The possible future development of a market for PEM fuel cell road vehicles – A SD based analysis within an EC funded project

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Abstract

Hydrogen fuel cells are increasingly seen as the propulsion technology of the future for road transport. However, despite the potential of this technology to reduce the environmental impact of road transport and to improve energy efficiency, both technical and economic barriers need to be overcome for it to be successfully introduced in mass markets.

At Imperial College we are currently undertaking an analysis of the possible future dynamics of the PEM fuel cell market for road transport in Europe. This study is part of an EC-funded, Integrated Project involving 18 partners from both industry and academia; this allows extensive interaction with key market players.

This paper presents a dynamic simulation model which addresses all main feedback loops influencing the market introduction of PEM fuel cells in road transport applications in Europe, with a particular emphasis on modelling the effects of cumulative production and R&D on technology attributes.

Keywords: hydrogen; fuel cell; road transport; AFV

1. Introduction

The project "HyTRAN – Hydrogen and Fuel Cell technologies for Road Transport" (2003) is an integrated project co-funded by the European Commission under the Framework Programme 6. It involves 19 partners from both industry (OEMs and suppliers) and research (research institutes and universities) across 7 European countries. The overall aim of the project is to advance the PEM fuel cell[1] technology towards a commercially viable solution in terms of performance and cost. Main current technological bottlenecks are addressed by developing specific components and sub-systems and by testing them in two innovative fuel cell systems: an 80 kW direct hydrogen fuel cell powertrain[2] and a 5 kW diesel reformed gas fuel cell Auxiliary Power Unit (APU)[3]

The study presented in this paper is carried out as part of the project HyTRAN. Its objectives are:

- To evaluate the contribution of HyTRAN in bringing PEM fuel cells closer to market
- To assess key areas of cost reduction and performance improvement for the technology
- To make recommendations on adequate policy measures and instruments which can favour its market uptake in road transport applications

In order to achieve these objectives, the study addresses the dynamics influencing possible future market introduction of PEM fuel cell-powered road vehicles. In particular, we investigate the effects of the main attributes of the PEM FC-based technologies, of the incumbent technologies and of market conditions in general on their large-scale, commercial introduction.
Given the R&D nature of the project, the emphasis here is on the dynamics influencing the development of the technology; however, all dynamics relevant to the market introduction of the technology are also considered.

The problem of market penetration of the technology under study is addressed by developing and using a system dynamics simulation model. This is constructed based on the perspectives brought by the project partners, on previous similar work done and models developed at Imperial College and, where necessary, on relevant literature. It provides a learning environment where interactions among factors and their sensitivity can be analysed, and possible alternative scenarios tested. This also allows performing policy analysis as required.

This paper starts with a brief discussion of the current status of the PEM fuel cell technology and its perspectives for large-scale market adoption in road transport. The

[1] A PEM (Proton Exchange Membrane) fuel cell is an electrochemical system capable of generating electrical energy when its anode and cathode are fed by hydrogen and oxygen gas respectively. They use a proton-conducting membrane as electrolyte, operate at temperatures around 80 °C and, also thanks to the potentially high power density of the system, are currently seen as the most promising type of fuel cell for road transport applications (Hamann et al. 1998).

[2] A vehicle's powertrain consists of all the components that generate power and deliver it to the road surface. This includes the engine, transmission and final drive (Wikipedia 2006)

[3] A vehicle's APU is a small generator that provides power for various purposes when the vehicle is idle

methodology of the study is subsequently outlined. The boundaries of the model are then discussed, followed by a description of the main dynamic structures characterising the problem. Finally, model validation and expected results are discussed.

To date we have constructed the model and it was then reviewed by project partners in a workshop. Data assimilation and scenario building are underway. In parallel, the model is being tested and refined. Results will soon be generated, analysed and discussed with partners in a dedicated session. This will suggest areas for improvement of both the model and the input, and further refinements will be made in an iterative fashion until the desired results are achieved. The study is expected to be completed early in 2007.

2. PEM fuel cell technology – status and perspectives

Hydrogen fuel cells are increasingly seen as the propulsion technology of the future for road transport. PEM fuel cells particularly are becoming the dominant fuel cell technology for transport applications, thanks to their high theoretical energy density which makes them suitable for light-duty vehicles, to the low operating temperature which allows quick start-up and shut-down, and to the high tolerance to CO_2 (Cropper 2004). However, despite the potential of this technology to reduce the environmental impact of road transport and to improve energy efficiency, both technical and economic barriers need to be overcome for it to be successfully introduced in mass markets.

PEM fuel cell systems are still not competitive with conventional internal combustion engines. Their cost is still very high, due to various reasons: fuel cells are currently not mass-produced, use expensive catalysts and manufacturing processes also need to be improved. Moreover, the power density of actual PEM fuel cell systems is not yet as high as theoretically possible and various components still need to be optimised; while this may be adequate for heavy duty vehicles, the overall volume of the system needs to be considerably reduced to make it viable on-board small light-duty vehicles. Finally, there is still little evidence that sufficient durability and reliability of fuel cell in real systems have been achieved.
While these technical barriers are currently being addressed in the HyTRAN project other issues are also present, related to the need to improve technologies for hydrogen storage on board vehicles, and to build up a hydrogen production, distribution and refuelling infrastructure.

