A SD-based analysis of the market for hydrogen fuel cell urban buses

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Abstract

The paper investigates the potential of urban transit buses to provide an early market for hydrogen proton exchange membrane fuel cells (PEM FCs) in road transport. System Dynamics has already been used to explore the transition towards the large scale use of hydrogen fuel cells in road transport as a whole. Given the importance of establishing early and niche markets first, on the route to mainstream markets, this paper focuses on one early market in road transport which is considered to be particularly important: urban transit buses. A System Dynamics model has been developed in order to address this particular market in detail. The model is currently still being refined; however results generated so far suggest that the market uptake of PEM FC buses will not be rapid and will require significant public support.

1 Background and introduction

1.1 PEM FCs in road transport and the role of niche/ early markets

Hydrogen-fuelled proton exchange membrane fuel cells (PEM FCs) offer a promising alternative to internal combustion engines (ICEs) in road transport, with the potential to significantly mitigate the issues of oil dependency, greenhouse gas emissions and urban air pollution currently associated with it (US DoE 2002; European Commission 2003).

Accordingly, PEM FC research and development (R&D) activities worldwide have been steadily increasing in recent years (Fuel Cell Today 2007). Moreover, several countries have also given themselves "roadmaps" and, in agreement with industry, are aiming to start commercialisation of this technology in the passenger car market by 2015-2020 (US DoE 2002; HFP 2005; NEDO 2006; US DoE 2006).

However, achieving commercialisation of PEM FCs in mainstream road vehicles crucially depends on overcoming a number of technological, market and infrastructural barriers. Firstly, the cost of PEM FCs needs to reduce by an order of magnitude while their durability, power density and efficiency all need to further improve. Secondly, a widespread hydrogen refuelling infrastructure needs to be in place for PEM FC cars to be adopted; however, there is no business case for developing a hydrogen infrastructure until there is actual demand for the vehicles; this is often referred to as a “chicken-and-egg” dilemma. Finally, public perception and consumer preferences also matter.

To overcome these barriers, sustained R&D efforts are necessary but not sufficient. It is widely recognised that, for PEM FCs to become competitive with ICEs in mainstream road vehicle markets, they will have to successfully penetrate niche/ early markets first (Agnolucci and McDowall 2007; HFP 2007). This would generate the learning effects and scale economies that are needed to bring costs and performances closer to those of the incumbent technology (Rogner 1998). Moreover, niche/ early markets can also allow prospective users to familiarise with the technology; hence they are also important in view of improving public perception and facilitating future adoption of the technology. In this context, while the formation of early markets for PEM FC outside road transport would undoubtedly be beneficial, due to the specific characteristics of road transport applications it only early road transport markets can bring the full benefits outlined above. Therefore, in this study we make a distinction between these two possible type of early markets, and we focus our attention on the latter type.

1.2 Why urban transit buses

In principle PEM FCs could be used to propel all types of road vehicles, from scooters to heavy-duty trucks. However, for technical and commercial reasons, PEM FC passenger cars and urban buses are the only types of vehicles that numerous OEMs worldwide have manufactured as prototypes or small series. It has to be mentioned that prototype PEM FC scooters and motorbikes have also been developed, and a PEM FC scooter jointly developed by Intelligent Energy and Suzuki (FCB 2009) is now on its way to commercialisation; however, there is little evidence of other OEM being involved in developing PEM FC scooters and motorbikes. At the other end of the spectrum of road vehicles there are heavy-duty, long-haul trucks. The main barrier here are the significantly shorter range that hydrogen PEM FCs can afford to this type of vehicles (conventional heavy duty trucks can cover up to 2,000 km on a tank of diesel fuel) and the relatively high efficiency achieved by truck diesel engines when operating at a constant regime which diminishes the advantages of PEM FCs for this specific application.

Urban buses instead are generally regarded as a potentially favourable early market for hydrogen fuel cell vehicles for the following reasons:

- Buses are usually operated by transit agencies which are publicly funded and have a remit towards societal welfare. Thus the adoption of alternatively fuelled vehicles can be mandated by local or regional policies and subsidisation schemes are relatively straightforward to implement.

- Unlike smaller vehicles, buses are relatively flexible in their construction and can easily accommodate diverse powertrain components as well as bulky fuel storage.

- Buses are centrally refuelled and maintained, which means that they require very limited infrastructure and suffer less from the chicken-and-egg problem than passenger cars.

- They have a high but constant daily utilisation, which allows for careful planning of fuel consumption and maintenance intervals

- They are operated by a limited number of drivers, which can be specifically trained at limited cost.

- They are highly visible to the general public and thus guarantee a good return on the investment in terms of image.

Because of these various reasons, several prototypes of hydrogen fuel cell buses have been built over the years and tested in numerous demonstration projects worldwide since the mid 1990s (Callaghan Jerram 2008). As a result of these activities, in October 2006 a "Hydrogen Bus Alliance" was formed (HBA 2006) which brings together cities and regions that are willing to commit to adopting hydrogen fuel cell buses on a large scale; key objectives of the Alliance are: to share information on hydrogen bus procurement and operation; to give industry a strong signal that the demand is there; to develop a strategy for joint activities (possibly also including joint purchasing) aimed at bringing hydrogen fuelled buses closer to commercialisation. The establishment of the Hydrogen Bus Alliance effectively indicates that hydrogen fuel cell buses are moving from demonstration to a pre-commercial phase.

Finally, it has to be stated that in principle a number of depot-based urban fleets of light-duty vehicles also share some of the characteristics outlined above for urban buses. However, the potential for introducing alternatively fuelled vehicles in light-duty vehicle fleets appears to have been overestimated in the past (Nesbitt and Sperling 1998) and the actual willingness to adopt alternatively fuelled vehicles is often limited, especially where previous trials have led to negative experiences (Clarke 2004). Moreover, unlike urban buses, the demonstration of PEM FC light-duty vehicles in real fleets so far has only been very limited. It is therefore clear that the light-duty vehicle market for PEM FC powertrains somewhat lags behind the urban transit bus market.

1.3 Aim and methodology of the paper

The aim of the study is to analyse whether urban transit buses have the potential to become a significant early market for PEM fuel cells in road transport, contributing to making this technology viability in the passenger car market. Due to the nature of the problem, involving feedbacks, accumulations and delays, the transition towards hydrogen-fuelled PEM FC road transport has already been tackled using System Dynamics concepts and modelling (Christidis, Hidalgo et al. 2003; Welch 2006; Green and Leiby 2007; Struben and Sterman 2008). However, these studies mainly addressed the mainstream market for passenger cars and not specifically niche/early transport markets, the importance of which has been discussed previously. Instead, we have used System Dynamics modelling in a previous paper studying the potential market for PEM FC auxiliary power units (APUs) for long-haul trucks (Contestabile 2009); in this paper we use the same approach to study the PEM FC urban bus market.

The structure of the paper is as follows. Section 2 defines the scope of the analysis in terms of the timeframe, the geographic dimension and competing technologies considered. Section 3 then discusses all main market and technology data, scenarios and assumptions used as an input to the analysis. Section 4 provides a brief description of the main modules of the market model used to support the analysis. Model results are analysed in Section 5. Finally, Section 6 provides conclusions on the market potential of PEM FCs in urban buses and formulates policy recommendations. At present the model is still being tested and refined, so result and conclusions are provisional.

2 Scope of the analysis

2.1 Potential market for hydrogen PEM FC powertrains on urban buses

The global urban transit bus market for hydrogen PEM FC powertrains has been so far largely driven by public policy. Demonstration projects have started as early as the mid 1990s; the first one in 1995 involved a fleet of 3 buses operated in Chicago and powered by Ballard fuel cells. These activities have since grown in numbers and single bus trials have progressively given way to small fleets. According to the latest FuelCellToday market survey, buses have to date been demonstrated in the US, Canada, Japan, China, South Korea, Iceland, Australia, Brazil and the European Union, with the latter leading in terms of the number of buses both manufactured and deployed (Callaghan Jerram 2008).

In Europe the EC-funded CUTE (Clean Urban Transport for Europe) project has been running between years 2003-2006 and has involved the deployment of a total of 27 Daimler Citaro hydrogen buses powered by Ballard fuel cells in 9 cities. The follow-up project HyFleet:CUTE allowed the same buses to continue running until 2008. As a result of the successful demonstration activities of the last few years, new public policy initiatives have been put in place in Europe which are providing further market drivers for hydrogen fuel cell buses. In particular, the establishment of the Hydrogen Bus Alliance (HBA) in 2006 has effectively marked the beginning of a pre-commercial market phase for hydrogen fuel cell buses; moreover, some of the municipalities that have participated in the CUTE project (Hamburg and London in particular) are now independently purchasing more buses in order to expand their fleets, while other European municipalities are acquiring buses as part of the new EC-funded demonstration project CHIC (Clean Hydrogen in European Cities).

Outside of Europe, significant hydrogen bus deployment activities are taking place in North America, and more are expected in the future. In particular, 20 hydrogen fuel cell buses have been introduced in Vancouver, British Columbia, for the 2010 Winter Olympics. Most importantly, in California regulation introduced in year 2000 by the Air Resource Board (ARB) mandates the demonstration and subsequent purchase of zero emission buses by transit agencies. Purchase requirements apply to transit agencies with a fleet of more than 200 buses and set the target of 15% of new buses purchased annually to be ZEBs (Zero-Emission Buses). In order to comply with the ZEB purchase requirement, transit agencies will have to introduce a progressively growing number of ZEBs in their fleet every year until the target is reached. However, due to the lack of commercially ready ZEBs, the date by when this will have to happen has been repeatedly postponed. The ARB is now carrying out a consultation process with the aim of setting new target dates by July 2012 at the latest. Until then, transit agencies are exempted from complying with the ZEB purchase mandate (ARB 2009; ARB 2010).

