ELSEVIER

Journal of Power Sources 106 (2002) 353–363

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

# Options for refuelling hydrogen fuel cell vehicles in Italy

R. Mercuri[a], A. Bauen[b,*], D. Hart[b]

[a]*EniTecnologie, Strategic Planning and Technology Innovation, 00016 Monterotondo, Rome, Italy*
[b]*Imperial College, Centre for Energy Policy and Technology, RSM Building, Prince Consort Road, London SW7 2BP, UK*

## Abstract

Hydrogen fuel cell vehicle ($H_2$ FCV) trials are taking place in a number of cities around the world. In Italy, Milan and Turin are the first to have demonstration projects involving hydrogen-fuelled vehicles, in part to satisfy increasing consumer demand for improved environmental performance. The Italian transport plan specifically highlights the potential for FCVs to enter into the marketplace from around 2005.

A scenario for FCV penetration into Italy, developed using projected costs for FCV and hydrogen fuel, suggests that by 2015, 2 million Italian cars could be powered by fuel cells. By 2030, 60% of the parc could be FCVs. To develop an infrastructure to supply these vehicles, a variety of options is considered. Large-scale steam reforming, on-site reforming and electrolysis options are analysed, with hydrogen delivered both in liquid and gaseous form. Assuming mature technologies, with over 10,000 units produced, on-site steam reforming provides the most economic hydrogen supply to the consumer, at US$ 2.6/kg. However, in the early stages of the infrastructure development there is a clear opportunity for on-site electrolysis and for production of hydrogen at centralised facilities, with delivery in the form of liquid hydrogen. This enables additional flexibility, as the hydrogen may also be used for fuel refining or for local power generation. In the current Italian context, energy companies could have a significant role to play in developing a hydrogen infrastructure.

The use of hydrogen FCVs can substantially reduce emissions of regulated pollutants and greenhouse gases. Using externality costs for regulated pollutants, it is estimated that the use of hydrogen fuel cell buses in place of 5% of diesel buses in Milan could avoid US$ 2 million per year in health costs. The addition of even very low externality costs to fuel prices makes the use of untaxed hydrogen in buses and cars, which is slightly more expensive for the motorist than untaxed gasoline or diesel, competitive on a social cost basis.

*Keywords:* Hydrogen infrastructure; Fuel cell vehicle; Hydrogen energy; External cost; Cost of hydrogen; FCV; Emissions reduction

## 1. Introduction

Consumer demand for local and global environmental quality, in the form of reduced noise and air pollution, including greenhouse gas emissions, may help drive the introduction of hydrogen fuel cell vehicles ($H_2$ FCVs). Furthermore, the demand for environmental quality is likely to rise as demand for road transport increases worldwide, together with demand for improved vehicle performance and comfort and affordable mobility. The success of $H_2$ FCVs will depend on their ability to satisfy different consumer requirements.

This paper aims to understand possible drivers for $H_2$ FCV demand in Italy, develop a scenario for $H_2$ FCV introduction, analyse different supply routes for $H_2$ fuel and assess the potential environmental benefits of $H_2$ FCVs.

## 2. Road transport and environmental quality

About 70% of the European population lives in urban centres and is exposed to air and noise pollution as a result of road transport. A survey conducted by the Italian Ministry of Environment indicates that 80% of families in Milan, 75% in Bologna and 65% in Florence and Turin consider air pollution in the area in which they live to be ‘‘very or quite high’’ [1]. Road transport accounts for 24% of the total $CO_2$ emissions in Italy [2] and 17% worldwide [3]. It is the principal contributor to noise in urban areas, with 50% of the families in Milan, Florence and Turin considering noise pollution to be ‘‘very or quite high’’ and 86% attributing it to road traffic. The World Health Organisation estimates that about 97% of Europe's population is exposed to noise levels above 55 dB (A), of which about 72% to levels above 65 dB (A) and 27% to levels above 75 dB (A). This is of concern since it can, amongst other things, affect people's verbal communication and sleep and result in nervous disorders [4]. Notwithstanding growing concern over the environmental implications of road transport, private transport appears to be expanding gradually at the expense of public transport [5].