Along with the technical challenges here outlined, a number of financial and commercial issues are also currently preventing PEM fuel cell vehicles from competing with conventional internal combustion engine vehicles. This complexity has stimulated growing research interest and, in recent years, numerous studies have looked from different angles at the possible future market penetration of hydrogen fuel cell-based technologies in transport.

For instance Adamson (2005) has developed a framework for evaluating consumers' willingness to pay for fuel cell cars showing that, even when the technology is not yet mature for mass market adoption, opportunities may exist for its early adoption in niche markets. Other studies, such as Tsuchiya et al. (2004), have investigated the possible

effects of mass production on PEM fuel cells for transport by applying a technological learning curve model.
However, few studies so far have attempted to rigorously address the dynamics that may bring the hydrogen PEM fuel cell car on the market. Gether (2004) has investigated the possible transition to a hydrogen energy system using System Dynamics modelling. More recently Struben (2006) has addressed the adoption of alternatively fuelled vehicles, including hydrogen fuel cell, by comprehensively modelling feedback loops arising from scale economies, R&D, learning by doing, driver experience, word of mouth, and complementary resources such as refuelling infrastructure.

The study here described has similarities with the work by Struben and was largely performed in parallel with it. However, the scope of our study is less broad, its emphasis being on the main feedback loops that influence the development of the PEM fuel cell technology. Consumer behaviour and possible policy measures are also addressed in some detail. All other relevant feedback loops are considered in a more aggregated way, if compared with the model by Struben.

3. Methodology

The methodology for this study is based on System Dynamics. Both the analysis of the problem and the modelling make use of concepts and tools derived from System Dynamics. In particular, the modelling methodology is structured as a number of successive steps, adapted from Sterman (2000), which are iterated as necessary.

In this study, the purpose of building and using a simulation model is two-fold: firstly, the development of the model itself offers a practical and effective way of analysing the problem in depth. Then the simulation model provides a learning environment, where to experiment with, for instance, different technology learning rates or policy measures and by means of which to identify possible counterintuitive behaviours that may be difficult to predict otherwise.

The analysis and modelling are entirely carried out at Imperial College, while the role of other project partners involved in the study is to provide input to the problem definition, technology and market data, reality check and validation of results.
The model will be used to test selected scenarios; sensitivity analysis on variables having high levels of uncertainty will be performed. One main output of the model are curves describing the market penetration over time of PEM FC vehicles under different conditions.

4. Model boundaries

The broad objectives of the study are set by the project Description of Work (HyTRAN 2003). These were further discussed with project partners and refined accordingly. In particular, we discussed the definition of the problem to be addressed and the factors that are endogenous to it. The boundaries of the model as agreed with the relevant project partners are summarised in Table 1 and briefly discussed below.

Table 1. Model boundary chart

Endogenous	Exogenous	Not included
PEM fuel cell technology development	Other relevant technologies for hydrogen FC vehicles (e.g.; on-board hydrogen storage)	Influence of uptake of PEM FC vehicles on road transport demand
Market penetration of PEM fuel cell cars, LDVs and buses	Market penetration of PEM fuel cells in early and niche markets	Influence of price of fuels on transport demand
Hydrogen refuelling infrastructure development	Price of primary energy sources (mainly oil and natural gas)	Possible future intermodal transport shifts
Consumer choice to adopt PEM fuel cell vehicles	Incentives, taxes and other relevant policy measures *(this may be made endogenous at a later stage)*	

- The technologies under development in HyTRAN are respectively an 80kW PEM FC-based powertrain for road vehicles and a 5kW diesel reformate PEM FC APU unit for trucks. For this reason, the model explicitly addresses the market penetration of hydrogen PEM FC private cars, light duty vehicles and buses, as well as that of trucks equipped with a PEM FC APU unit.
- The development of early and niche markets for PEM fuel cells is expected to play a crucial role in improving the technology and its attributes, thus influencing its mass market uptake in road transport applications. However it would be beyond the scope of our model to endogenously represent all such niche markets. Instead, the technological learning and scale economies these may provide are addressed exogenously, based on plausible scenarios.
- The main technology variables that are modelled endogenously are: cost, durability, reliability, fuel efficiency, volume and weight. These are all attributes of the technology that still need to be improved, to different extents, in order to make it commercially viable.
- Other related technologies that are vital to the development of hydrogen powered vehicles, such as on-board hydrogen storage, are at least initially modelled exogenously.
- A number of possible policy measures potentially capable of affecting the market introduction of PEM FC vehicles are modelled, such as the creation of zones only accessible to zero-emission vehicles, taxation of fuels to reflect their lifecycle carbon emissions and so on.
- The effect that the introduction of PEM fuel cell vehicles may have on total demand for transport and on possible intermodal shifts is not accounted for, as we considered it beyond the scope of our study. Similarly, the effect of fuel price variation on transport demand is also not addressed.
- Since our study focuses on the initial phases of the mass market penetration of PEM fuel cell vehicles, the spatial boundaries of our model are set at city level. In fact it

is widely recognised that the introduction of these technologies would start from densely populated areas, such as major European cities, and only then extend to rural areas.