Despite uncertainties with respect to timing, however, it is clear that the ZEB purchase requirements will create a market for hydrogen fuel cell buses and therefore this makes California also a very important early market for these vehicles.

Significant activities have also been taking place in Asia, and particularly in Japan, South Korea and China. Hydrogen buses have been demonstrated in Beijing during the Olympic Games in 2008 and PEM FC bus prototypes are currently being developed in China. Demonstration activities have also been taking place in Japan for several years using Toyota Hino hydrogen fuel cell buses; numbers however have so far not significantly increased since the first demonstrations. South Korea has also recently joined these two countries, deploying four Hyundai fuel cell buses (Callaghan Jerram 2008). Overall, despite activities in Asia are not negligible, it appears that the market signals are currently not as strong as in Europe and California, therefore these markets will not be modelled as part of this study.

2.2 Competing powertrain technologies for urban buses

Apart from the conventional technology of diesel ICE buses, there are a number of alternative fuels and powertrain technologies currently being tested by municipalities in Europe and worldwide alongside hydrogen PEM FC buses and which also can contribute to making urban bus transport more sustainable. The main ones are:

- Diesel hybrid buses; diesel ICE buses equipped with an electric motor, batteries and/or supercapacitors for regenerative braking.
- Natural gas/ biomethane ICE buses.
- Hydrogen ICE buses; hydrogen-fuelled buses which use an internal combustion engine instead of fuel cells.

Of the three technologies, the diesel hybrid can be seen as the natural evolution of the conventional diesel bus technology. A hybrid powertrain has significant efficiency advantages over a conventional powertrain, particularly on a heavy-duty vehicle used in an urban driving cycle, as is the case of transit buses. It is expected that a diesel hybrid bus should be around 20-30% more fuel efficient than its conventional counterpart. Although diesel hybrid buses are still considerably more expensive than conventional diesel buses, they are now being commercialised by major bus manufacturers such as Daimler (with the Mercedes-Benz Citaro G BlueTec Hybrid bus launched in 2009) and are an important part of short-to-medium term emission reduction strategies of major transit agencies. London Buses in the UK for example is introducing a growing number of hybrid buses in the fleet, in view of only buying hybrids buses from 2012 onwards (GLA 2010).

Moreover, the hybrid architecture is being deployed in all latest generation PEM FC buses as well, such as the Mercedes-Benz Citaro fuelCELL-hybrid bus (FCB 2009). The advantages are several: not only this powertrain architecture allows to recover braking energy, it also allows to downsize the fuel cell and to use it in near steady-state conditions which contributes to significantly improving its durability. So hybrid bus powertrains represent both an important improvement relative to conventional diesel buses and a stepping stone towards new-generation PEM FC buses.

As for alternatively-fuelled internal combustion engine buses, those running on compressed natural gas (CNG) are particularly popular and have been tested and adopted by several transit agencies in Europe and elsewhere. (Ealey and Gross 2008) state that CNG buses account for around 50% of new bus sales in Western Europe. The European Natural Gas Vehicle Association (ENGVA) only reports figures on the current vehicle parc, not the market shares of CNG vehicles; these show that CNG buses of various types currently account for around 1.4% of the total transit bus parc in Western Europe; a similar percentage is reported also for the US (source: http://www.ngvaeurope.eu/statistical-information-on-the-european-and-worldwide-ngv-status). This suggests that although current market shares of CNG buses may be quite high, their level of penetration of the transit bus fleets are still fairly low due to the recent start to their introduction. However, numbers also vary significantly across municipalities, strongly influenced as they are by local policies. Overall it appears that CNG-fuelled buses are to play an important role in the short to medium term; this is because, if compared to conventional diesel buses, they offer lower lifetime costs (the capital cost is similar to that of a conventional diesel bus, but fuel costs are lower thanks to the fact that CNG is cheaper than diesel) with lower emissions of greenhouse gases (about 20% less than conventional diesel buses). All other options, including diesel hybrid buses, today offer more expensive carbon emission reductions than CNG buses and this makes the latter particularly attractive. However, in the long run the potential of other technologies to improve and become more efficient and less expensive than CNG is such that this technology is bound to be eventually outcompeted. For this reasons, despite its importance today, the CNG bus technology is not further examined in this report.

Hence, based on the reasons outlined above, the present study will only compare PEM FC buses to conventional and hybrid diesel buses.

2.3 Timeframe of the analysis

Since the aim of the study is to analyse whether urban transit buses have the potential to be a significant early market for PEM FCs in road transport, and since the target for initial mass market rollout of PEM FC cars is set around year 2015-2020, the analysis mainly focuses on this timeframe. However, in order to better assess the potential rate of penetration of PEM FCs in the urban bus market, the analysis and the modelling have been extended up to year 2030.

3 Market and technology data, assumptions and scenarios

This Section presents the key technology and market data, scenarios and assumptions that are used in the model and in the analysis of its results.

3.1 Market data and demand for hydrogen buses

According to the International Organisation of Motor Vehicle Manufacturers (OICA), total production of buses and coaches worldwide amounted to 702,672 units in 2008, 96,862 units of which manufactured in Europe[1]. The market study by (Ealey and Gross 2008) provides significantly different figures, suggesting that the total demand for buses and coaches was around 286,000 units in 2005 and expected to rise up to 352,000 units in 2010 mainly due to the rapid expansion of markets in Asia and particularly China; the Western European market is reported to be relatively stable, with a size of approximately 33,000 units. These numbers, which are considerably lower than those provided by the OICA, are inclusive of three main categories of vehicles: small buses (less than 45 passengers, used for a variety of purposes), transit buses and motor coaches, but exclude minibuses. The latter may explain the discrepancy with the OICA figures, at least partly. However, the discrepancy may also indicate that (Ealey and Gross 2008) provide a more conservative estimate of the market; for this reason we use figures from the latter study in the present report.

In (Ealey and Gross 2008), transit buses alone account for around 48,100 units in 2005 and 58,300 in 2010 worldwide. It is clear from this figure that the global transit bus market is relatively small. A breakdown by region of the global transit bus market is not available in (Ealey and Gross 2008), however (Callaghan Jerram 2008) reports that in the US the annual market for transit buses is in the order of 4,000-5,000 units; based on figures from the OICA, it is reasonable to assume that the European transit bus market has a similar size to the US market.

As discussed before, California and the municipalities that are part of the HBA (most of which are European) constitute the likely early market for hydrogen buses over the next decade or so. It is therefore necessary to further characterise these markets in order to be able to model them.

Hydrogen Bus Alliance

The HBA currently consists of the following 10 municipalities and regions: Amsterdam, Barcelona, Berlin, British Columbia, Cologne, Hamburg, London, South Tyrol and Western Australia. The HBA document “Strategy for 2010-2015 Alliance activities on hydrogen fuelled public transit buses” (HBA 2008) provides important information on both the size of the market for hydrogen fuel cell buses and the willingness to pay a premium for this technology by municipal transit agencies. The following information has been extracted or adapted from this document.

The 10 municipalities that are currently part of the HBA operate a total of 14,000 buses and, with an average lifetime of ten years, they on average purchase 1,400 buses per year. This therefore defines the size of the market within the HBA at least until 2015 or so. It is expected that more municipalities will join the HBA in the future, so the figure above provides a conservative estimate.

The municipalities that are part of the HBA are all committed to the adoption of hydrogen buses, which means they are prepared to pay a premium for these vehicles on the route to their mass commercialisation, under the assumption that hydrogen buses will eventually be economically competitive with conventional buses. Information from (HBA 2008) suggests that the number of buses that the municipalities would be prepared to adopt is a function of the capital cost of the buses (see Table 1 below).

[1] Source: www.oica.net

In reality the willingness to pay is a function of the estimated lifecycle cost of the buses over a defined amortisation period; lifecycle cost also includes fuel cell stack replacement cost and fuel cost. So a cost-demand curve would have to be based on relative annual cost of the fuel cell buses, not on the bus capital cost alone; however, the above figures constitute a useful starting point for building such a demand curve.

Price ($)	Willingness to adopt (number of buses)	Other cost assumptions
1.6 – 2 M	none	at this price (that is, the actual cost of H_2 FC buses as of 2008) only very few buses would be purchased, with the purpose of demonstrating technical feasibility
1 M	up to 100 buses in total (i.e.: 10 per city on average)	at this price the HBA municipalities would be willing to start adopting in small numbers, aided by the additional support of JTI funding
600,000	around 500 buses in total (i.e.: 50 per city on average)	this price corresponds to around $ 100,000 more than a diesel hybrid bus. Additional assumptions: lifetime cost of $ 50-100k for fuel cell stack replacement; hydrogen cost 5 $/kg or less

Table 1: Willingness to pay a premium for hydrogen fuel cell buses of HBA municipalities (extracted from (HBA 2008)).

<u>California</u>

In California as of 2009 there are 10 transit agencies that operate more than 200 buses, for a total of 6,800 buses (which constitutes about half of the total transit bus population in California). Assuming that the annual rate of replacement is 10% of the parc (which corresponds to an average bus lifetime of 10 years), the number of buses purchased every year by these 10 transit agencies is in the order of 680, and therefore the mandated 15% of new buses to be ZEBs corresponds to around 100 buses per year.

As the mandatory purchase requirement is deferred, a second-phase demonstration of 12 ZEBs will start in 2010, involving 4 transit agencies in the Bay area. Performance milestones and pre-established metrics for technology readiness are currently being discussed which would be linked with the ZEB mandatory purchase. The mandatory purchase is therefore expected to only begin once the ZEB technology is deemed to have reached commercial readiness (ARB 2009; ARB 2010). When the mandatory purchase begins (best case scenario is 2013), transit agencies will have 3 years to reach the 15% target (OAL 2009). Although a decision on linking mandatory purchase to commercial readiness is still to be made, this possibility suggests that transit companies in California will only be paying a relatively modest premium for the ZEVs that they introduce in their fleets. For the purposes of this study, we have assumed the definition of commercial readiness that California will adopt corresponds to the same maximum costs of buses, fuel cell stack replacement and hydrogen for which the HBA municipalities would be prepared to adopt a total of 500 FC buses (i.e.: capital cost of

FC bus: $600,000; FC stack lifetime replacement cost: $50,000-100,000; hydrogen cost ≤5 $/kg).