---

[*] Corresponding author. Tel.: +44-20-7594-9332;
fax: +44-20-7594-9334.
*E-mail address:* a.bauen@ic.ac.uk (A. Bauen).

PII: S0378-7753(01)01060-6

### 2.1. The role of fuel cells

Automotive and energy companies have been making considerable efforts to produce cleaner vehicles and fuels based on the internal combustion engine (ICE) and using improved petroleum fuels. However, more innovative solutions are likely to be required for sustained mobility while meeting different consumer demands. Battery electric vehicles (BEVs), FCVs and some hybrid ICE or FC/battery designs hold promise.

The Italian General Transport Plan (Piano Generale dei Trasporti, PGT) highlights these potential technology solutions, while indicating that no significant market penetration is likely to occur before 2005 and that recent rapid developments in FCVs may lead them to prevail over other technologies beyond that date [6]. Both BEVs and $H_2$ FCVs offer the advantage that they are truly zero emission vehicles (ZEVs) at the point of use, and that their operation results in very low noise levels. However, BEV market penetration has been hampered by low range and long refuelling time, and by the high cost of the vehicle and of electricity, in Italy in particular. FCVs may provide a solution to the issues of range and refuelling time and FC engines have been projected to achieve greater cost reductions through mass manufacturing compared to batteries, and possibly ICEs [7].

FCV development worldwide is progressing rapidly, but a number of issues remain to be addressed, with regard to the fuelling of cars in particular. The fuelling of buses is less of an issue because space constraints are less important and their refuelling generally takes place at depots. While direct hydrogen fuelling of cars is likely to result in the simplest design, intensive R&D is directed to the development of on-board reformers to allow fuelling with fuels, such as methanol, gasoline and, possibly, natural gas. On-board reforming, if technically viable, could provide a transitional solution to issues associated with the development of a hydrogen infrastructure and its storage on-board cars.

The question of fuel choice for FCVs remains open, but the viability and benefits of on-board reforming appear strongly questionable partly because of cost, complexity, start-up time, transient response and power density issues, in particular if regarded as a transitional solution. $H_2$ FC buses have been extensively demonstrated and a number of $H_2$ FC car prototypes are being tested on the road (e.g. $H_2$ Ford Focus) [8].

$H_2$ FCVs may be an important element in moving towards sustainable transport. They appear as the most likely option capable of simultaneously ensuring long-term sustained mobility while ensuring high levels of environmental quality, vehicle performance and comfort. However, different factors will affect the success of $H_2$ FCVs and the rate of their uptake.

- Technology readiness, availability and costs.
- Associated refuelling infrastructure availability and costs.
- Market structure, norms and regulations.
- Public acceptance.
- Government policy.

A number of perceived barriers may affect $H_2$ FCV market penetration.

- $H_2$ health and safety issues.
- Public perception.
- Technology readiness.
- $H_2$ fuel and FCV cost.
- $H_2$ fuel infrastructure.
- Norms and standards (for vehicles and refuelling infrastructure).

Hydrogen fuel is not thought to represent additional risks compared to conventional or other alternative fuels and most health and safety issues could be resolved by setting adequate norms and regulations, training qualified personnel and educating the public [9]. The public perception of hydrogen remains of concern, though surveys of potential FCV users and passengers seem to disprove this myth [10]. Technology readiness is still an issue, in particular with regard to FC engine system reliability and durability and advanced on-board hydrogen storage. Hydrogen is produced at large scale for captive use or for export as a commodity chemical, transported in gaseous or liquid form by truck or pipeline. On-site hydrogen production and refuelling systems should not present particular technical challenges. FCV cost appears as a barrier, with FC buses currently about 10 times more expensive than a conventional diesel engine bus, but several studies indicate that the mass manufacture of FCs could make them competitive with ICE vehicles on a life cycle cost basis. The establishment of a $H_2$ infrastructure and associated costs are commonly perceived as strong barriers. However, other studies have shown that a $H_2$ infrastructure need not be created overnight and that different options, as illustrated in this paper, exist to adapt the fuelling infrastructure to a potential phased-in demand for FCVs [11]. Also, as discussed later, hydrogen could be produced at a cost that would make FCVs competitive with other vehicles under certain circumstances. It is imperative that norms and regulations related to $H_2$ FCVs and refuelling be developed early on as these may delay and discourage uptake. Finally, the commercialisation of $H_2$ FCVs is not likely to happen without adequate government policies aimed at realising their potential social benefits.

