.3.2.3. Other assumptions. As mentioned in Section 3.1.1, PEM electrolysis is only available for capacities of around $1\,t\,d^{-1}$ or less, therefore for higher capacities alkaline electrolysis is considered.

It is assumed that the delivery distance remains the same at the *medium* values (see Table 3). The on-site and off-site models are run for the above flow rates and load factor conditions. In order to make a decision on which of the pathways to follow, one needs to see what the average unit cost of H_2 is (for all the pathways), over the lifetime of the project (here assumed 15 years). For example for the medium growth rate, the average for each delivery pathway for each of the five year intervals is multiplied by 5, added together and then divided by 15, in order to obtain an overall average cost for that pathway.

3.3.2.4. Outcome of demand scenario analyses. Fig. 17 shows the results of the gradual conversion scenario analysis. It can be seen that for all growth rates on-site refuelling costs less than the off-site options. The least cost off-site pathway is SMR + road transportation (as CH_2 for low flow rates and low load factors, and LH_2 for higher flow rates).

From Fig. 17, it can also be seen that the faster the growth rate the lower the value of the average unit cost of the least cost option. This is not surprising, as the faster the growth, the sooner the load factor becomes equal to the highest value (in this case 70%); the higher the load factor the lower the overall unit cost of H_2.

In the case of the phased growth scenario, for all demand growth rates the trends are the same (see Fig. 18). The on-site pathways have the least cost; these are followed by the off-site SMR + pipeline transportation pathway.

Overall the least cost pathways for the phased growth scenario cost much less than those for the gradual growth scenario. From this it can be concluded that for the flow rates and distances considered complete phased conversion of depots is less costly than gradual conversions.

It can also be concluded that for the flow rates and distances considered, on-site production costs less than off-site production pathways. However, as mentioned before, it is possible that due to unavailability of suitable space and/or planning permission, on-site refuelling stations may not be possible to build. The next choice depends on the rate of growth in demand as well as conversion strategies for the bus depots:

- Gradual conversions of bus depots favour off-site pathways with SMR production and transportation via LH_2 tankers – for all demand growth rates.
- Complete conversions of bus depots, in phases, favour off-site pathways with SMR production and transportation via

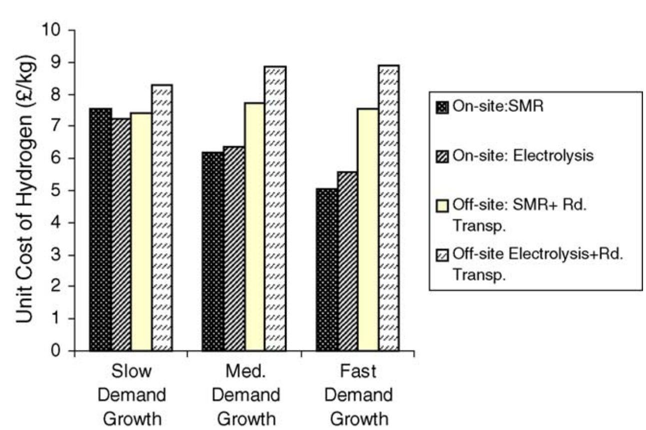

Fig. 17. Average unit cost of H_2 for gradual demand growth scenarios.

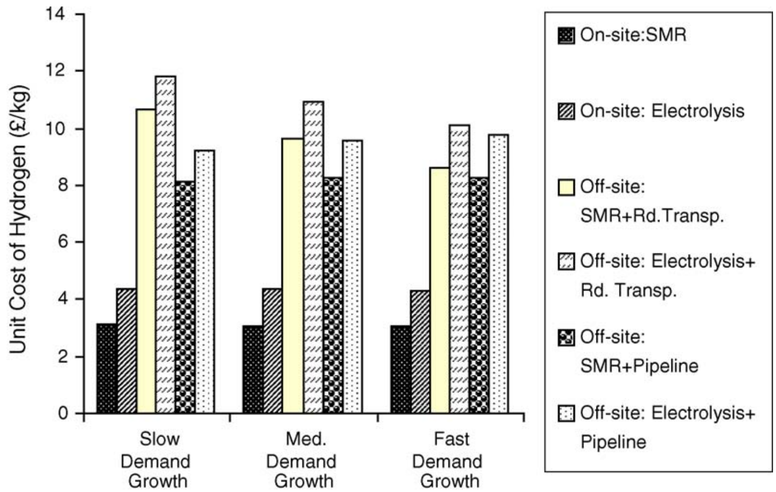

Fig. 18. Average unit cost of H_2 for phased demand growth scenarios.

pipeline. (In the case of high demand growth, transportation by LH_2 tankers is also cost competitive.)

- In the case of gradual conversions of bus depots, on-site electrolysis (via PEM electrolysers) could cost less than SMR for a slow growth in demand.

4. Conclusions

The models constructed for the analysis of H_2 infrastructure costs can consider 12 different possible pathways (from production to dispensing) at an on-site refuelling station and 18 for an off-site refuelling station. When looking for the least cost pathways, some of these can be dismissed due to very high unit costs under all circumstances and assumptions.