Based on the market data discussed so far, it appears that, despite the total size of the urban transit bus market in the US and Europe are comparable (around 4,000-5,000 units/year in both cases), Europe will lead as an early market for hydrogen fuel cell buses and California will follow suit, although on a smaller scale. Once these two regional early markets develop and lifecycle costs of the hydrogen fuel cell buses approach those of the conventional buses, adoption will begin in other regions and these vehicles will therefore start becoming mainstream. The market data presented so far are used, together with the cost data of the following Sections 3.2 and 3.3, to build a cost-demand curve for hydrogen fuel cell buses which is discussed in Section 4.2.

3.2 Cost and performance of diesel and diesel hybrid buses

Cost of conventional diesel buses

The purchase price of conventional diesel transit buses (typically over 10 metres long and weighing between 9-14 ton) varies significantly depending on the model and specifications; however, it is generally in the region of $100,000 to $300,000+ (Ealey and Gross 2008). In this study, in order to compare buses equipped with different types of powertrains, we assume a common bus platform for each of the types considered. Moreover, in order to be consistent with the HBA demand data (HBA 2008), we also use the HBA cost assumptions for conventional as well as diesel hybrid buses.

Accordingly, the conventional diesel bus is assumed to cost $400,000, of which we assume that $50,000 is due to the diesel powertrain. The whole bus except the powertrain would therefore cost around $ 350,000; this cost is assumed to be for a bus platform that is manufactured in at least 500 units per year; this is, according to industry sources, the minimum volume at which full scale economies in transit bus manufacturing can be realised.

So, when comparing different bus types, we will assume that the bus chassis and body are common and are manufactured in large enough numbers to enable full scale economies. The cost of different powertrain types are discussed in turn in this Section and in the following Section 3.3. However, economies of scale in the manufacturing of the different types of buses are addressed at the level of the powertrain, the cost of which also includes the installation into the common bus chassis platform.

Performance of conventional diesel buses

The fuel economy of conventional diesel buses is assumed to be in the order of 44 L/ 100 km, based on a driving cycle which is representative of the average conditions of the HBA municipalities (HBA 2008).

Cost of hybrid diesel buses

As the same bus platform is used, the cost of the diesel hybrid bus is defined as the cost of the conventional diesel bus plus the cost of the hybrid powertrain components; the latter essentially consist of electric motors, power electronics and batteries or supercapacitors (depending on the powertrain design). Prototype diesel hybrid buses have been tested in recent years in London and other cities worldwide. However, only recently these are being produced in series and commercialised by major bus manufacturers, as is the case of the new Daimler Citaro G BlueTec Hybrid bus.

Prototype diesel hybrid buses tested so far in London have been reported to cost up to twice as much as conventional diesel buses (De Napoli 2010). However, with mass production, the cost of the components of the hybrid powertrain and of their installation on the bus chassis should significantly decrease. The HBA report assumes that the cost of a hybrid diesel bus is $100,000 higher than that of a conventional diesel bus; so for the bus platform considered, the cost of a diesel hybrid bus would be around $500,000. Although over time the capital cost difference between a conventional and a hybrid diesel bus may further reduce, we will make the conservative assumption that the cost difference remains constant at $100,000 throughout the timeframe considered.

Performance of hybrid diesel buses

The fuel economy of a hybrid urban transit bus depends on the powertrain architecture, the vehicle size and weight and, crucially, the driving cycle. Significant improvements (up to 40% higher fuel economy) compared to conventional diesel buses have been reported in London as a result of the initial trials conducted (Transport for London 2006). The HBA report however is more conservative, assuming that the fuel economy of the diesel hybrid bus platform considered is around 34 L/ 100 km (i.e.: a 22.7% improvement over the corresponding conventional diesel bus). For consistency with the other data previously discussed, we will use the figures from the HBA report here.

3.3 Cost and performance of hydrogen PEM FC buses

Capital cost

There are essentially two ways of modelling future costs of PEM FC buses: a top-down approach based on OEM input on total costs of developing and manufacturing new bus technology, or a bottom-up approach which takes into account the cost of individual components as provided by supply-chain firms (HBA 2008). Here we will take the latter approach and model the hydrogen fuel cell bus costs as the sum of three separate main components:

- Bus chassis
- Hybrid drivetrain
- Hydrogen FC system (stack + balance-of-plant components + hydrogen tank)

The bus chassis is the same as that of conventional diesel buses; as already stated in Section 3.2, the cost of this component is assumed to be $350,000 and not to vary over time. The hybrid drivetrain is assumed to be the same as that of a diesel hybrid bus. This assumption is supported by the fact that the same drivetrain (i.e.: axles fitted with electric hub motors, lithium-ion battery packs and all electrically powered ancillary components) is used by Daimler for both its diesel hybrid and its fuel cell hybrid Citaro buses (FCB 2009). The cost of this component is assumed to be \$100,000. Finally, the PEM FC system is modelled endogenously; details of this are provided in Section 4.

Operating cost

Operating costs essentially consist in the following:

- Fuel cost
- Maintenance cost

Fuel costs are a function of usage (i.e.: the number of kilometres driven annually, which we assume to be the same as conventional buses), of the fuel economy of the bus and of the cost of hydrogen per unit weight or energy. Fuel economy is discussed in the next sub-section, whereas the cost of hydrogen fuel is addressed specifically in Section 3.7.

Maintenance costs consist of the following: a) ordinary powertrain and drivetrain maintenance costs; b) periodic replacement of the fuel cell stack.

Ordinary maintenance costs incurred during field trials of PEM FC buses (such as the CUTE project) have been reported to be very high, due to the novelty of the technology and also to complicated codes and standards (CUTE 2006; HBA 2008). However, it is expect that eventually these costs will decrease below those of conventional diesel buses, thanks to the fewer components and absence of moving parts in a fuel cell system. For this reason, ordinary maintenance costs are not accounted for in this study.

The need for periodically replacing the fuel cell stack is however a separate issue and one that is likely to be a major cost item over the lifetime of the bus. The expected lifetime of an automotive fuel cell stack today is much shorter than that of a bus and indeed of a diesel engine. The total cost of replacing fuel cell stacks over the vehicle lifetime is a function of stack durability and cost, both of which are modelled endogenously; therefore, the cost of maintenance associated with the replacement of the stack is also endogenously generated in the model.

Discussion of how durability of PEM FCs is modelled can be found in Section 4. However, it is important to note that durability crucially depends on various aspects of the FC system design as well as on its operating strategy. It is therefore not possible to define FC durability in absolute terms, but rather this important parameter should be put in the context of the specific FC system considered and how this is operated. In particular, FC systems on buses have much higher durability requirements than those used for passenger cars. And it is probably because they are made to last longer that FC systems for buses are generally reported to cost more than passenger car systems. In fact while a durability of more than 4,000 hours was demonstrated during the CUTE project by stacks onboard the Daimler Citaro buses, it is expected that new generation hydrogen buses will have the fuel cell stack guaranteed for around 10,000-12,000 hours (HBA 2008) and this will probably be possible by using more sophisticated (and hence more costly) stacks and balance of plant components. In the present study, however, we only model one type of fuel cell system, namely a generic automotive-type fuel cell system; therefore costs will be lower per kWh than the typical fuel cell system used onboard urban buses, but durability will also be shorter. This assumption is justified by the fact that at least some manufacturers will be using passenger car-type fuel cells also onboard buses; for example, Daimler uses two 80 kW B-class fuel cell modules together in the 160 kW fuel cell system of the new Citaro fuel cell bus.

Performance

As for performance of PEM FC buses, the most important parameter for the purpose of the present study is fuel economy. Fuel economy of the PEM FC bus is a function of the efficiency of the hybrid drivetrain and of the efficiency of the FC system. Modelling the fuel economy from the bottom up (i.e.: starting from the physical characteristics of the vehicle, the efficiency of its components and the driving cycle used) requires complex vehicle simulation software and is beyond the scope of the present study. Instead, we use data from (HBA 2008) linking the fuel economy of the bus with the efficiency of the FC; by interpolating the data points available we build a lookup function which is used in the model. The data points used are two: a) the demonstrated fuel economy of 10 km/kgH_2 for current PEM FC buses where the efficiency of the FC systems is 45%; b) the projected fuel economy of >12 km/kgH_2 for future PEM FC buses where the FC system is expected to reach an efficiency of 50%. Just like cost and durability, the efficiency of the FC system is also generated endogenously by the model.

3.4 Bus utilisation assumptions

The way the bus is operated clearly is important when calculating the relative economics of the different types of buses. In general urban transit buses are subjected to very heavy usage with very limited maintenance. In London for example conventional diesel buses are used for up to 18 hours/day for 364 days/year, which adds up to 6,552 hours of operation per year. Average bus speeds in London tend to be very low; if we assume an average speed of 15 km/h, this translates into more than 98,000 km/year. This usage level can be seen as an upper bound, and on average bus utilisation in London and elsewhere tends to be less extreme. Again, we will use the assumptions of the HBA study, which are 5,000 hours/ year and 75,000 km/year (hence, average speed of a bus is 15 km/hour); these are considered as representative of average usage patterns of transit bus fleets in the HBA cities. No data is available for the HBA cities on the average number of hours per day and number of days per year in which buses are used; so here we will assume that buses are used on average for 340 days/year, which corresponds to 14.7 hours/day or 220.6 km/day.

Another important parameter is the lifetime of the bus. Urban transit buses are generally expected to operate for 7 to 12 years (Callaghan Jerram 2008). In this study, for simplicity we assume the economic lifetime of the buses to be of 10 years.