### 2.2. Alternative fuels and vehicles and policy developments

Most Italian cars are gasoline fuelled, although other fuels, diesel in particular, are becoming more common. Liquid petroleum gas (LPG) and compressed natural gas (CNG) use is growing, albeit slowly. Most buses are diesel-fuelled, followed by gasoline and LPG buses, although other fuels, such as white diesel[1], biodiesel in certain regions and

---

[1] Consists of a mixture of diesel, water (10%) and special additives (1.7%). It has been commercialised under the name GECAM by CAM Tecnologie, part of the Pirelli Group.

Table 1
Split of Italian vehicle population according to fuel (1999)

| | Gasoline | Diesel | LPG | CNG | Others | Total |
|---|---|---|---|---|---|---|
| Cars | 26,386,617 | 4,132,262 | 1,253,774 | 256,739 | 8,899 | 32,038,291 |
| Buses | 1,203 | 84,052 | 67 | 92 | 348 | 85,762 |

CNG are all experiencing growth. Table 1 provides a split of Italian cars and buses according to their fuel [12].

The number of CNG cars is expected to grow from about 300,000 to 600,000 and LPG cars from about 1,170,000 to 1,500,000 by 2005 [13]. However, the numbers of LPG cars may not grow as predicted, both because of a lack of sufficient communication and competition from CNG and diesel cars [14]. Some growth is predicted in CNG buses, and a growing number of buses are fuelled by ''white diesel'', which already fuels around 3,600 buses mainly in the Lombardy region, but with prospects of expanding to other regions [15].

A number of economic incentives, mainly in the form of tax breaks, are aimed at alternative fuels, as shown in Table 2. While taxes represent about 70% of the price of gasoline and 60% of the price of diesel, their level is of about 43% for LPG, 27% for ''white diesel'' and it is negligible for CNG [16]. Biodiesel also benefits from tax breaks, with a production of up to 300,000 ton per year, to be used pure or as a blend, totally tax exempt [17]. The principal objective of the tax breaks is to encourage switching to fuels that produce lower emissions than petrol and diesel.

Economic incentives are also directed to vehicle purchases or conversions. Legislation has been passed to provide incentives aimed at renewing the bus fleet (Law no. 194 dated 18 June 1998), about 60% of which is over 10 years old. About US$ 7 million (LIT 15 billion) have been allocated annually between 2001 and 2003 to promote purchase of electric cars and motorbikes (BEV, FCV, hybrid) and conversion of cars to CNG or LPG fuel (Ministerial Decree 5 April 2001).

### 2.3. FCV activities in Italy

Several $H_2$ fuel and FCV activities are planned for the short-term in Italy.

FIAT has revealed a prototype $H_2$ FC car (spring 2001), the 600 $H_2$ FC Elettra, and has announced the development of a FC Punto with multi-fuel on-board reforming [18]. ENEA in collaboration with De Nora, Centro Ricerche Fiat, CNR-TAE, and the Universities of Milan, Brescia, Genova and Rome has plans to develop a FCV with a natural gas reformer on-board [19].

Table 2
Fuel price and taxation

| Fuels | Price | Tax (%) |
|---|---|---|
| Gasoline (no lead) (US$/l) | 1.0 | 70 |
| Diesel (US$/l) | 0.8 | 60 |
| LPG (US$/l) | 0.5 | 43 |
| CNG (US$/m$^3$) | 0.4 | 1 |
| White diesel (US$/l) | 0.8 | 27 |

The city of Turin ''City-Class Fuel Cell'' project aims to demonstrate a fleet of Irisbus buses fuelled with hydrogen produced from a small-scale electrolysis plant [20]. The project, co-funded by the Italian Ministry of Environment, involves the city of Turin, ATM (municipal transport company of Turin) IRISBUS (joint-venture between IVECO and Renault), International Fuel Cells (IFC), SAPIO Group (Industrial gas company in partnership with Air Products), Ansaldo Ricerche, TÜV (German safety organisation) and Compagnia Valdostana delle Acque (hydroelectricity generator-CVA).

