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Modelling of hydrogen infrastructure for vehicle refuelling in London

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Abstract

One of the principal barriers to the widespread use of hydrogen as a road transport fuel is the need for a refuelling infrastructure to be established. The lack of an adequate refuelling infrastructure would severely inhibit an uptake of hydrogen vehicles. On the other hand, without significant penetration of these vehicles, the demand for hydrogen would be insufficient to make a widespread conventional refuelling infrastructure economic.

The infrastructure is likely to develop initially in cities, due to the high concentration of vehicles and the anticipated air quality benefits of a switch to hydrogen as a road transport fuel. While trial schemes such as the Clean Urban Transport for Europe (CUTE) bus project will establish initial hydrogen refuelling sites, it is not clear how a transition to a widespread refuelling infrastructure will occur. Indeed, the number of possible different ways and scales of producing and distributing hydrogen means that the possible configurations for such an infrastructure are almost endless.

Imperial College London is examining transition strategies for a hydrogen infrastructure for vehicle refuelling in London under a project funded by the UK Engineering and Physical Sciences Research Council (EPSRC). Imperial has five project partners from industry and local government to assist in this study: the Greater London Authority (GLA), BP, BOC, BMW and Air Products.

This paper presents initial results from technical modelling of hydrogen infrastructure technologies and how they could be deployed to provide an initial facility for the refuelling of hydrogen fuel-cell buses in London. The results suggest that the choice of H_2 production technology can have significant effects on when the infrastructure would be installed, and the timing of hydrogen production, and bus refuelling.

Keywords: Hydrogen; Infrastructure; Modelling; London; Buses; Fuel-cell

1. Introduction

It is considered likely that buses and fleet vehicles will make the switch to hydrogen before private vehicles, due to their use of depots for refuelling, which avoids the need for widespread refuelling infrastructure to be in place [1]. This project therefore focuses on looking at how an infrastructure for refuelling hydrogen buses and fleet vehicles might develop in London, and whether this initial infrastructure might provide a sufficient and suitable platform for a more widespread infrastructure for private vehicle refuelling.

Initial work has focused on the technical modelling of infrastructure technologies and analysis of some of the issues relating to the introduction of hydrogen fuel-cell buses in London, such as the location and size of bus depots and the potential uptake rate of fuel-cell buses. This analysis of local issues provides data and scenarios for the more generic technical model, meaning that the results take into account some of the particular aspects of H_2 infrastructure development that are specific to London.

This paper presents the methodology for technical modelling of hydrogen infrastructure and an analysis of the technical issues for installing an initial facility for bus refuelling in London.

2. Introducing hydrogen buses to London

As one of nine cities involved in the EU-funded Clean Urban Transport for Europe (CUTE) bus project, London is due to receive three fuel-cell buses at the beginning of 2004. These buses, supplied by DaimlerChrysler, run directly on compressed hydrogen, stored in cylinders in the roof compartment at 35 MPa. The hydrogen for these buses is to be supplied to the refuelling point in east London in liquid form, transported by truck from Rotterdam.

At present, approximately 6000 buses run in London on more than 700 routes from 78 depots [2]. Clearly, for

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fuel-cell buses to become even a small proportion of the London bus fleet would take considerable commitment on behalf of the Mayor and Transport for London, the body responsible for public transport in London. This contrasts with Iceland, where the three fuel-cell buses being introduced under the Ecological City Transport System (ECTOS) project will comprise 4% of Reykjavik's bus fleet [3].

Beyond the 2-year lifetime of the CUTE project, the prospects for hydrogen fuel-cell buses in London are uncertain. Although the present Mayor "strongly supports the development of hydrogen and fuel-cell technologies in London" [4], it is not known how quickly these vehicles can, or will, penetrate into London's bus fleet. In addition to the uncertainty inherent in political support, another significant factor will be the cost of the vehicles such as buses, themselves. It is difficult, therefore, to predict the rate at which fuel-cell buses will penetrate into London's bus fleet.

This uncertainty about the pace of a possible transition to hydrogen as a fuel is a crucial factor in the planning of a hydrogen refuelling infrastructure; it affects not only the rate at which the infrastructure is installed, but also, potentially, the type of infrastructure. For example, faced with a significant element of uncertainty about the rate of demand growth, an investor might decide to install smaller production units on an incremental basis, rather than a single larger unit.

This paper focuses on the technical aspects of a hydrogen infrastructure and how it would perform in serving different numbers of buses. It is not important for this analysis to know in which year there are, say, 10 or 60 hydrogen buses in London.

2.1. Bus refuelling in London

Buses refuel at depots, of which the 78 in London are spread fairly evenly across the capital. The depots vary in size: the largest, in Holloway, houses 237 buses running on 20 routes, while the Acton depot uses just 9 buses on a single route. The frequency with which buses run varies throughout the day; generally it is highest during the peak hours of the morning. The change in frequency of bus trips over the hours of a weekday, both for the entire bus fleet and for a few selected individual depots, is illustrated in Fig. 1. The day is divided into five time periods, each of which has an associated bus frequency for each route. The graph plots the vehicle-kilometres travelled per hour for each of the five time periods, relative to the morning peak. Bus services are generally less frequent on weekends, particularly on Sundays, although night bus services are more frequent on weekends than weekdays.