3.5 Scenario for PEM FC R&D investment and early markets

Scenarios used here are the same already used in (Contestabile 2009). In brief, a baseline scenario is assumed where the global level of public and private investment on PEM FC technology remains constant on today's levels, i.e.: in the order of $2B/year. As for early markets for PEM FCs outside road transport, these are already starting to develop. Particularly promising are the stationary markets for micro-cogenerators of heat and power (μ-CHP) and for uninterruptible power supply units (UPS), which have been developing fast in recent years and show a positive outlook for the future. Smaller but also promising markets are niche transport applications, such as forklift trucks and light delivery vehicles, and portable generators, mainly for military uses. We have therefore developed a baseline scenario for early markets which is largely based on Fuel Cell Today survey available online (www.fuelcelltoday.com) and is also consistent with the EC targets for niche/ early markets (HFP 2005).

3.6 Cost of diesel fuel for buses

The crude oil price scenario on which we base the projections for the cost of diesel in Europe is based on the "high price" oil scenario of the US DOE (EIA 2006). Despite dating back to 2006, this scenario is remarkably consistent with average historical oil prices since then as well as with recent future projections. For example, the 2009 fossil fuel price assumptions used by the UK government for their analysis (DECC 2009) are characterised by a wide range of future oil prices, of which the scenario we have selected falls right in the middle.

In order to translate the oil price scenario into a scenario for the price of diesel fuel, we can vary the fraction of diesel price that is due to the price of crude oil while keeping the rest constant. The average price of untaxed diesel in Europe in 2008 was approximately 0.50 €/L, and the average price of taxed diesel was approximately 1 €/L (Eurostat 2008). Hence, the fraction of the price of diesel at the pump which is due to taxes in Europe in 2008 was around 50%. The cost of untaxed diesel can be broken down into the following components: crude oil 32.7%; refining 12.5%; distribution & marketing 4.8%. We can then translate the oil price scenario into a diesel price scenario for Europe by keeping all the contributions to the cost of diesel constant except for the oil price contribution.

3.7 Hydrogen refuelling infrastructure and cost scenarios

The type of hydrogen infrastructures that will develop in a given city or region and the corresponding cost of hydrogen delivered at the pump will depend significantly on the following factors:

- The local price and availability of feedstock for hydrogen production, and its spatial distribution
- The presence of existing hydrogen streams (for example as a by-product of industrial processes) and transport infrastructures (such as hydrogen pipelines as part of industrial complexes)
- The volume of demand, its spatial distribution and the rate at which it grows over time
- Policy directly or indirectly affecting the development of hydrogen infrastructures, and favouring specific routes over others

Despite all this uncertainty it is clear that, when choosing between all the infrastructure options that are potentially compatible with the given level of demand considered, lowest-cost hydrogen pathways will always be favoured.

In order to identify the most plausible hydrogen production and delivery options for the various levels of demand, and hence estimate the price of hydrogen as a function of demand, let us start by looking at the demand volumes associated with a growing number of buses.

Based on the fuel economy and bus utilisation discussed in Sections 3.3 and 3.4, it follows that the average daily hydrogen consumption of a fuel cell bus is in the order of 20 kg(H_2)/day. So this defines the minimum daily hydrogen demand that a transit bus depot can have. As more buses are introduced, one possible strategy is to initially base all of them in the same depot, in order to minimise the costs of refuelling and maintenance infrastructure. In particular, let us assume that, for each city represented in the model, the first 20 to 40 buses or so would all be located at the same depot. This means that initially the amount of fuel that is dispensed at a single depot would vary between the minimum of 20 kg(H_2)/day and a level of approximately 400-800 kg(H_2)/day. Then, as more hydrogen buses are introduced, new depots would begin to be converted and demand for hydrogen in each one of the depots would gradually grow. Eventually, when all new buses purchased are hydrogen fuel cell buses, demand would continue to grow in all these depots beyond the 1,000 kg(H_2)/day/depot mark.

In terms of optimum hydrogen infrastructures associated with these growing levels of demand, as said above, these will vary depending on a number of factors. However, for the purposes of our study we can restrict the attention to essentially two specific types of infrastructure which are generally most economic and assume that, where other hydrogen production routes or infrastructure architectures are adopted, these will have to be economically competitive with the two we choose as baseline.

The two types of infrastructures considered are the following:

a) Mobile refuelling infrastructure with liquid hydrogen delivery by cryogenic truck
b) On-site hydrogen production via reforming of natural gas

Mobile refuelling infrastructure has the advantage of having the lowest investment costs of all the available options, with very little equipment being put on the ground. Besides, its mobile nature makes it suited to being transported, if needed, in order to physically follow demand. The hydrogen would be produced by large-scale reforming of natural gas and liquefied centrally, which allows to realise significant scale economies; moreover, transporting hydrogen in liquid form is the cheapest option for relatively small amounts that are transported over long distances (Yang and Ogden 2007). The amount that a single truck can transport is however quite substantial, at around 4,000 kg (H_2), so this option is at least in theory viable up to fairly high levels of penetration of hydrogen buses into the urban transit fleet. One drawback of this approach though is that hydrogen liquefaction is a very energy intensive process; moreover, long-distance transport further adds to the costs. So, as soon as demand reaches a level whereby onsite hydrogen production becomes practically feasible, this could potentially provide a lower cost option.

In particular, the cost of hydrogen delivered by mobile infrastructure and based on its transport by truck as cryogenic liquid significantly depends on the level of the demand and on the duration of the supply contract. Assuming a conservative contract duration of 5 years, an estimate of the cost of hydrogen as a function of demand is provided in Figure 1 below. As can be seen, the cost per kg of hydrogen is expected to decrease quite significantly with volume, approaching the 4 €/kg(H_2) mark for volumes above 1,000 kg/day (which corresponds to depots operating more than 50 hydrogen buses) (HBA 2008).

Prototype small-scale reformers of natural gas have been tested as part of various demonstration projects worldwide. In Europe, a large amount of operational and cost data has been collected for this technology as part of the EC-funded project CUTE (Clean Urban Transport for Europe). The cost of hydrogen delivered using small-scale reformers as part of the project CUTE was generally very high, ranging between 9 and 22 €/kg(H_2); this was due to both the prototype nature of the infrastructure and also the very low levels of utilisation (each depot was operating up to 3 fuel cell buses). However it was also estimated that, as demand reaches the order of 1,000 kg(H_2)/day per depot and reformers are manufactures in sufficient numbers to significantly drive costs down (small scale reformers would benefit from significant learning effects and production scale economies), the cost of hydrogen delivered would drop to 4-8 €/kg (H_2) (CUTE 2006).

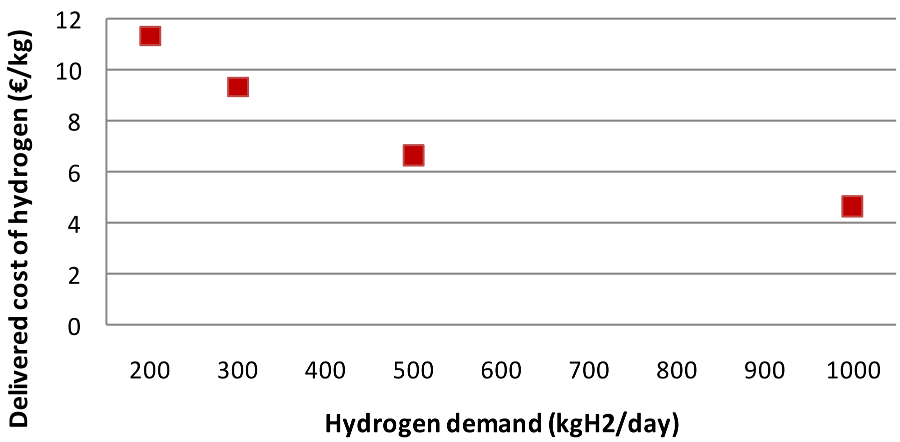

Figure 1. Cost of hydrogen at the pump as a function of daily demand. Case of mobile infrastructure and hydrogen produced from centralised reforming of natural gas and transported by truck in liquid form. Source (HBA 2008)

As demand grows further and adoption of fuel cell vehicles becomes more widespread, centralised hydrogen production and pipeline distribution infrastructures may start to develop, which would allow the cost of hydrogen delivered to further decrease. However, growing energy prices and the introduction of taxes on hydrogen may offset this further cost decrease and keep the price of hydrogen at the pump around this value; hence for the purpose of this study we will assume that the minimum price of hydrogen delivered is 4 €/kg over the whole timeframe considered, for any depot in which demand for hydrogen is 1,000kg/day or higher.

4 Market and technology model for powertrains

A causal loop representation of the model used in the study is provided in Figure 2. PEM FC attributes such as cost, durability, efficiency are a function of both cumulative R&D and cumulative production. They are modelled based on a learning curve approach. The learning curve has been calibrated in order for the cost, durability and efficiency to meet international R&D targets under the baseline scenario for R&D and early markets. In other words, this corresponds to assuming that if international programmes are funded as planned and are successful then their targets will be met. For more details see also (Contestabile 2009).

R&D investment is modelled exogenously. Exogenous early market uptake scenarios as well as the endogenous uptake of PEM FC buses (L1) contribute to driving cumulative production, but also provide scale economies. Loop 2 represents the effect that the size of the stock of PEM FC buses has of the further adoption of the technology: the more the buses in the stock, the more the experience of the adopters (i.e.: transit agencies), the more likely it is that new adopters will join in. This effect is usually referred to as "word-of-mouth".