- Different regional market conditions will be modelled, to reflect differences in transport demand, geography and availability of hydrogen refuelling infrastructure across the various cities that have been selected for developing technology introduction scenarios.

Finally, it is worth noting that, given the iterative nature of the process, the boundaries discusses above may be subject to future refinements and changes as the analysis proceeds and new insight is gained.

5. Structure and dynamics

The main feedback loops identified in this study and addressed by the model are shown in Figure 1. The PEM fuel cell technology may improve as a consequence of experience acquired through cumulative production, and therefore we have identified a reinforcing feedback loop linking the number of PEM fuel cell vehicles sold and the improvement of the technology. Niche and early markets, treated exogenously in this study, also contribute to technological learning. Another way in which the PEM fuel cell technology may improve is by means of R&D activities.
The improvement of the technology results in better economics and performances of PEM fuel cell, which in turn positively affect the utility of the vehicle to the potential adopter. Therefore, this feedback loop can be better represented by the two related reinforcing loops R1 and R2.

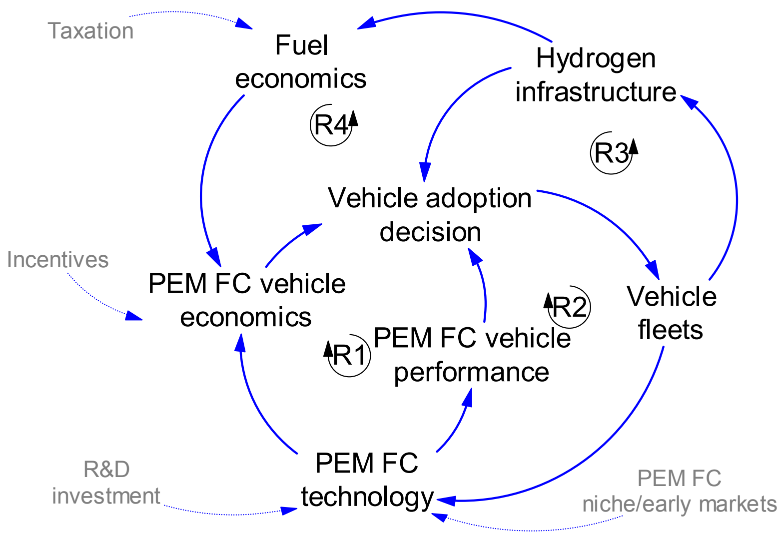

Figure 1. Main feedback loops affecting the development and market introduction of PEM fuel cell in road transport applications

The uptake of PEM fuel cell vehicles also influences, and is influenced by, the build-up of a hydrogen refuelling infrastructure. This generates another reinforcing feedback loop (R3) that may positively affect the decision to adopt PEM fuel cell vehicles when activated. Moreover, as the refuelling infrastructure grows, so does the demand for hydrogen fuel and hence the rate of its production; this generates economies of scale which have a positive impact on the cost of fuel and ultimately on the economics of the vehicle (R4).

All the feedback loops shown in Figure 1 are included in our model. Other feedback loops are also included in the model which are not shown here for simplicity; these will be briefly discussed later in this paper.
The main effort has been devoted to the parts of the problem under study which are more relevant to the HyTRAN project. For this reason, the development of the technology has been modelled in detail, and the vehicle adoption decision also requires careful consideration. The remaining parts of the problem have been modelled on a level which is relatively aggregate but we regard as fit for the purpose; should it appear necessary as the analysis proceeds and new insight is gained, however, the detail of these parts of the model will be increased. The main structures of the model are here discussed in turn.

5.1. PEM fuel cell vehicle fleets

The fleets of vehicles we consider in this study are private cars, light-duty commercial vehicles (LDVs), urban buses and APU-equipped heavy-duty commercial vehicles (HDVs). These fleets are modelled separately albeit all based on the same basic dynamic structure. Here we illustrate this structure using private cars as an example; with minor differences, the same applies to the other vehicle fleets.