2.2. Strategies for the introduction of fuel-cell buses

The variation of bus frequencies could have a significant effect on the development of a strategy for the introduction of fuel-cell buses. The data in Fig. 1 show that while the frequency with which buses run does not vary much within the main daylight hours, more significant variation occurs during the evening and night. This is of interest when considering how best the fuel-cell buses might be managed and allocated to depots. As the cleanest, most efficient and most expensive vehicles in the bus fleet, it is reasonable to suggest that the fuel-cell buses should be used as much as possible and, therefore, in preference to conventional buses. This makes little difference during the day, as the fleet will be operating at or near full capacity and all the buses will have high utilization. During the evening and night, however, the bus frequencies fall and as a consequence either fewer buses are required, or all of the buses could run, but only sporadically.

A strategy leading to the maximum utilization of fuel-cell buses would be to allocate them to depots only up to the point where they are fully utilized. This would result in a relatively small penetration of the buses into each depot. For example, taking as a guide the relative frequency of night journeys compared with the peak, a maximum penetration

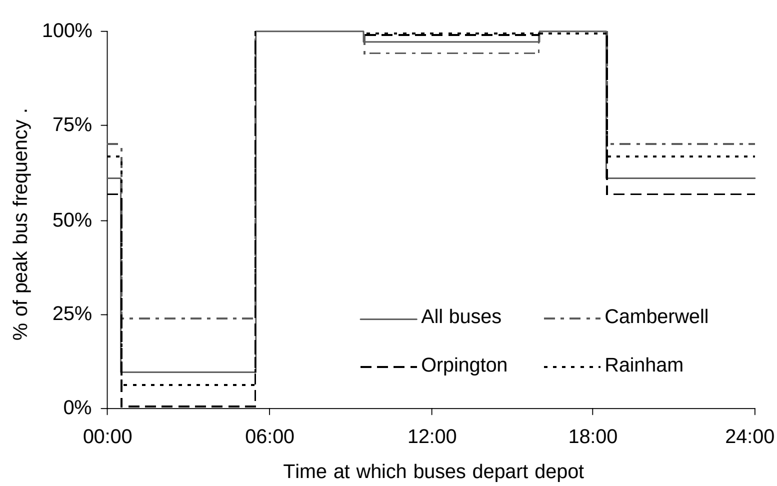

Fig. 1. Variation of bus frequency within each weekday.

of 25% might be expected for Camberwell, with an average penetration of 10% across other depots. Intuitively, such a strategy would seem to contradict common sense, which would suggest allocating the buses to no more than a few depots initially to concentrate both infrastructure development and technical expertize in a smaller number of depots. A reasonable compromise might therefore be to allow penetration up to the point where all the buses are fully utilized during the evening period and only partially at night; this point would be when buses comprise 60–70% of the depot's bus fleet. Under this strategy, and in order to concentrate the buses in as few depots as possible, it would seem sensible to allocate them to larger depots and then to those with the highest relative frequency during the evening period.

The availability of land to accommodate infrastructure for hydrogen production, storage and dispensing may be an issue, in London more so than elsewhere, due to high prices and scarcity of suitable land. The availability of land within, or very near to, the bus depots in London is not known; clearly this would be a factor in the choice of which depots would be selected to house fuel-cell buses, if a significant amount of onsite infrastructure were required.

3. Hydrogen infrastructure options for refuelling London buses

The two technologies most often considered for hydrogen production are electrolysis of water and steam reforming of methane (SMR) in natural gas. One of the reasons for their prominence as options for hydrogen production stems from their potential availability, due to already established distribution infrastructures for electricity and natural gas. In addition, reforming of natural gas is usually the lowest cost method of producing hydrogen at present [5], while electrolysis offers the possibility of a zero-carbon fuel chain if the hydrogen is produced via non-fossil electricity.

When considering the development of hydrogen infrastructure to serve fuel-cell buses in London, two important factors are the size of the hydrogen demand and the rate of demand growth. The level of demand is clearly a major determinant of the scale of the infrastructure that is installed, but the rate of demand growth is also important. The economics of installing a large hydrogen production plant would not be very favourable if it takes 20 years for demand to reach full production capacity, whereas if this level were reached within, say, 5–8 years, this may be acceptable.

For this reason, given the relatively low demand and the uncertainty about the rate of demand growth, it would seem sensible to develop production capacity incrementally, where possible. It is unlikely that large-scale centralized hydrogen production plants would be built until the level of demand is significant and uncertainty is reduced. However, it is also true that many technologies, including SMR plant, benefit from significant economies-of-scale. Thus, despite demand being a relatively low proportion of capacity in the early stages, an onsite plant sufficiently large to eventually fuel most of a bus depot may, economically, be the best option for the reforming of natural gas.