The remaining pathways (three on-site and three off-site ones) are found to take the least cost position, depending on flow rates at the refuelling station (or demand for H_2), delivery distance, distribution of refuelling stations and pipeline structure (in the case of pipeline transportation). For the baseline assumptions made, the following least cost pathways were identified:

On-site:

- *For low flow rates (less than around 0.2 t d^{-1}):* Production via electrolysis (alkaline or PEM) or SMR + storage as CH_2 + dispensing as CH_2.
- *For higher flow rates:* Production via SMR + storage as CH_2 + dispensing as CH_2.

Off-site:

- *For low flow rates (below around 0.4 t d^{-1}):* CH_2 transportation by road + dispensing as CH_2.
- *For higher flow rates:* Either LH_2 by road + dispensing as CH_2 or LH_2, or pipeline transportation of CH_2 + dispensing as CH_2. (The choice between these two pathways depends on both flow rates and delivery distances.)

In addition, for off-site infrastructures the least cost production technology is likely to be SMR, as required flow rates are usually higher than 1 t d^{-1}, for which SMR is the least cost production option.

On-site refuelling was found to cost less for all the flow rates and delivery distances considered, except for very low flow rates (0.15–0.25 t d^{-1}). For this latter case, off-site refuelling stations being supplied by CH_2 transported by road is less costly.

In order to find out what kind of refuelling pathways are best suited for a particular demand set-up, e.g. for a group of refuelling stations for buses in London, it was found that not only should flow rates and delivery distances be considered, but it is important to know the rate and pattern of growth of H_2 demand for the group of refuelling stations. Moreover, it was found that the one by one conversion (or phased conversion) of a group of bus depots to H_2 is less costly than the gradual conversion of all the depots.

It is important to note that the unit costs of H_2 derived in this paper depend to a great extent on the baseline values assumed for the various input parameters in the models used. A change in these is unlikely to affect the trends mentioned above, but will most certainly affect the threshold values for flow rates and delivery distances, at which one pathway becomes less (or more) costly than another. A sensitivity analysis, which should identify the possible deviations from these threshold values is in progress.

A special feature of the analysis presented in this paper is that it focuses on the costs of an early H_2 infrastructure in the city of London. However, the results and conclusions of the analysis can be applied to other large cities such as London, as logistic factors have been found to have more of an effect on hydrogen costs, than local ones. The sensitivity analysis will further clarify the significance of local factors.

As well as the sensitivity analysis, future work (or work in progress) includes investigating the potential changes in the relative costs of the H_2 production–delivery pathways over time; these could be due to technological changes, variation in energy prices and/or different rates of demand growth (for H_2).

Appendix A. Baseline assumptions for input parameters

See Tables A.1 and A.2.

Table A.1
Example of baseline assumptions: SMR

Parameters	Range of values	Baseline value	Source(s) of data
SMR			
Annual O&M cost (as % of capital cost)	1.5–3.0	2.7	Howe-Baker BOC
NG consumption (kWh kg^{-1})	54.1–61.7	57.8	Industry and Literature[a]
Electricity consumption (kWh kg^{-1})	Varies with capacity	Varies with capacity	Industry and Literature[a]
Water consumption (l kg^{-1})	Varies with capacity	Varies with capacity	Howe-Baker, BOC
Lifetime (years)	15–20	15	Industry and Literature[a]
Footprint	Varies with capacity	Varies with capacity	Industry and Literature[a]
Labour (no. of Engineers)	<5 t d^{-1} = 0; other = 1	<5 t d^{-1} = 0; other = 1	BOC
Wages (£ h^{-1})	10–20	15	Estimate
Installation cost (as % of capital cost)	10–25	20	Howe-Baker BOC
Shipment cost (as % of capital cost)	<5 t d^{-1}: 3.8-5.5; other: 6–7	<5 t d^{-1}: 4.5; other: 6.5	Howe-Baker BOC

Table A.2
Baseline values for key parameters

	Values	Sources
Number of storage days		
Production site		
LH_2 storage prior to road transportation	5	[13,14]
CH_2 storage prior to road transportation	2	[13]
CH_2 storage prior to pipeline transport	0.5	[13]
Refuelling site		
LH_2 or CH_2 storage following road transportation or on-site production	1[g]	[13]
CH_2 following pipeline transport	0–0.5	[3,13]
Buffer storage	0.2[h]	[13]
Pressure of CH_2 (MPa)		
For storage on production site	20	[7,8,10]
Prior to road transportation	29	[7,8,10]
On-board pressure for transportation	22.8	[7,8,10]
For storage at refuelling site	20	[7,8,10]
For buffer storage on refuelling site	44.4	[6–9]
For dispensing	44.4	[6–9]
Local parameters		
NG price (p kWh^{-1})	1.2	[15]
Electricity price (p kWh^{-1})	3.7	[15]
Price of land–production site (£ m^{-2})	200	[16]
Price of land–refuelling site (£ m^{-2})	400	[16]
Discount rate	12%	Industry estimate

Keys: a, based on Information from a number of publications and/or industry sources; b, based on values for electrolysers; c, based on values for CH_2 cylinders; d, based on value for H_2 compressors; e, this value corresponds to the tube trailer size for which capital costs are used in the models; f, these values are also used for pump and vapouriser, storage valve and panel and sequencer; g, this storage capacity has to be at least equal to the size of the tanker/trailer in the case of road transportation; h, this storage capacity has to be at least equal to the maximum fuel requirement of one vehicle.

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