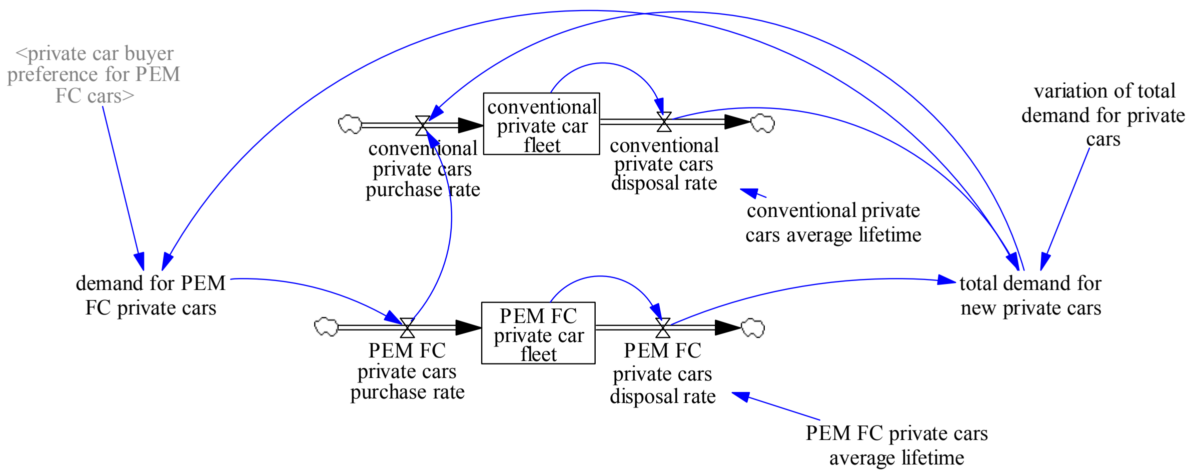

Figure 2: Diagrammatic representation of the structure for private cars

The basic model structure for private cars, shown in Figure 2, essentially consists of two stocks: circulating conventional (also including hybrid) and PEM FC cars; both stocks are subject to continual discard of old vehicles and replacement with new ones. If total demand for cars is kept constant, it is when vehicles are replaced that the alternative option of buying a conventional vehicle or a PEM FC one presents itself. If private car users decide for the latter, PEM FC vehicles enter the market and their share in the relevant fleet increases. The model also allows for total demand for cars to exogenously vary over time, should we expect this to happen in the cities we use as case studies. Whether consumers are purchasing only conventional cars, only FC ones or a combination of both, the total number of new cars purchased must equal the total demand for private cars; this is calculated by adding the number of cars discarded plus the variation of total demand for cars.

In any case we assume that, whatever is the ratio between conventional and PEM FC cars, this does not influence the overall level of demand for private cars and its development over time. This is of course a simplification which does not take into account the possible feedback loops between the introduction of new, disruptive technologies and shifts in transport modes. However, for our purposes we consider such simplification acceptable.

5.2. PEM fuel cell technology

The evolution of the PEM FC, of the reformate PEM FC and of the fuel processor technologies, as well as of all necessary additional components, are modelled in detail. All key attributes of these technologies, which are relevant to their market introduction, are represented. Their evolution over time is essentially determined by two factors: R&D efforts and cumulative production.

Technology development is therefore modelled as a function of both R&D and cumulative production. In particular, unit cost is expected to decrease as cumulative R&D investment and cumulative production increase. This phenomenon, widely documented in literature for both manufacturing and service organisations, is usually referred to as “learning curve” or “learning by doing” (Argote 1990).

In the model, we calculate the effect of R&D and cumulative production on unit cost using Equation 1 below, which is based on a typical learning curve formulation:

$$C_t = C_0 * [(P_t / P_0) \wedge (\ln F_p / \ln 2)] * [(I_t / I_0) \wedge (\ln F_I / \ln 2)] \qquad \text{(Equation 1)}$$

Where:
C_t is the unit cost of the technology at time t
C_0 is the initial unit cost of the technology, at t=0
P_t is the cumulative production at time t
I_t is the cumulative R&D investment at time t
F is the so-called progress ratio, which expresses the rate at which learning occurs. F_p is the progress ratio for cumulative production and F_I is the progress ratio for cumulative R&D investment; in general these are assumed to be different.

It is important to note that the progress ratio can only be rigorously measured starting from historical production cost data. Different progress ratios have been experimentally found for different products or services. In spite of its original definition, the learning curve concept is now increasingly used for attempting to forecast future costs of new technologies as a result of mass production or R&D. In this latter case, obviously the progress ratio cannot be determined *a priori* but needs to be assumed. Applications of this methodology to fuel cells can be found in literature (Rogner 1998). However, the issue of choosing a suitable progress ratio remains. While lessons may be learned from historical data of similar technologies and a suitable range of values can be identified for PEM FC, considerable uncertainty remains and therefore sensitivity analysis is necessary when simulating the model.

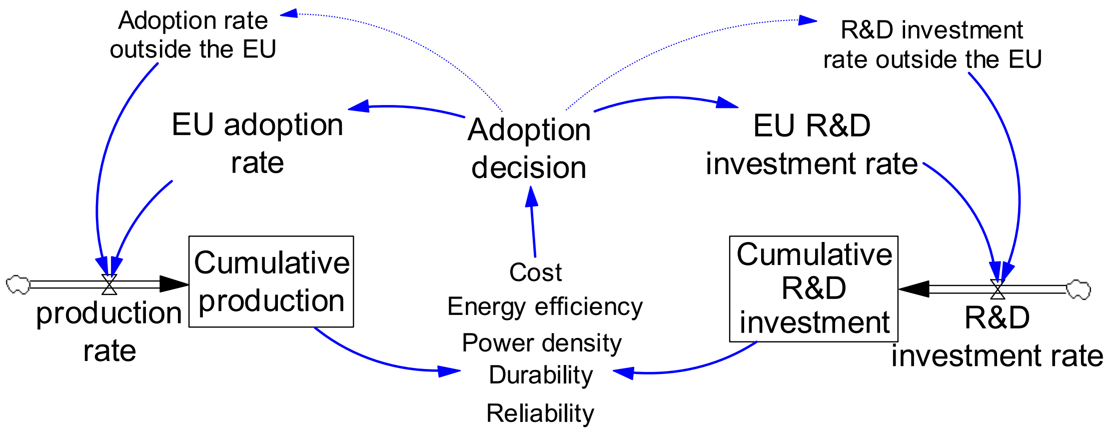

Figure 3. Main feedback loops influencing the development of the fuel cell technology attributes (centre). Dotted arrows represent weaker or indirect causal relations.