Electrolysis is potentially a source of zero-carbon hydrogen, if used in conjunction with non-fossil electricity. Nevertheless, greater reductions in carbon dioxide emissions may be achieved by using renewables to displace electricity produced from fossil fuels on the grid, rather than producing hydrogen [6]. Therefore, it could be argued that until there are surplus renewables available for hydrogen production, this route should not be promoted in terms of climate benefits. It should be noted, however, that if renewables are installed specifically for hydrogen production and would not have been installed otherwise, this would both produce zero-carbon hydrogen and may also help to stimulate the market for renewables in the UK.

A number of other options can be considered for supplying hydrogen in London. Trucking in liquid hydrogen from Rotterdam, as is planned for the CUTE buses, is one possibility; sufficient industrially produced hydrogen is available to fuel hundreds, if not thousands, of fuel-cell buses in the UK [7]. The purity of this industrial hydrogen is generally high, but further purification could be undertaken if necessary. In the case of liquid hydrogen, the liquefaction process produces hydrogen of a high level of purity. Liquifying hydrogen does, however, use a considerable amount of energy and the environmental consequences of such a route would therefore have to be considered carefully.

Producing hydrogen from the gasification of municipal solid waste (MSW) is another possibility, which would also help to address the issues of waste management that inevitably arise in a big city. Most commercial or near-commercial waste gasification technologies are large-scale, and can produce sufficient hydrogen for around 450 fuel-cell buses. Therefore, unless uses can be found for the remaining hydrogen, this is unlikely to be a suitable option for the initial stages of vehicle refuelling. If smaller-scale waste gasification technology becomes commercial within a suitable timeframe, however, this could provide a viable option for supplying buses in London, especially as the economics of such a plant could be improved by offsetting the fees levied for waste management [8].

Other possible sources of hydrogen for vehicles in London would probably involve a production facility located outside the capital, with hydrogen transported by either truck or pipeline. Such sources include remote renewable electricity, e.g., offshore wind, or the gasification of biomass or coal.

In the longer term, to reduce carbon dioxide emissions, it will be necessary to switch to hydrogen from renewables, nuclear energy, or fossil fuels with carbon sequestration. Infact, using low-carbon sources of hydrogen in the early stages may be less important than actually making the transition to hydrogen, even if early sources of hydrogen do not provide substantial environmental improvements. Decarbonization of the hydrogen supply chain can occur later, when more substantial volumes of hydrogen will be needed.

4. Technical modelling of hydrogen infrastructure

4.1. Model structure

The technical model of hydrogen infrastructures developed within this project has been designed on a nodal network structure. An 'infrastructure' is defined as a collection of technologies that are connected together in a specified way and are grouped into the following five categories:

- sources of energy
- conversion (including compression)
- fuel transportation
- storage
- demand.

All energy flows must begin with an energy source and end with a demand node. In between these end-points, there can be a series of conversion units, fuel transportation links and storage units.

Each of the infrastructure technologies is characterized individually, taking into account technical characteristics and constraints. The model is structured so that it can handle any technically feasible infrastructure configuration, to mirror the flexibility inherent in the many production and delivery options for hydrogen. The technical model is demand-driven, which means that the implications of different infrastructure options for meeting a given hydrogen demand can be compared directly.

The model simulates the energy flows within a specified infrastructure, driven by hourly hydrogen demand profiles on a weekly cycle. The use of such profiles captures the variation of demand and therefore infrastructure operation on a day-to-day basis, without going to a high level of detail that would still not allow any greater understanding. The use of a weekly cycle aims to capture the different ways in which the infrastructure could operate on weekends, compared with weekdays.

Once a configuration of the infrastructure is specified, the technical model simulates how it might be operated. The model assesses each individual infrastructure configuration and then makes decisions on infrastructure operation. The model has a standard process for doing this and is capable of assessing and simulating both small and large infrastructures.

4.2. Infrastructure assessment and operational simulation

Infrastructure components are categorized by the model into those that provide flexibility and those that do not. Flexible parts of the infrastructure are defined as those for which the input and output energy flows are not necessarily linked. The main source of flexibility in the operation of an infrastructure is in the use of hydrogen storage facilities, with linepack within hydrogen pipelines potentially providing a further source. Since the model is demand-driven, the required operating regime of any inflexible infrastructure component 'connected' to a demand node without any intervening flexible technology is also effectively determined by this demand and its profile. Equally, if hydrogen were being produced from a source of energy that could not be used on-demand, e.g., intermittent renewables, the operation of the upstream part of the supply chain would also effectively be determined.

The model analyses the network for points of flexibility and then seeks to prioritize decisions on infrastructure based on this analysis; the initial focus is placed on how storage should be operated. Determining the flows in and out of storage effectively determines all of the energy flows for the system, due to the lack of flexibility elsewhere. The main uses of storage are to flatten uneven production and/or demand profiles and to provide a buffer in case of unexpected high demand or low production. The model works out how storage can be operated in order to meet demand, while also achieving other operational objectives, such as flattening demand profiles. The methodology is able to handle relatively large and complicated network configurations, although this is unnecessary for most assessments of initial infrastructure for bus refuelling.