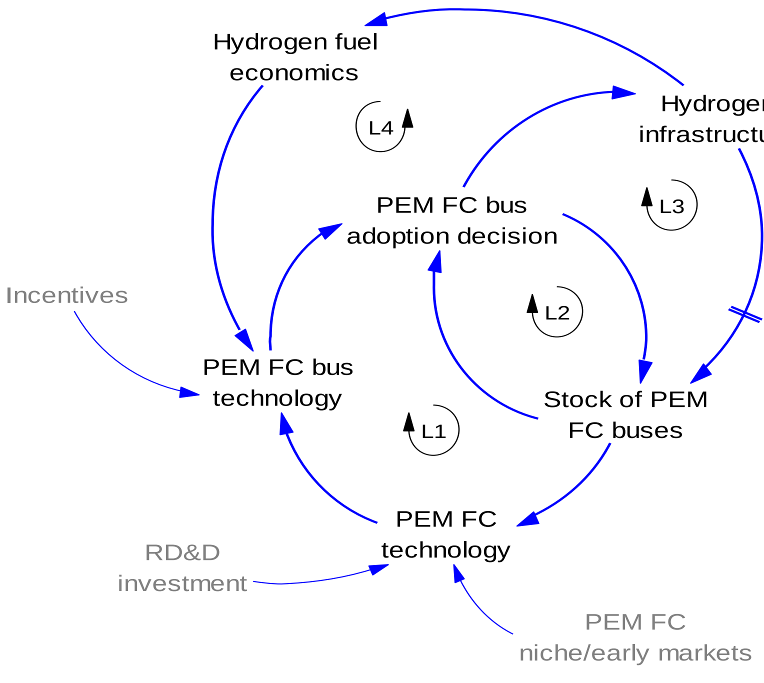

Figure 2: Simplified representation of the main modules of the general dynamic simulation model that are relevant to PEM FC buses. L1: loop linking the adoption of PEM FC buses to the development of the PEM FC technology; L2: link between the stock of PEM FC buses and the decision to adopt more of them (word-of-mouth); L3: loop linking the decision to adopt PEM FC buses with the build-up of refueling infrastructure; L4: Loop linking the development of the technology and its adoption with the cost of the hydrogen fuel.

The adoption of PEM FC buses relies on the presence of sufficient refuelling infrastructure, typically located within the bus depots where the PEM FC buses are based. When additional refuelling infrastructure is required to support the adoption of further PEM FC buses, the infrastructure needs to be built before the buses can actually be deployed and this can introduce delays in the adoption process. This feedback loop and related delay are represented by Loop 3 (L3) in Figure 2. Moreover, not only the capacity of the refuelling infrastructure physically constrains adoption wherever demand for hydrogen fuel exceeds supply, but it also indirectly affects adoption via the impact is has on the economics of PEM FC buses. As discussed in Section 3.3, the economics of PEM FC buses can be broken down into capital and operating costs; a component of the latter is fuel cost. The cost of hydrogen fuel at the pump in bus depots is a function demand volumes, particularly so in the early phases of the adoption process; this relationship and possible cost scenarios were discussed in detail in Section 3.7. Loop 4 represents the feedback mechanism linking the growing scale of the hydrogen infrastructure with the decreasing cost of operating the buses, which in turn positively influences adoption.

The following Sections expand on the details of key modules of the model.

4.1 Module representing the stocks of conventional and PEM FC buses

A schematic view of the module representing the stocks of conventional and PEM FC buses is provided in Figure 3 below. This shows that when new buses are needed, as a result of the retirement of old ones or because of an expansion in the size of the fleet, then bus operators are faced with the decision of what type of bus to buy. For the reasons already explained in Section 2.2, the choice in the model is restricted between conventional (i.e.: diesel hybrid) and PEM FC buses. Further details of the decision process are provided in the following Section 4.2. If the bus fleet operator decides to satisfy the need for new buses by purchasing a certain number of PEM FC, the procurement of the buses goes ahead provided that the refuelling infrastructure already present at the bus depots is sufficient to support them. If this condition is satisfied then the procurement is carried out and the buses are introduced in the fleet, subject to the usual lead time between placing an order and receiving the bus which is characteristic of the industry. If however the hydrogen refuelling infrastructure at the depots is not sufficient and needs expanding, the relevant procedures are activated and the infrastructure will be built. This however introduces further delays. Because of the need to keep the bus fleet running, all demand for new buses which cannot be satisfied with PEM FC buses in a timely manner is met by buying additional conventional buses.

4.2 Module on the adoption decision process

The adoption of PEM FC buses in the model is determined by the preference that bus operators have for these buses over conventional ones. This can be represented as follows:

Preference of bus operators for PEM FC buses [0, 1] = response to relative economics of PEM FC buses [0, 1] x response to relative performance of PEM FC buses [0, 1] x response to word-of-mouth/ indirect experience of PEM FC buses [0, 1].

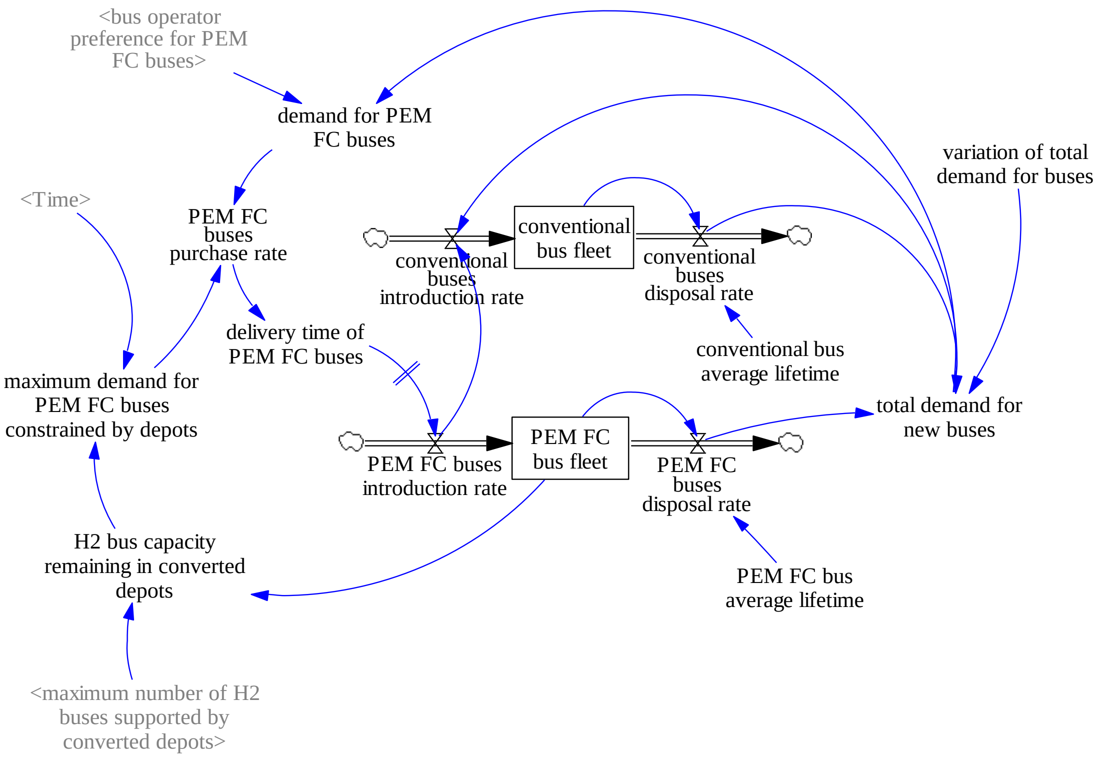

Figure 3: Schematic representation of the module on the stocks of conventional and PEM FC buses within the fleets considered.

So the preference of bus operators for PEM FC buses over conventional ones is a function of three relative factors. The three factors are briefly discussed in turn below. The overall preference is expressed as a number comprised between 0 (which indicates 100% preference for diesel ICE buses and no intention to adopt PEM FC buses at all) and 1 (indicating 100% preference for PEM FC buses and intention to only adopt this type of buses). A similar logic applies to the individual factors, which are also expressed by a value comprised between 0 and 1.

<u>Response of bus fleet operators to the relative economics of PEM FC buses</u>

Because urban bus operators have good knowledge of how their buses are operated and for how many years, it is expected that they make a rational economic decision when procuring new buses. Unlike for example passenger car users, who are known to mostly consider capital costs and discount operating cost very heavily when deciding to buy a new car, bus fleet operators should consider the total costs of ownership of the different bus technologies available when deciding which one to adopt. Hence, in our model we assume the following: when the capital cost of PEM FC buses is less than 50% higher than the capital cost of a conventional bus, then the response of bus fleet operators to the economics of a PEM FC bus is a direct function of its relative annual cost. In other words, the relative preference of bus operators for PEM FC buses is a function of the ratio between the total (i.e.: capital and operating) annualised cost of a PEM FC bus and the total annualised cost of a diesel ICE bus. In particular, we assume that when the ratio is one (i.e.: the total annual cost of a PEM FC bus and that of a diesel ICE bus are the same) then the bus fleet operator will only want to adopt PEM FC buses, at least based on economics. Then we use the relevant HBA demand data previously presented in Section 3.1, and by interpolating we obtain the demand curve of Figure 4 below.

However, based on the HBA data (which are summarised in Table 1 above), it is evident that for high values of the capital cost of the PEM FC buses this parameter becomes important in itself. In other words, if the purchase price of PEM FC buses is at least 50% higher than that of diesel ICE buses or more, then the willingness of HBA municipalities to pay for PEM FC buses becomes a function of the capital cost alone and not of the total annualised cost. Again, based on the HBA data points and interpolating where needed, we have derived a cost-demand function for PEM FC buses which is solely based on their capital cost (see Figure 5 below).