Figure 3 shows the basic structure used to model the development of the PEM fuel cell technology. We have already discussed how cumulative production and cumulative R&D investment influence the cost of the technology. Similarly, relations have been identified which link these stocks to the other attributes of the technology such as energy efficiency, power density, reliability, durability and start-up time. These relations are built based on historical data, when available, and on the experience of the relevant project partners with the technology. All these attributes of the technology form an input to the function describing decision-making of potential adopters, thus generating the feedback loops of Figure 3.

It is important to note that PEM fuel cells are a global industry; therefore, improvements in materials and processes are likely to soon become available worldwide, regardless of where they have originated. For this reason, in our study we need to consider not only production and R&D in Europe but also worldwide. Reasonable scenarios are hence developed and used for production and R&D outside the EU; the base case is that market introduction of PEM fuel cell vehicles occurs largely simultaneously in Europe and in countries like the US and Japan. Alternative scenarios however will also be considered, to assess the implications of Europe leading or lagging behind.
Moreover, the effort going into R&D is consequence of both public and private investments; while both of these are, to different degrees, linked to favourable public policies, private investment is also related to the revenues generated by sales of the technology. This generates a reinforcing feedback loop between private R&D investment and sales of PEM FC units.
Finally, under the scenario where the market introduction is simultaneous in and outside the EU, cumulative production is linked in these two regions. However, the feedback

loop between adoption of PEM FC in the EU and cumulative production outside the EU can be disabled when exploring different scenarios.

5.3. PEM fuel cell vehicle adoption decision

The decision to adopt PEM fuel cell vehicles is essentially determined by their relative attributes, compared to the incumbent technologies.
However, in order for PEM fuel cell vehicles to be actually purchased, potential adopters must be aware of their existence, of their cost, performance and other attributes. Moreover, they must have enough confidence in the technology, which can be built by indirect experience or by hearing comments from those who already use it. All this is captured by the concept of "word of mouth", which originates from the work of Bass (1969) and has since been extensively applied in modelling diffusion of new products.
Finally, sufficient hydrogen refuelling infrastructure needs to be in place as a necessary condition for the adoption of the vehicles. This is summarised in Figure 4.

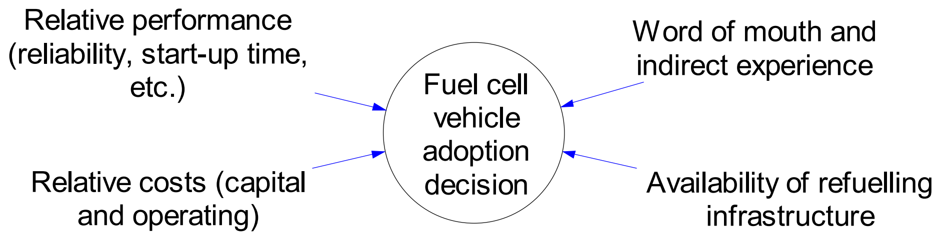

Figure 4. Factors entering the decision-making process of adopting PEM fuel cell vehicles

The possible future adoption of PEM FC-powered and PEM FC APU-equipped vehicles is ultimately subject to the choice of the consumer, be it a private car user or a company operating a fleet of LDVs, trucks or buses. Different groups of consumers react differently to the various characteristics and attributes of the new technology, relative to the incumbent, as they change over time. Potential adopters of the different technologies under study have been modelled separately, following however a similar approach which is described here using again as an example the case of private car users.

The first assumption made is that the population of car users, just like those of the users of other types of vehicles considered in the analysis, is not homogeneous: not all individuals value the attributes of a new technology in the same way. In other words, as the new technology develops, not all potential users decide for its adoption at the same point in time. This is common practice when modelling diffusion of new products (Rogers 1995). In fact we could arbitrarily divide potential adopters in the following broad groups: "innovators", "early adopters", "early majorities", "late majorities" and "laggards". Overall, the distribution of the different types of adopters across the whole population can be represented by a curve of the type shown in Figure 5.

Differences among these groups are essentially related to their attitude towards new technology in general, their willingness to pay a premium for unique attributes, their degree of rationality and their attitude towards risk. Moreover, even within the same group, consumers would not all behave in exactly the same way.