Decisions within the model on the operation of storage will eventually be driven by economic as well as technical considerations. This module is not yet complete. Therefore, as an interim measure, the technical model can be set either for all storage facilities or for each individually, i.e.,

- minimize storage utilization—use the available storage as little as possible and therefore meet as much as possible of demand from 'just-in-time' production/delivery.
- flatten profiles—utilize storage such that the production/delivery profile required to meet non-constant demand is as flat as possible (and to flatten the available supply profile when intermittent energy sources are used to produce hydrogen).

Selecting one or other of these options does not affect the ability of the infrastructure to meet demand; it merely determines how that demand is met, with consequences for the profiles of hydrogen production and storage utilization. To calculate the final energy flows, the model performs a number of iterations, which address different parts of the system according to the priorities identified in the initial assessment of the infrastructure.

4.3. Characterizing different technologies and modelling operational constraints

Hydrogen infrastructure technologies cannot always be operated as flexibly as may be desired. For instance, the output of a hydrogen production unit cannot necessarily be varied according to the demand for hydrogen. Operational constraints vary between technologies and it is important to understand these constraints in order to assess their influence on hydrogen infrastructure development.

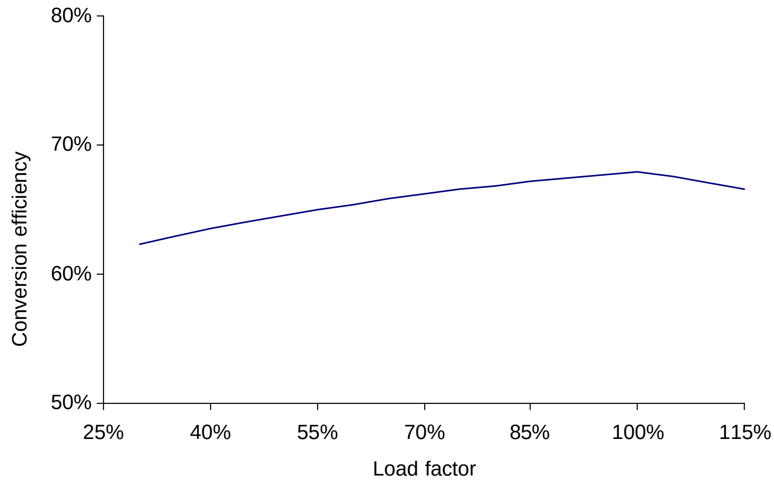

Fig. 2. Variation of SMR efficiency at different loads.

Different operating regimes for certain infrastructure technologies can have effects on their lifetime, operational efficiency, or the purity of the hydrogen that is produced. For example, the efficiency of SMR units varies with the load on the unit; maximum efficiency is achieved when operating at full rated capacity, with the efficiency dropping non-linearly as the load decreases. The units can actually be operated at higher than the rated capacity, up to about 115%, although there is a drop-off in efficiency above the rated capacity. The variation of efficiency with load is illustrated in Fig. 2. Clearly, the efficiency penalty for reducing the load exceeds the efficiency benefit from a corresponding increase in load. Overall efficiency is therefore maximized by keeping the unit at a constant load than varying it up and down.

Running SMR units at loads of below 30% of rated capacity can cause significant damage. Moreover, it takes a considerable amount of time to shut-down and ramp up such units without damaging them. Size is also a factor, with large SMR units being around 5% more efficient than small units [9]. Within the model, SMR units are currently constrained to run constantly, without shutdowns, at a minimum load of 30% of capacity.

The gas produced by the reformer is then fed through a pressure swing adsorption (PSA) unit, which cleans the hydrogen stream to a sufficient level of purity for use in fuel-cell vehicles. The PSA unit can recover 90% or more of the hydrogen produced in the reforming process at a purity in excess of 99.95%. The remaining hydrogen is contained in the waste gas, which is fed back into the burner to maintain the reforming temperature. The main contaminant to be avoided in the H_2 output is carbon monoxide, which must be kept below 100 ppm and preferably below 20 ppm to avoid poisoning of the platinum anode catalyst [10] inside the PEM fuel-cells used in current and planned fuel-cell vehicles. Any unconverted methane in the hydrogen would pass inertly though the PEM fuel-cell, acting only as a diluent and therefore slightly reducing the power produced by the fuel-cell at that time, due to the lower concentration of hydrogen [11].

Electrolysis is a more flexible H_2 production technology than SMR. Shut-down and start-up times are minutes or seconds, rather than hours, which enables the units to be switched on and off as required. The efficiency of the electrolysis process actually increases slightly at lower loads but at these loads the gas impurities (oxygen in hydrogen, and vice versa) are higher. This is because the potassium hydroxide electrolyte contains small quantities of dissolved H_2 and O_2, which can find their way into the wrong output stream. At lower loads, less ‘fresh’ gas is produced to dilute these impurities leading to higher levels of impurity in both the H_2 and O_2 streams. More cleaning is hence required, resulting in a higher overall energy consumption per unit of H_2 produced. Electrolysis units are therefore usually operated at loads of 80–100% and switched off when not required [12].