The ''Milano Bicocca'' project plans to demonstrate a stationary FC for power generation, and part of the hydrogen generated on-site will be used to fuel a fleet of buses and cars. The main partners are the city of Milan, Zincar (subsidiary of the municipal energy company of Milan AEM), ENEA (Italian agency for new technologies, energy and the environment) and other fuel cell, automotive and industrial gas companies [21]. The city of Florence, through a consortium led by $i^2t^3$, also has plans to demonstrate an FC bus [22].

### 2.4. FCV penetration scenario for Italy

A $H_2$ FCV penetration scenario has been developed for Italy, based on a FCV penetration model described in [23], to provide an indication of the potential $H_2$ FCV growth and associated $H_2$ demand in Italy over the period extending to 2030 (Fig. 1).

The following main assumptions are made in modelling $H_2$ FCV penetration.

- Fuel price: $H_2$ price per distance driven is initially half that of gasoline (taxed). The price of gasoline is assumed to increase by 1.8% per annum. The cost of hydrogen is assumed to increase by 2% per annum.
- Vehicle price: The cost of a FCV is initially 20% higher than that of a conventional vehicle. A learning factor of 10% is applied to the initial real (unsubsidised) cost of the vehicle. Conventional vehicle prices are assumed to grow at a rate of 1% per annum.
- Willingness to pay: 2% of vehicle owners are willing to pay a premium for ZEVs (this means that 2% of new vehicles are FCV whatever the cost).
- Refuelling stations: The number of $H_2$ refuelling stations is assumed to grow by 1% per annum.

The assumptions used provide a relatively optimistic scenario for fuel cell penetration (shown in Fig. 1) which indicates that $H_2$ FCV could represent about 65% of the vehicle parc by 2030. This corresponds to an annual $H_2$ fuel demand of about 1.4 million ton by the year 2030. However, even under optimistic conditions uptake will be gradual,

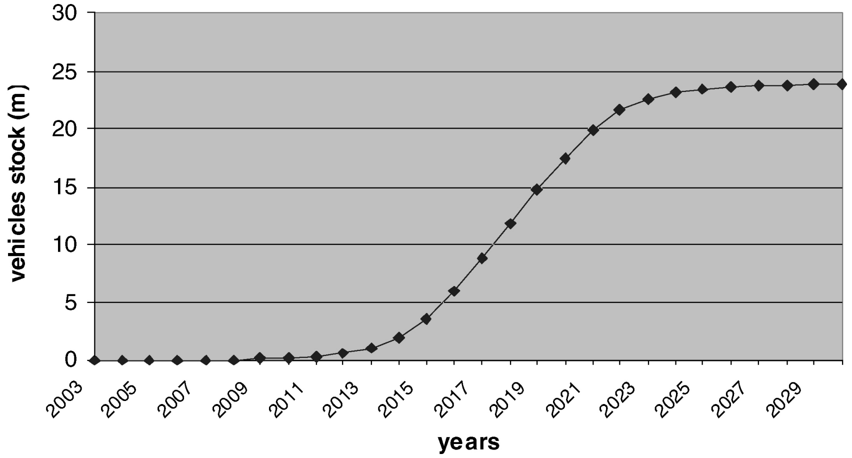

Fig. 1. A penetration scenario for FCVs in Italy.

with about 6% of the vehicle parc (about 2 million cars) converted to $H_2$ FCV by about 2015, corresponding to an annual $H_2$ fuel demand of about 150,000 ton.

### 2.5. FCVs and the environment

The demand for environmental quality is a main driver behind the development of FCVs. Use of FCVs should result in very low well-to-wheels emissions of regulated pollutants, the $H_2$ FCV being the only true fuel cell ZEV with regard to on-board emissions, and will generally offer significant benefits over conventional and other alternative vehicles. The benefits of FCVs over other vehicles in terms of energy efficiency and GHG emissions depend largely on the fuel from which hydrogen is derived and, in the case of electrolysis, the source of electricity used. Tables 3 and 4 provide a well-to-wheels comparison of emissions and energy use for different cars and buses based on [24]. These values are indicative and based on UK data. Emissions for an Italian situation would differ somewhat due to the different network associated with fossil fuel extraction, processing and transportation, while emissions associated with derived fuel (e.g. methanol and hydrogen) production and, if necessary, distribution would be very similar. On a well-to-wheels basis the emissions and energy use for the cases considered are likely to differ little between the geographic regions.