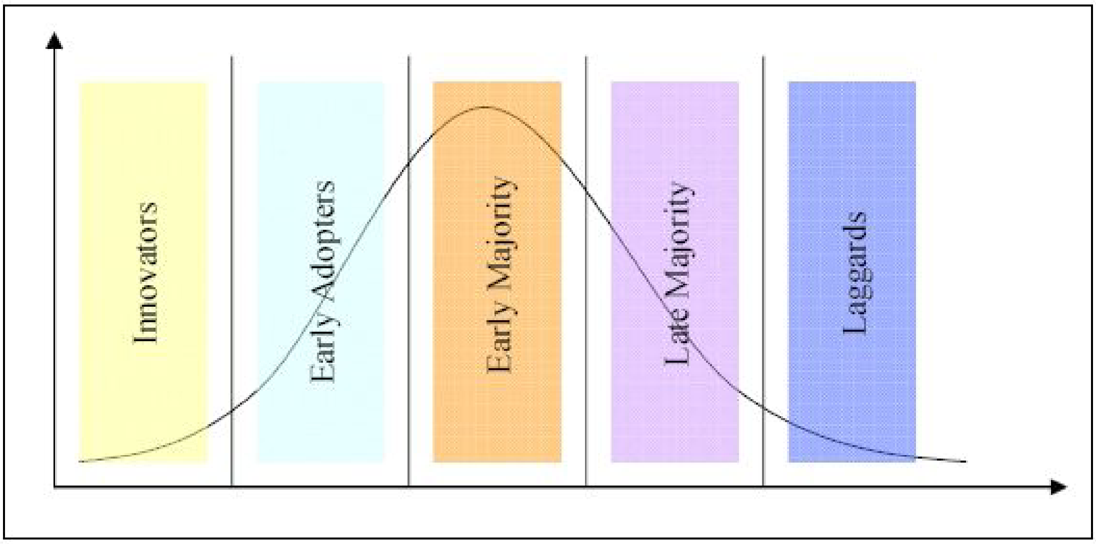

Figure 5. Distribution of potential adopters of new technology. Source: Burham (2005).

Each individual consumer, when purchasing a new vehicle, makes his or her decision on whether or not to switch to the new technology based on a combined valuation of its attributes, compared to those of the incumbent. This combined valuation is the result of separate valuations of each relevant attribute, each one weighted according to the importance it has for the group of potential adopters we are considering. Therefore, at a given time t and for the generic group g of potential adopters, the decision making function can be generally expressed by Equation 2:

$$n_g(t) = N_g * f\{w_{1,g} * f_g[A1(t)], w_{2,g} * f_g[A2(t)], \ldots, w_{n,g} * f_g[An(t)]\} \quad \text{(Equation 2)}$$

Where:
$n_g(t)$ is the number of consumers from the generic group *g* deciding to adopt the new technology at time *t*.
g is a generic group of potential adopters (such as innovators, early adopters, etc.)
N_g is the total number of consumers in group *g*
$f_g[An(t)]$ is the response of the generic group *g* to *An*. As for these functions, an obvious choice is to use a logit model, which is by far the most commonly used qualitative choice model; it has also been extensively applied to transport demand modelling (Train 1986)
An(t) is the relative value of the generic attribute *n* (e.g.: cost, performance, etc.) of the new technology compared to the incumbent, and is a function of time.
$w_{n,g}$ is the relative weight that the generic attribute *n* carries in the decision making process, for the generic group *g*

It appears from the equation above that the same set of variables, or attributes of the technology, enters the decision making process for all groups of adopters, although with different weighting factors. Moreover, not only different groups of potential adopters attach different relative importance to different attributes, but their responses to the relative values they take over time are also different. In Figure 6 is shown an example of different response to the relative costs of fuel cell cars, compared to conventional ones, respectively for “early adopters” and “laggards”.

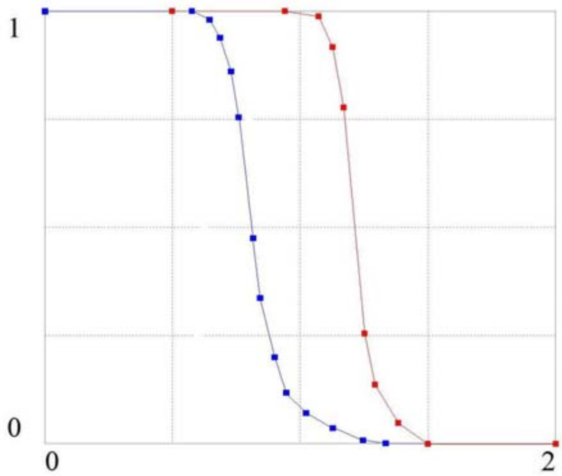

Figure 6. Fraction of car users deciding to adopt the new technology (y axis), in response to the relative price of the new technology compared to the incumbent (x axis). Red = “early adopters”; blue = “laggards”.

When talking about attributes of the technology that enter the decision making process, we essentially refer to the following categories:

- Costs
- Performances
- Availability of refuelling infrastructure
- Unique attributes of the new technology
- Indirect experience and word of mouth

Considering again the example of PEM fuel cell powered private cars, a unique attribute they have is, for instance, that of being zero emission vehicles. In cities where access to some areas is restricted to low or zero emission vehicles, this constitutes an attribute some users may be prepared to pay a premium for. Modelling the adoption decision-making process, the economic value of such attributes cannot therefore be neglected. In this way, we also indirectly model the effect on possible future adoption of PEM FC vehicles of particular policy measures, such as the institution of restricted areas in cities.