The technical model characterizes these operational constraints, by allowing specification of minimum load factors of each technology, variation of conversion efficiencies with load and start-up and shut-down times. Modelling these technical characteristics and constraints, provides a better understanding of the effect they have on which technologies might be chosen in the development of a hydrogen infrastructure, and on how such an infrastructure might be operated.

5. Modelling results

This section presents results of the technical modelling of hydrogen infrastructure as applied to the development of initial infrastructure for refuelling fuel-cell buses in London. The results are presented as snapshots of how the infrastructure might exist and operate at different levels of demand. It should be noted that although these demand levels could be associated with different points in time, this is not necessary for the analysis or understanding of the results. Timing issues are more relevant when assessing the economics and

Table 1
Hydrogen consumption for different numbers of buses (t H_2 per day)

Number of buses	Weekdays	Saturday	Sunday	7-day average
10	0.34	0.34	0.34	0.34
60	1.71	1.75	1.75	1.72
120	3.35	3.11	2.57	3.21

potential financing of the infrastructure than for the technical aspects.

The analysis is focused on the development of infrastructure to supply a bus depot such as Rainham, which is the depot that will be home to the three CUTE fuel-cell buses. The depot is the second largest in London in terms of the number of vehicle-kilometres driven by its buses each week. It also has the advantage of being towards the outer part of London (in the east) and therefore probably has a better chance than most depots of having available or affordable land for hydrogen infrastructure. For the Raimham depot, the relative frequency of buses on weekday evenings as a proportion of peak frequency, is 67%. This depot currently houses 182 conventional buses, so according to the strategy discussed in Section 2.1, 121 of these should eventually make way for fuel-cell buses.

The results in this section present snapshots of the different infrastructures when servicing 10, 60 and 120 buses. The equivalent hydrogen consumption is presented in Table 1. The hydrogen consumption of the buses is assumed to be 13.5 MJ/km [13], using the lower heating value of hydrogen of 120.2 MJ/kg. The assumed average distance travelled per bus varies between 191 and 307 km per day, depending on the day of the week and the potential to use the buses in the evenings and at night. At higher penetrations of fuel-cell buses into the depot, the average distance the average distance travelled per bus will decrease, as the additional buses may not be required in the evening or at night.

When the depot is serving 60 buses, the greater number of night bus services on weekends implies a slightly higher daily consumption than on weekdays, while the greater number of evening services on weekdays dominates when the depot is serving 120 buses. The consumption of each bus is therefore in the range 21–34 kg H_2 per day, which is less than the 40 kg onboard storage capacity of the buses, meaning that the buses should not have to refuel more than once per day.

5.1. Hydrogen infrastructure scenarios

The infrastructure scenarios for which results are presented focus on two hydrogen production technologies—steam reforming of natural gas and electrolysis of water—and the different scales at which such plant can be installed. Although the economics of hydrogen infrastructure are not directly considered in this analysis, they are taken into account in the building of the scenarios used for the technical simulations, for example in determining the hours at which electricity is available for hydrogen production.

Dispensing of hydrogen is not addressed in these results, as it assumed that this is dependent on the number of buses being refuelled and is not dependent on the other infrastructure installed. Storage of hydrogen is assumed to be at 44 MPa in compressed hydrogen cylinders at the depot.

5.1.1. Scenario A: incremental onsite electrolysis

As a relatively flexible and modular technology that does not significantly benefit from economies of scale, electrolysis can be tailored closely to the specific refuelling requirements at a given point in time. Its modular nature means that additional production capacity can be added when needed, rather than being installed at the outset. Its flexible operation also means there are few issues relating to the minimum amount of hydrogen that is produced.

The cost of hydrogen production from electrolysis is highly dependent on the cost of the electricity used [5]; for this reason, off-peak power is generally preferred for hydrogen production. For a given level of daily consumption, however, the use of fewer hours to produce the hydrogen requires electrolyzers of higher capacity.

Within this scenario, two sets of results are presented as follows:

- Scenario A1: hydrogen is produced only during a 'standard' 8-h off-peak period, between 11:30 p.m. and 7:30 a.m. This might represent a situation in which the electricity comes from standard power plants on the grid, at market prices.
- Scenario A2: the hydrogen can be produced in an 18-h period between 9:30 and 3:30 p.m., avoiding the evening electricity peak. The model aims to concentrate production in the off-peak period and use as few daytime hours as possible. This might represent a situation in which dedicated renewable electricity is being used for hydrogen production, except at peak times when the electricity is sold to the power market to benefit from the higher prices.

The capacity of the electrolyzer under consideration is 0.3 t of H_2 per day (tpd). Electrolysis units are added as necessary for scenarios A1 and A2, so that sufficient hydrogen can be produced within the specified hours. As there are fewer production hours under scenario A1, a higher production capacity is required, so electrolysis units will tend to be added at a faster rate than for scenario A2.