FCVs, like BEVs, are characterised by much lower noise emissions than IC engines; experimental vehicles emit about 65 dB. The difference in noise levels is more significant for the larger vehicles, such as trucks and buses.

The reduced emissions and noise levels of FCVs compared to conventional and other alternative ICE vehicles can result in significant social benefits. The ExternE study provides the greatest effort to date to attribute a monetary value to the impacts on the environment (externalities) of energy and transport activities, air pollution in particular

Table 3
Well-to-wheels emissions and energy use comparison for different cars

| Application | | $NO_x$ (g/km) | $SO_x$ (g/km) | CO (g/km) | NMHC (g/km) | $CO_2$ (g/km) | $CH_4$ (g/km) | PM (g/km) | Energy (MJ/km) |
|---|---|---|---|---|---|---|---|---|---|
| Gasoline ICE car | Absolute values | 0.26 | 0.2 | 2.3 | 0.77 | 209 | 0.042 | 0.01 | 3.16 |
| Diesel ICE car | Absolute values | 0.57 | 0.13 | 0.65 | 0.25 | 154 | 0.03 | 0.05 | 2.36 |
| | Relative to gasoline (%) | 219 | 64 | 28 | 33 | 74 | 72 | 489 | 75 |
| CNG ICE car | Absolute values | 0.10 | 0.01 | 0.05 | 0.05 | 158 | 0.12 | <0.0001 | 2.74 |
| | Relative to gasoline (%) | 39 | 5 | 2 | 6 | 76 | 277 | <0.5 | 87 |
| Hydrogen ICE car[a] | Absolute values | 0.11 | 0.03 | 0.04 | 0.05 | 220 | 0.15 | 0.0001 | 4.44 |
| | Relative to gasoline (%) | 43 | 17 | 2 | 7 | 105 | 364 | 1 | 141 |
| MeOH fuel cell car | Absolute values | 0.04 | 0.006 | 0.014 | 0.047 | 130 | 0.072 | 0.0015 | 2.63 |
| | Relative to gasoline (%) | 15 | 3 | 0.6 | 6.1 | 62 | 169 | 14 | 83 |
| Gasoline fuel cell car | Absolute values | 0.08 | 0.13 | 0.01 | 0.41 | 147 | 0.03 | 0.0002 | 2.24 |
| | Relative to gasoline (%) | 30 | 68 | 0.4 | 53 | 70 | 71 | 2 | 71 |
| Hydrogen fuel cell car[a] | Absolute values | 0.04 | 0.01 | 0.02 | 0.02 | 87.6 | 0.06 | <0.0001 | 1.77 |
| | Relative to gasoline (%) | 16 | 7 | 1 | 3 | 42 | 145 | <0.5 | 56 |
| Battery car | Absolute values | 0.17 | 0.06 | 0.08 | 0.02 | 88.1 | 0.06 | 0.0001 | 1.71 |
| CCGT electricity | Relative to gasoline (%) | 67 | 32 | 4 | 3 | 42 | 150 | 1 | 54 |

[a] Assumes steam–methane reforming at the refuelling station.