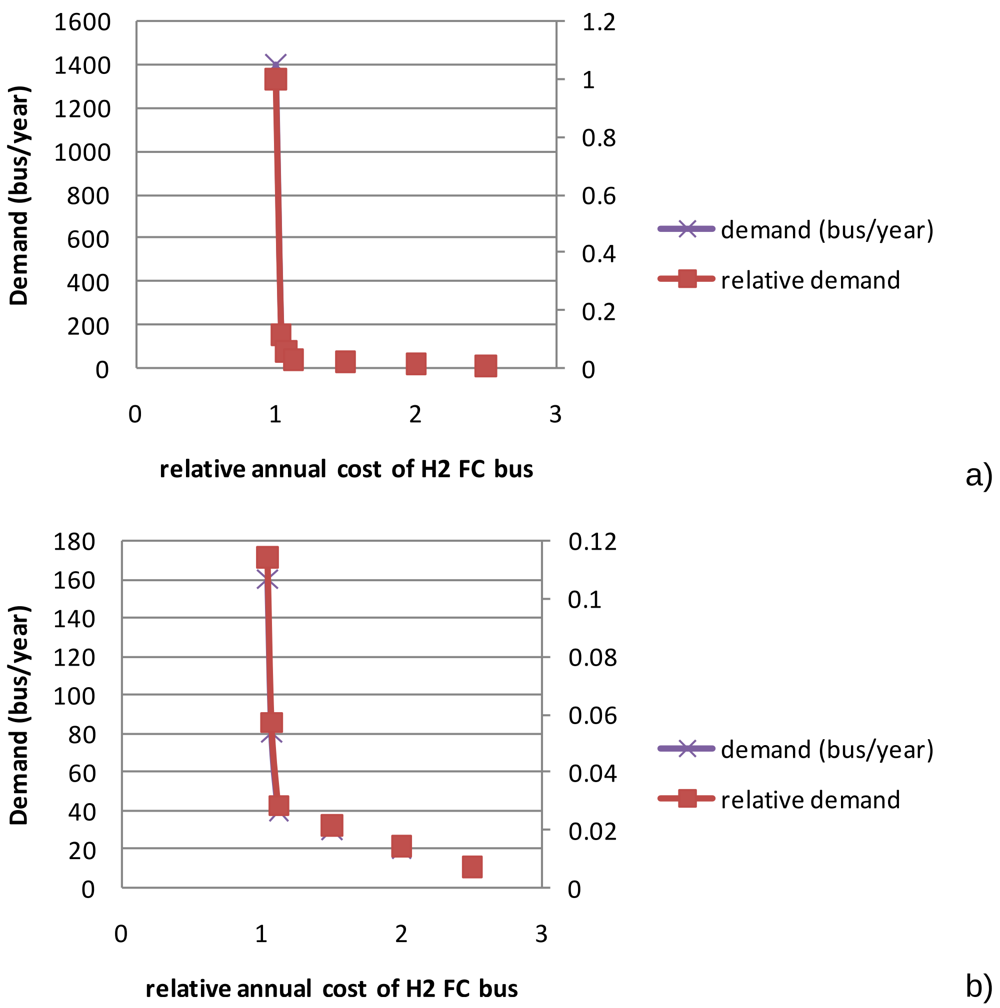

Figure 4: Demand as a function of relative total annual cost of PEM FC buses. a) shows the curve in its entirety, with PEM FC buses reaching cost parity with diesel PEM FC buses; b) offers a magnified view of a particular part of the curve.

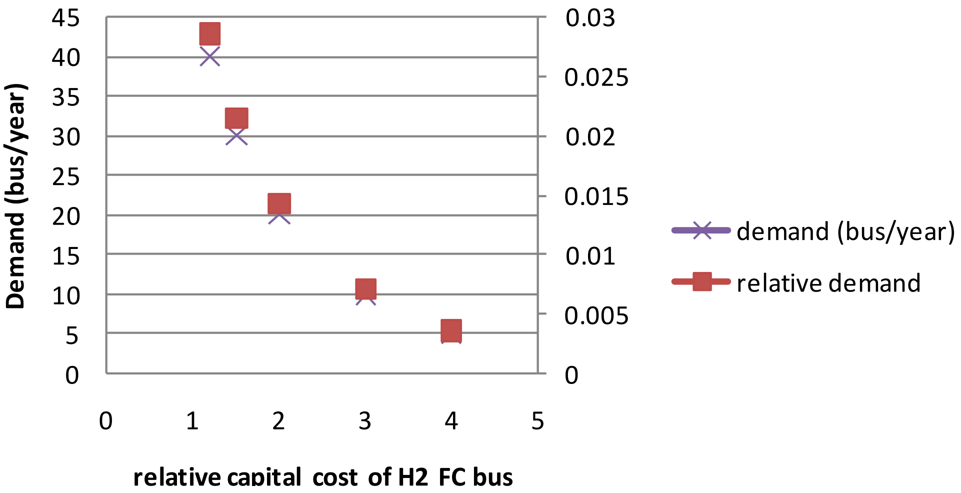

Figure 5 Demand as a function of relative capital cost of PEM FC buses

In the model, the response of the bus fleet operator to the relative economics of PEM FC buses is based on the cost curve of Figure 4 when the relative capital cost of the PEM FC bus is lower than 1.5 and on the cost curve of Figure 5 when it is equal to 1.5 or higher. Finally, it is important to note that the bus demand numbers shown in the figures above are only relative to the HBA municipalities. However, the analysis will also account for California and the rest of the global transit bus market.

Response of bus fleet operators to the relative performance of PEM FC buses

Key performance parameters which we have considered for PEM FC buses in the model are: start-up time, reliability and power density of the PEM FC powertrain (if this is too low it affects the weight and volume of the bus). Minimum acceptable values have been set for each one of these parameters. For performance parameter values which are at least matching the minimum acceptable value the model returns a value of 1, which corresponds to 100% positive response to PEM FC buses by fleet operators. For performance parameters values below the minimum acceptable levels the model returns a value of 0, which means that fleet operators will not adopt PEM FC buses at all because these don't meet their minimum technical specifications.

Response of bus fleet operators to "word-of-mouth" on PEM FC buses

We assume that the level of familiarity of potential adopters with PEM FC buses is a function of the relative presence of PEM FC buses in the existing stock of urban transit buses. Moreover, we assume an arbitrary information delay of 1 year, which is the time that it takes fleet operators to receive, assimilate and act upon information on PEM FC buses being used by other fleet operators worldwide.

4.3 PEM FC bus technology module

Cost reductions and performance improvements of the PEM FC bus technology is largely dependent on the development of the PEM FC technology itself, which in turn is driven by the growing cumulative RD&D investment and production of the technology. Moreover, production costs of PEM FC systems can be significantly driven down by scale economies. So at each point in time the model calculates the unit cost of a PEM FC system based on cumulative RD&D efforts, cumulative production and also on overall demand volume.

However, the cost of a PEM FC bus not only depends on the cost of the PEM FC system, but also on the costs of the hybrid powertrain components; these are the same for diesel ICE hybrid buses and PEM FC buses; assuming that the former are produced in large enough numbers from the onset, we can ignore economies of scale for these components and keep their cost constant.

In any case it is worth noting that full economies of scale for bus manufacturing are already achieved at very low volumes (i.e.: around 500 units per year per manufacturer) and that, unlike passenger cars, transit buses tend to be manufactured in the same region where they are sold (Ealey and Gross 2008). So if we assumed that only one manufacturer would supply PEM FC buses in the whole of Europe, based on the cost-demand data of Table 1, full scale economies could be reached relatively rapidly if the market takes up; so the need for the bus manufacturers to absorb the additional costs of manufacturing that are not accounted for in this study would be relatively limited. It is also for this reason that we deem the modelling approach taken for the cost of PEM FC buses acceptable.

4.4 Hydrogen refuelling infrastructure build-up module

Finally, when describing the overall structure of the model we already mentioned that the development of the hydrogen infrastructure that is required to refuel the PEM FC buses is an important part of the problem. Not only the scale of the infrastructure and its utilisation determines the economics of the hydrogen fuel and therefore of operating the PEM FC buses, but the need to expand the infrastructure as increasing number of PEM FC buses are introduced in urban fleets also creates delays and hence affects the rate of their uptake.

Figure 6 below provides a schematic view of how the hydrogen refuelling infrastructure for PEM FC buses and its build-up process are represented in the model. Conversion of new bus depots to hydrogen is driven by the introduction of additional PEM FC buses and it can follow different strategies. An example of a plausible strategy was discussed in Section 3.7. The model allows to experiment with different depot conversion strategies, particularly varying the number of buses per depot at which new depots are converted. When a new bus conversion does take place, the model accounts for the time needed to obtain planning permission first and then to build the hydrogen refuelling station inside the depot. We have assumed that each one of these steps requires on average 6 months, thereby introducing an overall delay of one year to the adoption of new PEM FC buses where a depot conversion is also needed.