5.1.2. Scenario B: industrial liquid hydrogen followed by onsite SMR

Steam methane reformer units benefit from significant economies-of-scale, due to the nature of their construction, as they contain many cylindrical parts such as pipes. Larger SMR plants are more efficient than small ones; as such, they would generally be sized to supply the maximum hydrogen demand that might be needed, which in this case needs to be sufficient for 120 fuel-cell buses, i.e., around 3.4 tpd on a weekday (Table 1). SMR units can be run at up to 15% above their rated capacity; this provides additional production capacity, should it be required. A 3.4 tpd SMR plant has therefore been assumed.

As described in Section 4.3, conventional SMR units suffer damage if operated below 30% of capacity, and also have very long shut-down and start-up times. For these reasons, a sensible approach would be only to install an SMR unit if there is sufficient hydrogen demand to consume at least the production that would result from running the unit continuously at 30% load. An onsite or very local plant that would provide a dedicated supply to this depot could therefore only begin to operate once at least 36 fuel-cell buses were in place.

In the interim period before a 3.4 tpd SMR plant would start to supply the buses, an alternative supply source is required. For this scenario, the hydrogen up until this point is to be supplied, as for the three CUTE buses, by liquid hydrogen trucked into London.

5.2. Scenario results

The following sections present the results produced by the technical model for the two different infrastructure pathways: steam methane reforming of natural gas and electrolysis of water.

5.2.1. Scenario A: incremental onsite electrolysis

The installed electrolyzer capacity required to supply different sized fleets of fuel-cell buses at the depot are shown in Table 2. The required capacities are based on the need to produce the highest daily consumption (taken from Table 1) in a period of either 8 h (scenario A1) or 18 h (scenario A2). Therefore, the required production capacity for 10 buses is the daily demand of 0.34 tpd multiplied by 24 h and divided by the number of hours of production. For scenario A1, 8 h of production implies a capacity requirement of 1.03 tpd, while the equivalent capacity requirement for the 18 h of production under scenario A2 is 0.46 tpd.

The installed capacities are rounded up to the next multiple of 0.3 tpd, as this is the size of electrolyzer unit that has been assumed. The modular nature of the electrolyzers is less significant when considering greater volumes of hydrogen, as the unit capacity is small compared with the overall installed capacity. The electrolyzers are assumed to operate at 100% load for as long as is necessary to produce the required quantity of hydrogen; as a result of this assumption, a greater over-capacity leads to a shorter time requirement to produce the hydrogen.

Table 2
Electrolyzer capacity requirements for different numbers of buses (tpd hydrogen)

	10 buses	60 buses	120 buses
Average hydrogen demand (assuming 24 h operation)	0.3	1.7	3.2
Capacity for scenario A1 (maximum 8 h operation)	1.2	5.4	10.2
Capacity for scenario A2 (maximum 18 h operation)	0.6	2.4	4.5

Table 3
Number of hours of operation for electrolyzers under different scenarios

	10 buses	60 buses	120 buses
Scenario A1 (maximum 8 h)			
Weekdays	6.9	7.8	7.9
Saturday	6.9	8.0	7.3
Sunday	6.9	8.0	6.1
Scenario A2 (maximum 18 h)			
Weekdays	13.8	17.5	17.9
Saturday	13.8	17.9	16.6
Sunday	13.8	17.9	13.7

Under scenario A1, an installed capacity of 1.2 tpd for 10 buses significantly exceeds the required capacity of 1.03 tpd on weekdays. As a consequence, production would occur for 6.9 h of the 8-h off-peak electricity period, assuming production at 100% of capacity. For 60, the electrolyzer capacity more closely matches that required for off-peak production, with the discrete nature of the electrolyzers becoming less significant at these higher production volumes. As a result, hydrogen is produced for a higher proportion of the off-peak period, between 7.8 and 8 h for 60 buses, depending on the day of the week. For 120 buses, the production period on weekdays is 7.9 h, but this falls to 6.1 h on Sundays. The time for which the electrolyzers need to operate at full load to produce sufficient hydrogen for bus refuelling under different scenarios is presented in Table 3.

For scenario A2, the installed capacity of 0.6 tpd for 10 buses is substantially greater than the required capacity of 0.46 tpd, so under this scenario, the units need not be operated for the full 18 h available, but for a substantially shorter period. The electrolyzers can produce 0.2 t of hydrogen during the 8 h of off-peak electricity and therefore need operate for only 5.8 h outside of this period.

The timing of hydrogen production from electrolysis will be driven by economics and is assumed therefore to occur mainly at night, when electricity is cheapest. Since the buses would only need to refuel once or at most twice each day, it would make sense for most of the refuelling to occur at night as the hydrogen is produced, rather than to store it until later. Importantly, by refuelling in this way, the storage of hydrogen onboard the buses would reduce the need for storage capacity at the depot.

The timing of these additional hours of production outside the off-peak period under scenario A2 would be determined by a combination of economics, related to the electricity price at different times, and the logistics of managing the bus refuelling.