Table 4
Well-to-wheels emissions and energy use comparison for different buses

| Application | | $NO_x$ (g/km) | $SO_x$ (g/km) | CO (g/km) | NMHC (g/km) | $CO_2$ (g/km) | $CH_4$ (g/km) | PM (g/km) | Energy (MJ/km) |
|---|---|---|---|---|---|---|---|---|---|
| Diesel bus | Absolute values | 5.8 | 0.78 | 2.2 | 3.2 | 962 | 0.19 | 0.11 | 14.6 |
| SPFC bus | Absolute values | 0.43 | 0.11 | 0.17 | 0.18 | 588 | 0.33 | 0.0031 | 11.7 |
| Central reformer | Relative to diesel (%) | 7 | 14 | 8 | 6 | 61 | 175 | 3 | 80 |
| SPFC bus | Absolute values | 0.27 | 0.08 | 0.11 | 0.13 | 560 | 0.39 | 0.0001 | 11.3 |
| Depot reformer | Relative to diesel (%) | 5 | 10.8 | 5 | 4.2 | 58 | 206 | <0.5 | 78 |
| CNG bus | Absolute values | 0.56 | 0.05 | 0.57 | 0.20 | 826 | 0.56 | 0.01 | 15.4 |
| | Relative to diesel (%) | 10 | 7 | 25 | 6 | 86 | 296 | 12 | 105 |
| Battery bus | Absolute values | 1.20 | 0.44 | 0.58 | 0.15 | 608 | 0.43 | 0.0009 | 11.8 |
| CCGT electricity | Relative to diesel (%) | 21 | 56 | 26 | 4 | 63 | 231 | 1 | 81 |

Table 5
Range of external costs for emissions in European urban centres (US$/ton)

| | |
|---|---|
| PM | 158,875–1,063,636 |
| $SO_2$ | 5,540–28,636 |
| $NO_x$ | 337–8,573 |
| NMHC | 237–1,561 |
| CO | 1.2–18 |
| $CO_2$ | 14–38 |

[28]. Table 5 provides a range of externalities estimates expressed per unit of pollutant based on the ExternE methodology [29]. The range represents estimates of externalities for the cities of Brussels, Helsinki, Paris, Stuttgart, Athens, Amsterdam and London. The lowest values apply to cities with low population, such as Helsinki and the highest values to cities with high population, such as Paris.

Tables 6 and 7 provides estimates of the externalities for different types of vehicles operating in urban centres.

The city of Milan, representative of a high-population urban centre, has about 1,500,000 cars and 1,500 buses. The potential avoided emissions and social benefit of substituting 0.5% of gasoline cars (7,500 vehicles based on penetration rate in Fig. 1) and 5% of diesel buses (75 buses) by $H_2$ FCVs by 2010 are shown in Table 7. The calculations assume average annual urban travel distances of 20 and 200 km per day for cars and buses, respectively.

Table 6
Range of external costs for different vehicles in European urban centres (US$/km)

| | External cost (US$/km) | |
|---|---|---|
| | Including $CO_2$ equivalent | Excluding $CO_2$ equivalent |
| Gasoline car | 0.0059–0.027 | 0.0030–0.020 |
| Diesel bus | 0.038–0.34 | 0.024–0.19 |
| $H_2$ FC car[a] | 0.0013–0.0050 | 0.00009–0.00077 |
| $H_2$ FC bus[a] | 0.0084–0.026 | 0.00058–0.0049 |

[a] Assumes steam–methane reformer at the refuelling station.

Table 7
Avoided emissions and external costs from partial introduction of $H_2$ FCVs in Milan ($H_2$ fuel from steam–methane reforming at refuelling station)

| Conventional fuel replaced | Cars (gasoline) | Buses (diesel) |
|---|---|---|
| Avoided emissions (kg per year) | | |
| PM | 542 | 602 |
| $SO_2$ | 10,403 | 3,833 |
| $No_x$ | 12,045 | 30,277 |
| NMHC | 41,063 | 16,808 |
| CO | 124,830 | 11,443 |
| $CO_2$ | 6625,955 | 21,77,955 |
| Social benefit estimate (inclusive $CO_2$) (US$ per year) | 412,535 | 29,13,998 |
| Social benefit estimate (exclusive $CO_2$) (US$ per year) | 288,713 | 2,079,757 |

$H_2$ FCVs could contribute significantly to meeting a demand for increased local and global environmental quality.