Finally, we have already discussed that different potential adopter groups show different attitudes towards new technologies; we can represent their distinctive behaviour also by relating it to the level of “word of mouth” it takes for them to decide in favour of the new technology. Here we refer to all types of exposure to the technology other than its direct use; this includes for instance exposure to circulating PEM FC powered vehicles and comments generated by its users; it also includes the effect of advertisement. This increases the level of confidence of potential adopters in the new technology. Depending on the group of users considered, however, the level of indirect experience

and word of mouth has a different weight in the decision making function: for example, “early adopters” generally require much less of it than “laggards” do to decide in favour of the adoption of the technology.
In our model, the level of indirect experience and word of mouth at a given time is a function of the stocks of circulating PEM FC vehicles. However, especially in early years, this level is significantly affected by advertisement and by the penetration of PEM FC in niche and early markets, not only in the transport sector.

5.4. PEM fuel cell vehicle economics

One key factor determining the choice between conventional vehicles and PEM FC ones is their relative cost. Although cost is not the only criterion, it is certainly one that carries a high weight and therefore needs to be analysed in detail.

First of all, when analysing the relative costs of the new technology, it is important to distinguish between fixed costs and variable costs.
Fixed costs are, respectively, the purchase price of the vehicle, excise duty, insurance, etc. Fixed costs can be affected by policy measures in form of, for instance, subsidies on the purchase of alternatively fuelled vehicles; excise duty also can be made to reflect the environmental performance of the vehicle through, for instance, vehicle eco-labelling schemes.
Variable costs on the other hand are associated to fuel, maintenance, etc. The cost of fuel is a function of the fuel price and of the vehicle’s fuel efficiency, and is proportional to the average annual mileage of the vehicle. The price of fuel is in turn largely determined by taxation, and therefore can be strongly influenced by possible policy measures, such as differential fuel taxation according to the fuel carbon content.

In our model, we assume that fleet operators make their decision essentially based on total annualised costs, while private car users behave somewhat less rationally and decide based on various categories of costs, such as purchase price, cost of fuel and maintenance, separately.

5.5. Hydrogen refuelling infrastructure

As already pointed out above, in addition to the attributes of the technology as such, there are other factors entering the decision making process. An important one is the density of hydrogen refuelling stations.
For private car users to be willing to adopt alternatively fuelled vehicles a minimum hydrogen refuelling station density is needed. To a lesser extent, urban buses and other commercial fleets also need dedicated hydrogen refuelling infrastructure; in this case though this is likely to be located at vehicle depots, thus reducing the number of refuelling points needed and considerably simplifying the logistics, too. This gives rise to situation often quoted in the literature on the hydrogen economy, where “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" (Joffe 2004, p. 13).

While it appears necessary, when investigating the market penetration of PEM FC vehicles, to consider the effect of density and availability of refuelling stations on consumers' adoption decision, it would certainly be beyond the scope of this study to model the dynamics of hydrogen production, transport and distribution as well. Instead, in this study we assume scenarios for hydrogen production that are deemed reasonable and consistent with the broader scenarios assumptions made and, based on existing studies and public available data, we calculate the cost of hydrogen fuel at the refuelling station. Moreover, we model the build-up of hydrogen refuelling infrastructure essentially as following demand for PEM FC vehicles but with a delay, which accounts for the time necessary for planning and constructing refuelling stations. We finally also consider possible synergies between refuelling infrastructure for fleets and for private vehicles, by means of which early development of refuelling infrastructure for buses and other fleets may serve as a bridge to the development of infrastructure for private vehicles.

5.6. Relevant early and niche markets for PEM fuel cells

There is growing evidence of PEM FC penetrating niche markets in recent years, both in Europe and worldwide (Adamson 2006). Potentially favourable niche applications of PEM FC at the moment appear to be forklifts, scooters, wheelchairs and portable electronics. This contributes to the development of the PEM FC technology and hence to its future penetration of road transport mass markets.

Just like the development of a hydrogen infrastructure, however, it would be beyond the scope of this study to model these markets explicitly in the same way we do for PEM fuel cell vehicle and PEM fuel cell APU-equipped vehicle fleets. Instead, we consider possible scenarios for PEM FC penetration of niche markets and early markets. We calculate cumulative production over time as it arises from such scenarios, and feed it into the relevant stock.

6. Model validation and possible areas for future development

The validation of the market model we have developed proceeds throughout the modelling and analysis activity. Initially the model is checked for robustness, by testing its behaviour under extreme conditions as well as performing a number of other routine tests. Subsequently, its ability to replicate historical data is assessed. In our case obviously there are no historical data on market penetration of PEM FC vehicles. However, subject to their availability, we use historical market penetration data for comparable technologies. For instance time series data of the uptake of diesel or LPG cars versus their costs and attributes allow us to check the behaviour of the model, particularly with reference to the adoption decision function. Finally, input from project partners on the model structure, on model input data and on the results generated will provide additional reality check.

It follows from the above that the identification and prioritisation of areas for further development of the model is strictly linked to the model validation process, and particularly important will be the interaction with project partners. Since this latter has only just begun, it is not yet possible to discuss areas for future development any further.

7. Expected results

The types of results we expect from modelling are two-fold: on the one hand the modelling activity *per se* is conducive to a thorough qualitative analysis of the problem under study; on the other hand the computer simulation of the model allows going beyond the qualitative level and provides an environment in which to experiment different conditions and variables, deriving quantitative information that would not be accessible otherwise.

In general the simulation of the model generates as output the time series values of all its endogenous variables. However, the key output for our analysis consists in the market penetration curves of the PEM FC-based technologies under development in HyTRAN. An example of such curve is given in Figure 7; this was obtained in a previous study (Clarke 2004) using a model similar to the one we have developed.