As the buses would generally be refuelling at the time the hydrogen is produced, the requirement for storage at the depot would be relatively small. Storage would be required to provide an emergency supply and to buffer any difference between the timing buses would be of production and bus refuelling, should this occur for logistical reasons. It is therefore difficult to assess the storage capacity required from a technical point of view, because the volumes needed for emergency back-up and to buffer for logistical purposes must be decided at the bus depot level.

The use of the fuel-cell buses at night as well as during the day might interfere with a cost-minimizing refuelling strategy if hydrogen is produced via electrolysis. Nevertheless, it should be possible to share the burden of the night routes amongst the hydrogen bus fleet, so that many, if not all, can be refuelled within this period. Ultimately the decision of whether to use the fuel-cell buses as night buses would be a trade-off between any economic disadvantages versus environmental and other benefits.

An advantage of having a relatively large number of electrolysis units is that load can be reduced when necessary by switching some units off, rather than by reducing load on all units. This allows the overall efficiency to be maintained at very close to the optimum. As a result the efficiency of each of the different scenarios would be at, or very close to, the optimum efficiency of the electrolysis units.

5.3. *Scenario B: imported liquid hydrogen followed by onsite SMR*

5.3.1. *Imported industrial liquid hydrogen*

If the hydrogen is delivered in liquid form by trucks coming from outside London, relatively little hydrogen infrastructure would be required at the depot. In addition to the dispensing equipment for refuelling the vehicles, a dewar for storing the liquid hydrogen would be required, together with compressors to supply the hydrogen to the buses at the necessary pressure. In supplying the hydrogen for refuelling the vehicles, the storage system would allow the appropriate amount of liquid hydrogen to evaporate, for compression and subsequent dispensing.

Tankers can carry more than 4 t of liquid hydrogen on each journey [14], which would be sufficient to supply 10 buses for more than 3 months. Delivery of such a large volume would, however, require an equivalently large onsite storage facility. Boil-off of the liquid hydrogen would not cause a problem, as this boil-off gas could be compressed and used to refuel the buses. The frequency of delivery of liquid hydrogen to the depot, and therefore, the onsite storage requirements, is therefore largely an economic decision. The trade-off between the costs of onsite storage and of additional journeys to transport the hydrogen would determine where the balance should be struck.

The storage of hydrogen in liquid form onsite means that the only constraints on when the buses might be refuelled would be on the number that could be refuelled simultaneously, which would depend on number of compressors and dispensers installed. As such, one would expect the number of buses that could be refuelled simultaneously should be kept as low as possible (maybe two or three), to minimize the cost of the onsite infrastructure required. Thus, the buses would need to be refuelled at different times throughout the day.

Once sufficient buses are housed at the depot to allow a steam reformer to be operated, supplies of liquid hydrogen to the depot would cease. The dewar for the storage of liquid hydrogen at the depot could then be removed, potentially to another depot, to be replaced by cylinders for storing compressed hydrogen.

5.3.2. *Onsite production of hydrogen via steam reforming of natural gas*

To supply 60 fuel-cell buses, the 3.4 tpd SMR plant has to run continuously at around 50% load. This would result in a reduction in the specific efficiency of the plant of about 5% compared with running at full load, i.e., 5% more natural gas is required per unit of H_2 produced. To provide the hydrogen required for 120 buses, the SMR unit would need

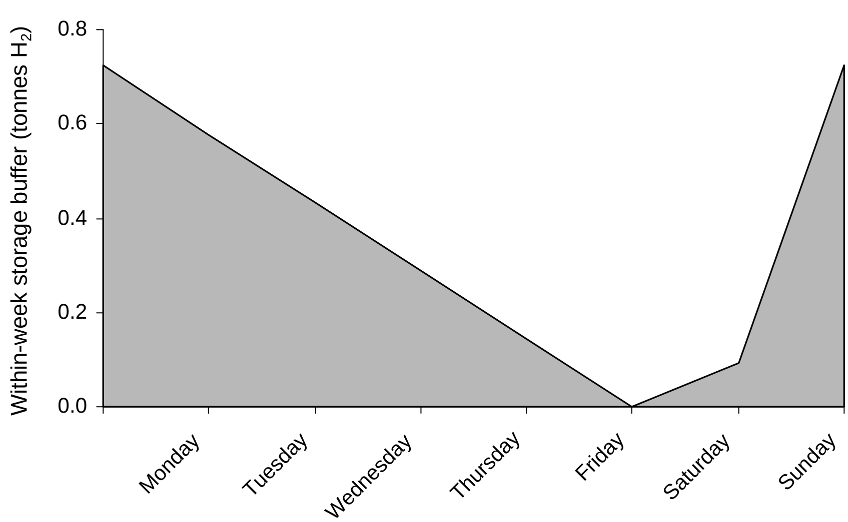

Fig. 3. On-site storage required to buffer demand for 120 buses.

Table 4
SMR production and efficiency according to daily requirements

	Weekdays	Saturday	Sunday	Weighed average	Constant daily rate
60 buses					
Hydrogen production (tpd)	1.7	1.6	1.3	1.6	1.6
Conversion efficiency (%)	69.7	69.4	68.5	69.5	69.5
120 buses					
Hydrogen production (tpd)	3.4	3.1	2.6	3.2	3.2
Conversion efficiency (%)	73.4	73.1	72.1	73.2	73.2

to be running at full capacity and would therefore operate at, or very close to, peak efficiency.