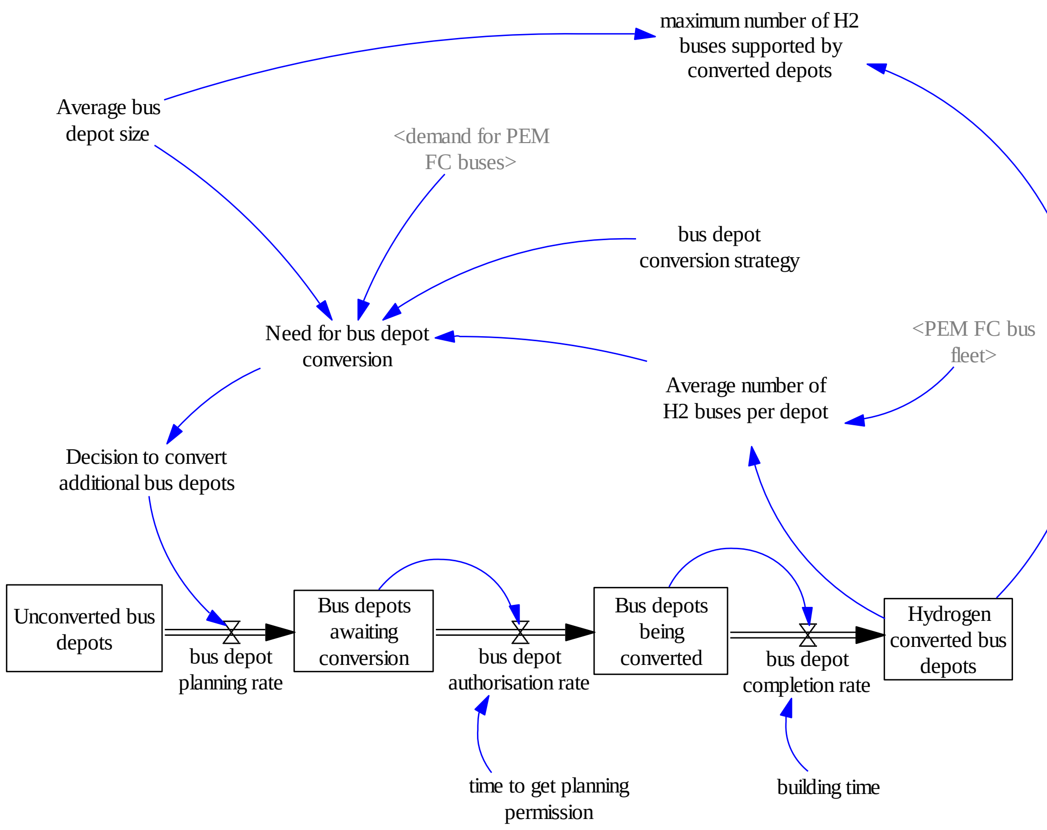

Figure 6: Schematic representation of the module on hydrogen refuelling infrastructure at bus depots and its development as driven by demand

5 Model results and discussion

Simulating the model under baseline conditions, it is quite clear that the capital cost of the PEM FC buses is the dominant factor in their initial uptake. As early markets develop, economies of scale in PEM FC manufacturing are realised and the capital cost of PEM FC buses decreases as a result. So HBA municipalities are expected to adopt the buses according to the cost-demand data of Table 1. Initially the PEM FC buses would be adopted in small numbers for demonstration purposes. However, as soon as the capital cost of the bus drops below 1.5 times that of a conventional bus, municipalities would start considering moving towards a pre-commercial phase and adopting growing numbers of buses. It is at this stage though that potential adopters would start considering the total costs associated with owning and operating PEM FC buses, and not only their capital costs. In the baseline scenarios the operating costs are dominated by the cost of hydrogen fuel. Because demand is low, the hydrogen is expensive and therefore the buses would be so costly to operate that no further adoption would occur. The fact that no significant adoption occurs, on the other hand, prevents hydrogen demand volumes to grow up to a point where the cost of hydrogen becomes competitive. Unless an external intervention or a significant change in overall market condition occurs, the PEM FC buses would remain in the demonstration phase indefinitely. The result of the baseline run is shown in Figure 7 below.

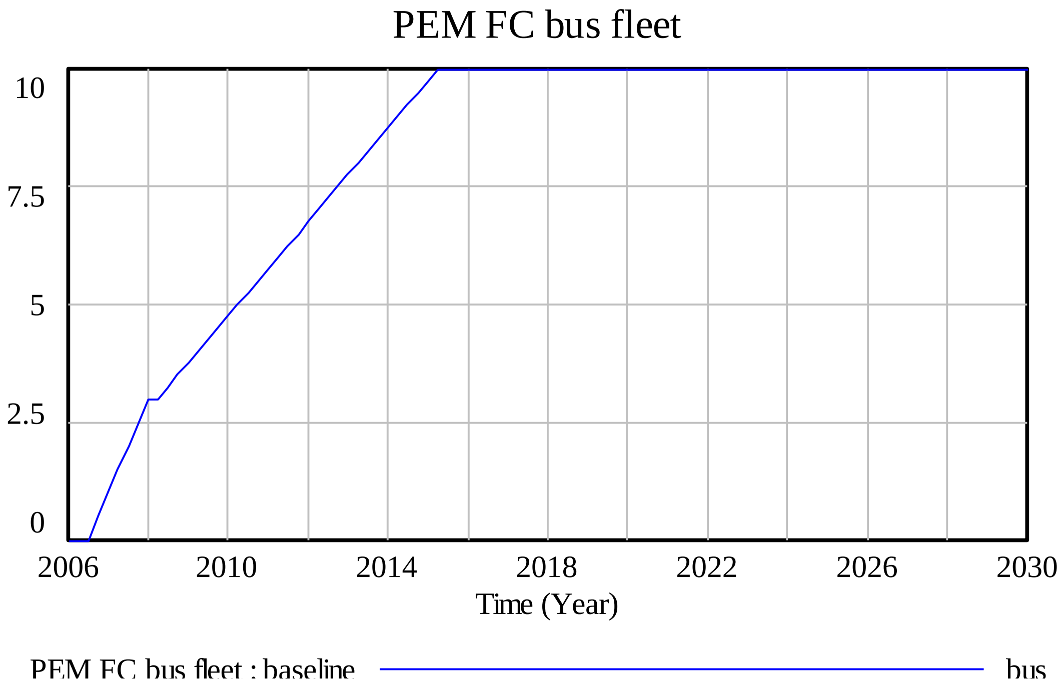

Figure 7: Development of the stock of PEM FC buses over time in the HBA cities under the baseline scenario

In order to overcome this hurdle, we have initially tested scenarios involving various levels of subsidisation of the cost of hydrogen at bus depots. The idea is to set the price of hydrogen to the bus fleet operator to a given level. The subsidies would cover the difference between the actual cost of delivering the hydrogen and its set price. The policy allows demand for hydrogen to grow, as more buses are introduced. This in turn means that the differential between real cost and subsidised price of hydrogen diminishes over time, until it reaches a point where subsidies are no longer needed. Figure 8 shows the impact of different levels of subsidisation on the uptake of PEM FC buses. It appears that very high levels of subsidisation would indeed be required, under baseline condition, for the uptake of the buses to proceed rapidly. The very high level of subsidisation in Figure 8 corresponds to setting the price of hydrogen at the bus depot to 2 €/kgH2 from the onset.

However, it must also be noted that the oil price and gasoline taxation levels in the baseline scenario are rather conservative. It is therefore worth exploring the effect that more optimistic assumptions for these two parameters would have on the need for subsiding hydrogen at bus depots. Figure 9 shows the results of: a) a scenario where oil prices are twice as high as in the baseline scenario; b) a scenario where diesel taxation is twice as high as in the baseline scenario; c) a scenario where a low level of hydrogen subsidisation is added to high oil prices and high diesel taxation.

It is quite clear from Figure 9 that, although these more favourable conditions allow the uptake of PEM FC buses to go beyond just demonstration, the overall effect is practically negligible if compared with scenarios of high hydrogen price subsidisation.

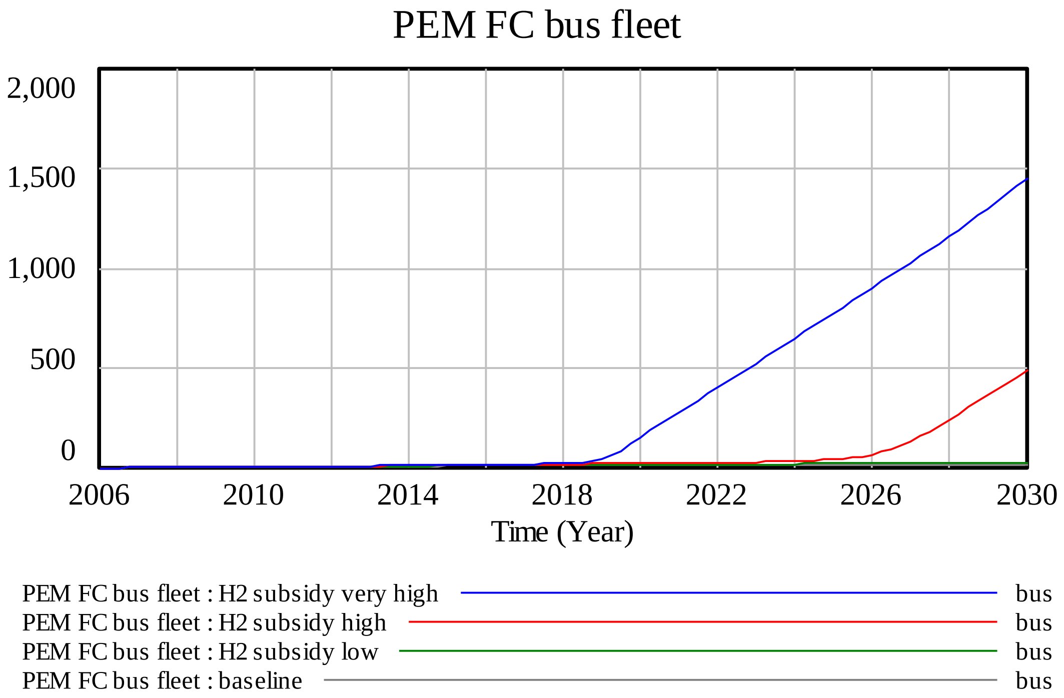

Figure 8: Development of the stock of PEM FC buses over time in the HBA cities, under different levels of hydrogen price subsidisation