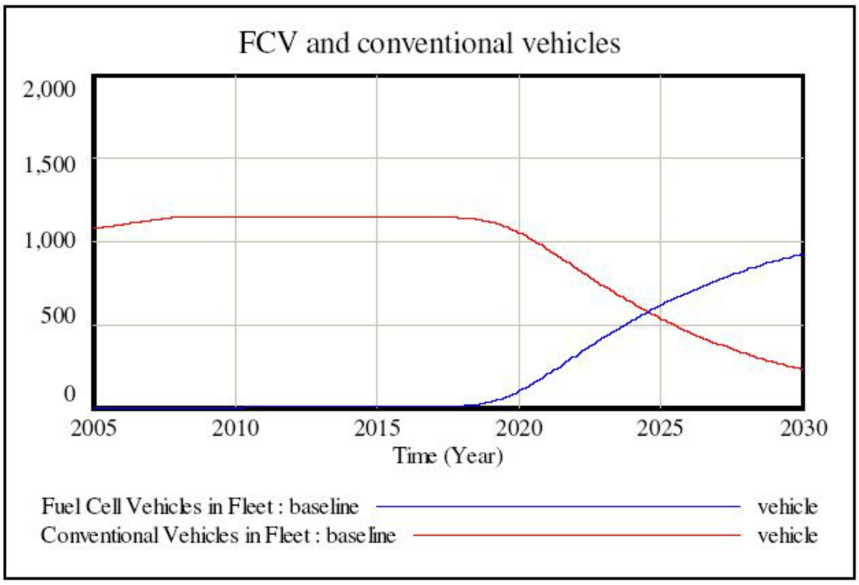

Figure 7. Uptake curve of FC vehicles over time (Clarke 2004).

Since the penetration of PEM FC vehicles is a function of many factors, a vital component of our study will be the analysis of the sensitivity of such penetration curves to a number of selected variables. Keeping all other variables constant, we run the model by varying a selected variable over a given range of values; in this way we generate a family of penetration curves. An example of this, taken from the same study mentioned above (Clarke 2004), is given in Figure 8. The wider is the spread of the family of curves, the higher is the sensitivity to the selected variable. In particular, our analysis will focus on the sensitivity of PEM FC vehicle uptake to technology development, market conditions and policy measures, in accordance with the objectives of the study.

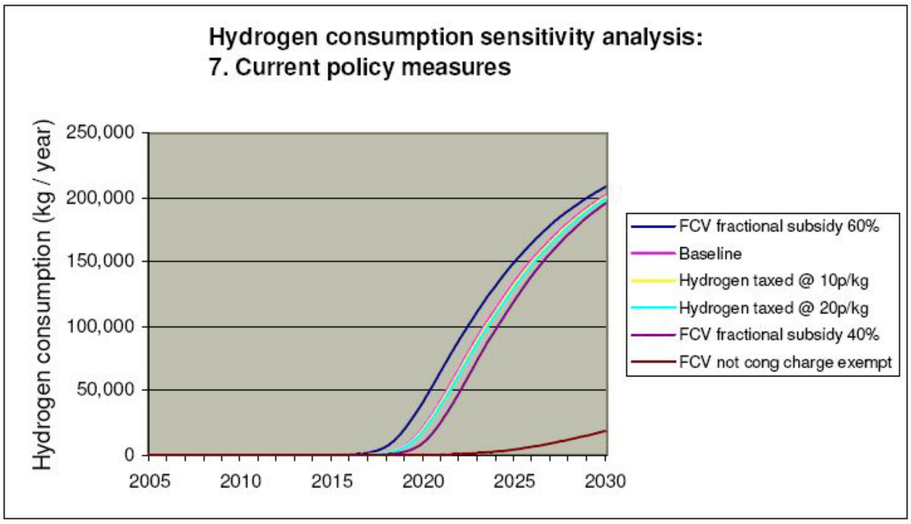

Figure 8. Sensitivity of FC vehicle uptake to current policy measures (Clarke 2004).

8. Conclusions

It this paper we have described the basic structure of the market model we have developed so far. Data collection is currently in progress and so is the development of suitable scenarios to be explored with the model. Results will soon be generated, analysed and discussed with partners in a dedicated session. This will suggest areas for improvement of both the model and the input, and further refinements will be made in an iterative fashion until the desired results are achieved. The study is expected to be completed early in 2007.

Work done so far and preliminary results obtained suggest that the model we have developed is overall fit for the purpose. The modelling process has already provided useful learning, and areas for improvement have been identified accordingly. Substantial input is still expected from project partners and the quality of the final results of this study will significantly depend on their contribution.

Outcomes of the study will include an analysis of the main technical, economic and policy drivers and barriers, and of particular interest are the possible dynamics that can arise from their interaction. Results will also include a discussion of the main consequences of some specific market penetration scenarios for this technology, particularly with respect to some selected European Member States.

The outcomes of the analysis will be used to develop a set of recommendations for key areas of cost reduction or performance improvement of the relevant technologies; it will also provide suggestions for policies and other conditions that are favourable to their development and market entry.

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