Applying the same rationale as previously, i.e., refuelling should take place as hydrogen is being produced, implies that bus refuelling should take place throughout the day, subject to this being possible in a logistical sense. This would also allow a reduction in the onsite compression and dispensing equipment, as fewer buses would need to be refuelled at any one time.

The difference between the hydrogen demand on the weekend compared with weekdays could either be accommodated by reducing production on the weekends, or by keeping production constant throughout the week and storing the weekend excess for use on weekdays. The storage capacity required to allow production to remain constant would be equivalent to 22% of 1 weekday's hydrogen demand, i.e., 0.36 t when supplying 60 buses or 0.72 t when supplying 120 buses. This stored hydrogen could also be used as backup for emergencies, and as a buffer to allow more flexibility in the timing of bus refuelling, although slightly greater capacity would also be required to also provide these services on the weekend. Variation in the volume of stored hydrogen, over a week is illustrated in Fig. 3.

The alternative to using within-week storage is to produce hydrogen according to daily requirements. This approach does, however, incur a slight efficiency penalty in the production of hydrogen. The production rates and consequent efficiencies under this approach are summarized in Table 4. As these results show, the overall efficiency benefits of maintaining a constant rate of production are minimal.

6. Conclusions

The main technical issues relating to the refuelling of fuel-cell buses at depots spring from the constraints of how the production technologies can be operated, especially in the case of steam reforming. Flexibility in the timing of vehicle refuelling means that relatively little storage capacity is required at the depot, as the buses themselves effectively act as a form of storage.

The technical issues related to the operation of SMR units and electrolyzers result in quite different infrastructure operation regimes and refuelling strategies. Technical constraints mean that SMR units should not be installed until there is sufficient demand for hydrogen to run it consistently at a minimum load of 30%. Also, because it is better to run the units at a constant level, to produce an even amount of hydrogen throughout a 24-h period. For this reason, in order to minimize storage requirements, buses should be refuelled throughout both day and night.

Technical issues cannot be divorced from the economics of hydrogen infrastructure. This is particularly true in deciding how electrolyzers might be operated, due to the dominance of electricity prices in determining the cost of the hydrogen produced. As a result, it is likely that hydrogen production via electrolysis would occur predominantly, if not totally, during the night. Consequently, bus refuelling would also occur predominantly during night-time hours, subject to any logistical constraints.

The choice of depots to house hydrogen buses will depend on a number of factors: the total number of buses serviced, the variation in vehicle-kilometres driven within each day, and the amount of space available at the depot for hydrogen infrastructure. A suggested penetration of buses into London depots is 60–70% in the near term.

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References

[1] D. Hart, et al., Hydrogen supply for SPFC vehicles, Energy and Environment Policy Research Group, Imperial College, ETSU F/02/00176/REP, 2000.

[2] The case for investing in London's buses—Presenting the results of the London Buses Strategic Review, Transport for London, UK, 2003 (available from http://www.tfl.gov.uk).

[3] Icelandic New Energy, Ectos—Why Iceland? http://www.newenergy.is/whyiceland.asp (accessed 14th September 2003).

[4] Green light to clean power—the Mayor's Draft Energy Strategy, Greater London Authority, UK, 2003 (available from http://www.london.gov.uk).

[5] C.E.G. Padró, V. Putsche, Survey of the Economics of Hydrogen Technologies, National Renewable Energy Laboratory, US Department of Energy, NREL/TP-570-27079, 1999.
[6] N. Eyre, M. Fergusson, R. Mills, Fuelling Road Transport, Department for Transport, UK, 2002.
[7] A. Amorelli, Personal communication, British Petroleum (BP), London, UK, 2003.
[8] A. Castillo-Castillo, The potential for hydrogen production in London utilising local waste resources, Department of Environmental Science and Technology, Imperial College London, UK, 2003.
[9] D. Winter, Personal communication, Air Products and Chemicals Inc., Hersham, UK, July 2003.
[10] J.C. Amphlett, R.F. Mann, B.A. Peppley, On board hydrogen purification for steam reformation/PEM fuel cell vehicle power plants, Int. J. Hydrogen Energy 21 (8) (1995) 673–678.
[11] D. Brett, Personal communication, Department of Chemical Engineering, Imperial College London, 2003.
[12] C. Machens, Personal communication, Vandenborre Hydrogen Systems, August 2003.
[13] G. Harman, Department for Planning and Infrastructure, Government of Western Australia, Sustainable Public Transport in Western Australia—an operational field trial of 3 Fuel Cell Buses in Perth: presentation given at H2002, Murdoch University, Perth, Australia, 2002.
[14] W.A. Amos, Costs of Storing and Transporting Hydrogen, National Renewable Energy Laboratory, US Department of Energy, NREL/TP-570-25106, 1998.