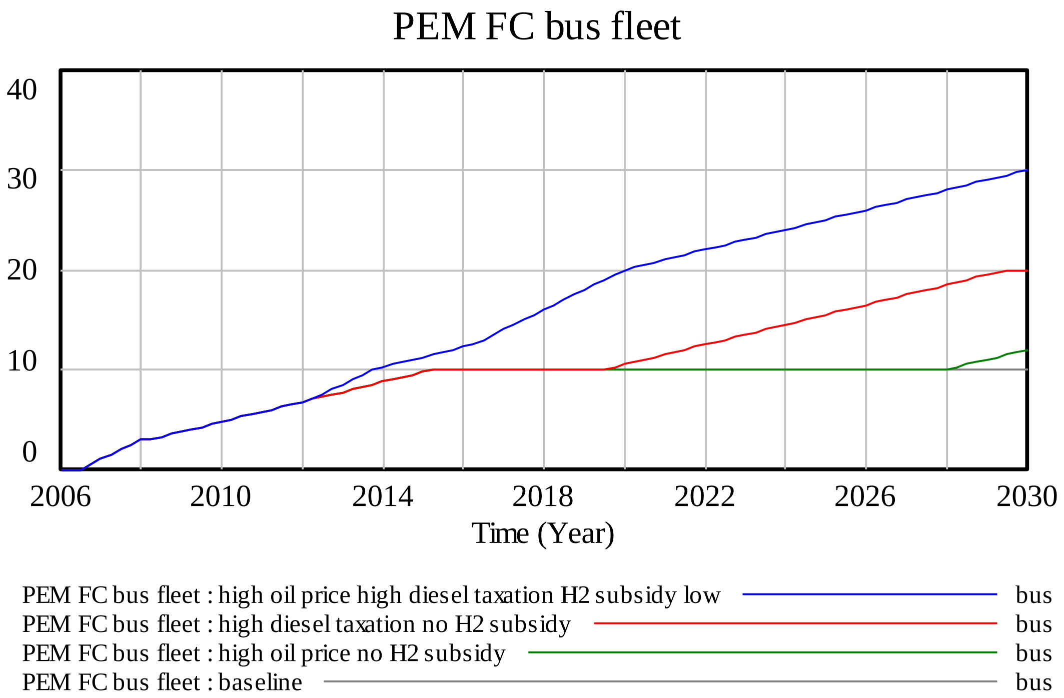

Figure 9: Development of the stock of PEM FC buses over time in the HBA cities under high oil price and high diesel taxation scenarios.

Another option worth exploring is the possible effect of subsidising the capital cost of PEM FC buses and whether it can speed up their adoption significantly. The results of the introduction of this additional subsidy can be seen in Figure 10. Essentially the capital cost subsidy has the effect of shifting the adoption curve towards the left. In particular, a 50,000 €/bus subsidy shifts the adoption curve by 2 years earlier in time, however it does not influence the overall dynamics of the adoption process very significantly. This suggests that capital cost subsidies for PEM FC buses are overall not particularly effective in order to promote the uptake of the technology in the long term.

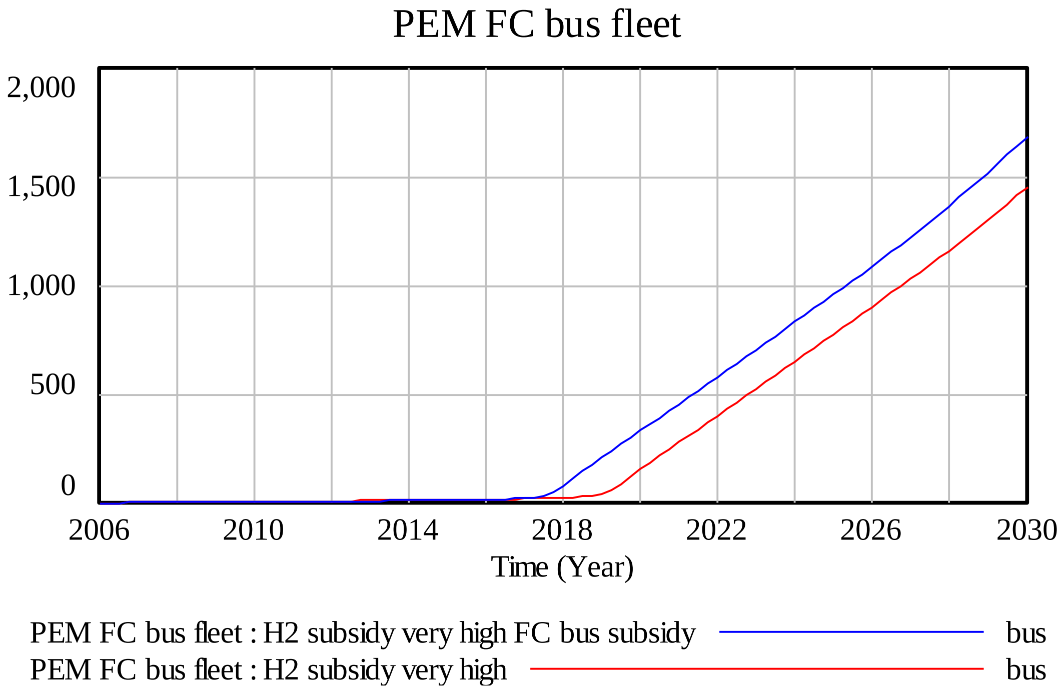

Figure 10: Development of the stock of PEM FC buses over time in the HBA cities under a very high level of hydrogen price subsidisation, with and without an additional subsidy on the capital cost of the PEM FC buses

Finally, we have also considered the effect that changes in early market development or RD&D funding may have on the uptake of PEM FC buses. The baseline scenario is quite optimistic because it assumes that the current level of RD&D for hydrogen and fuel cells will be sustained, and that early markets will develop according to the scenario outlined in Section 3.5. However, the possibility exists that either one of these conditions may not be verified; hence the consequences of such a possibility should be assessed.

Figure 11 shows the impact on PEM FC bus uptake of each one of these factors in isolation, in presence of a very high level of hydrogen price subsidisation. In particular, both the level of RD&D funding and the development of early market scenarios are reduced by half, compared to the baseline scenario. As the figure shows, the impact on PEM FC bus uptake is significant; however neither occurrence significantly alters the dynamics of the uptake process. However, the role of early markets appears to be comparatively more significant than that of R&D in the uptake rate of PEM FC buses.

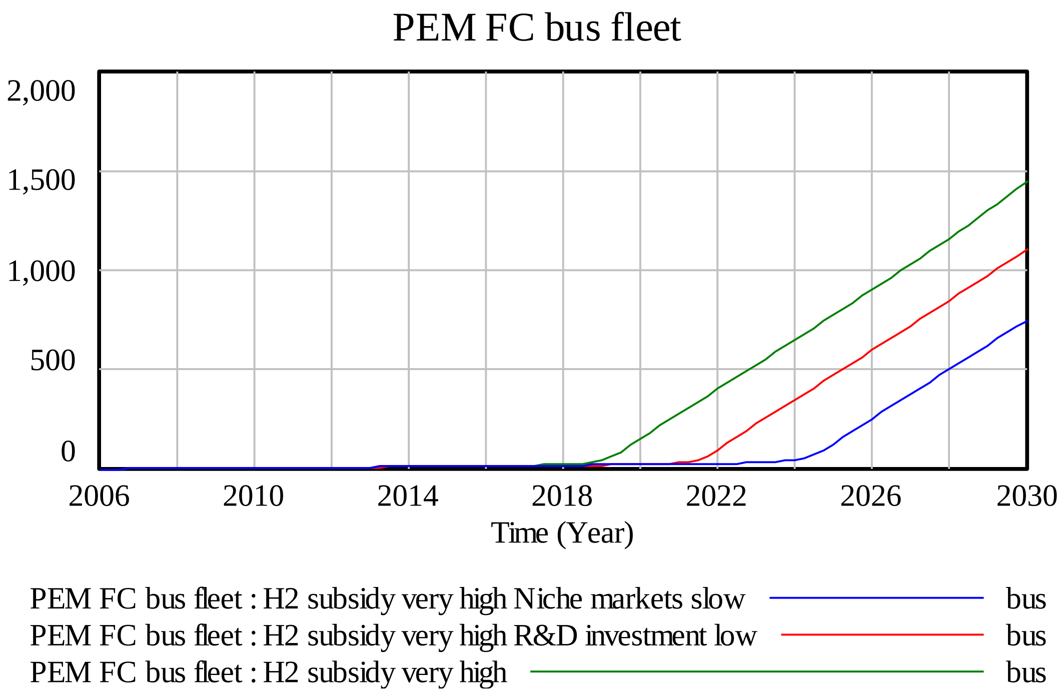

Figure 11: Development of the stock of PEM FC buses over time in the HBA cities, under very high level of hydrogen subsidisation and in cases where either R&D investment or niche market development are significantly lower than in the baseline scenario

6 Conclusions and recommendations

The transit bus market is generally regarded as a promising early market for PEM FCs in road transport and various initiatives are taking place aimed at supporting it, particularly in the EU and in California. However, the global transit bus market is relatively small, in the order of 60,000 units per year, with the EU and the US together accounting for approximately 10,000 buses per year. It is therefore clear that we cannot solely rely on the successful penetration of this market in order to achieve full scale economies in PEM FC manufacturing; instead other early markets, possibly also outside road transport, need to develop in parallel.

Initial results from the model simulation suggest that even reaching the full potential of the PEM FC urban bus market will require time and will probably not happen before 2030, even under the most favourable conditions. Initially the main barrier is the high capital cost of the PEM FC bus. However, thanks to the continuing R&D efforts and successful development of other early markets, in the baseline scenario the cost of the PEM FC bus rapidly reduces and makes this technology potentially commercially viable relatively early on. It is at this point though that the high cost of hydrogen fuel completely blocks further adoption under baseline conditions, because it makes the total annualised cost of PEM FC buses significantly higher than that of diesel hybrid buses. One possible strategy to overcome this barrier is to offer an initial subsidy on the price of hydrogen, so as to cap it at a level which makes the PEM FC bus competitive. As adoption of PEM FC buses takes place, the cost of hydrogen will then decrease and so will the subsidy, which will eventually be no longer needed. Even so, the uptake of PEM FC buses is expected to be a slow and expensive process, compared to the development of other early/ niche markets. These conclusions and recommendations however are provisional as the model is still being tested and refined.

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