## 3. $H_2$ supply economics

The price of a FCV will need to be similar to that of a conventional vehicle of similar performance for it to be accepted by consumers. The cost of $H_2$ fuel will affect the lifetime cost of a FCV and could be a determining factor in influencing consumer choice, especially for fleet vehicles. The cost of the fuel is currently perceived as one of the major barriers to its introduction. Hence, this section provides an analysis of $H_2$ supply costs in the context of Italy. Three scenarios for $H_2$ supply have been considered, distinguished mainly on the basis of centralised or on-site hydrogen production:

- centralised steam reforming of natural gas for hydrogen production and liquid hydrogen transport to refuelling station;
- on-site production and storage of gaseous hydrogen from steam reforming of natural gas;

- on-site production and storage of gaseous hydrogen from electrolysis of water.

The following main assumptions have been made.

- the refuelling station has a capacity to refuel about 50 buses or 300 cars per day, corresponding to a $H_2$ requirement of about 900 kg per day. The choice of refuelling station capacity is based on requirements compatible with dedicated bus depot refuelling and retail refuelling stations for cars. The case of a smaller refuelling station (180 kg per day) is also studied, in order to evaluate transitional aspects related to the build-up of $H_2$ FCVs and related refuelling infrastructure;
- hydrogen is dispensed in compressed gaseous form, a solution presently adopted for the refuelling of existing FCV bus demonstrations and which appears as a promising option through advanced compressed gas storage or storage in metal hydride or possibly carbon structures on-board cars. Various prototype $H_2$-fuelled cars currently store hydrogen on-board as a compressed gas (e.g. FIAT 600 $H_2$ Elettra);
- in the case of centralised $H_2$ production from steam reforming of natural gas, liquid $H_2$ transport, practised routinely, has been considered because of the substantially lower cost per unit of energy transported compared with compressed $H_2$. The latter may be viable for the transport of smaller quantities of hydrogen, because of the significant impact on cost of liquefaction facilities, while dedicated pipelines for the transport of compressed $H_2$ may become viable, either for captive users situated at short distances from the reforming plant or once a large stable $H_2$ demand becomes established.
- Natural gas has been considered as the feedstock of choice because of its widespread availability in Italy. Other feedstock could be considered, in particular for centralised production, such as refinery residues.

Investment costs and operation and maintenance costs for the different hydrogen fuel supply options are based on Berry [25], updated using an inflation rate value and adapted for the Italian context, in particular with regard to energy prices [26]. The initial costs and costs projections have been compared with other cost projections in the literature for small-scale electrolysis, reforming equipment and refilling station equipment [27]. Small differences were found, but these do not greatly affect the cost of hydrogen to the consumer, especially because of the high influence of the variable costs of electricity, gas and labour.

A progress ratio (learning factor) of 15% has been used to determine the cost reduction of new technologies, which corresponds to a 15% reduction in the cost of a product for every doubling in cumulative production capacity. The progress ratio is assumed to account for labour productivity gains, product and process optimisation and management efficiency gains. The progress ratio has been applied to the current cost of new hydrogen production technologies (i.e. small-scale electrolysis, small-scale steam reforming and $H_2$ refuelling station equipment) to project the cost of single units up to a cumulative global production of 10,000 units. A discount rate of 20% has been used, reflecting the rate of capital recovery.

Typical natural gas and electricity prices for industrial and large commercial users have been used. Table 8 summarises the main economic parameters used in the analysis.

Tables 9–11 show a breakdown of capital, maintenance and operation costs for the different options.

Fig. 2 illustrates the $H_2$ supply options considered and the contributions of the different production and handling stages to the final cost of $H_2$.

Table 8
Main economic parameters used in $H_2$ production analysis

| | |
|---|---|
| Scaling factor[a] | 0.8 |
| Utilisation factor (%) | 95 |
| Discount rate (%) | 20 |
| Inflation USA 1996–2000 (% per year) | 2.5 |
| Learning curve factor (%) | 15 |
| Exchange rate (LIT per US$) | 2,100 |
| Diesel price (US$/l) | 0.8 |
| Electricity price (US$/kWh) | |
| Large scale liquefaction plant | 0.12 |
| Small plant (electrolyser and filling station) | 0.09 |
| Natural gas price (US$/kWh) | |
| Large scale centralised plant (SMR) | 0.017 |
| Medium scale on-site SMR plant | 0.021 |
| Small scale on-site SMR plant | 0.026 |

[a] Used for determining economies of scale for liquefaction plant.

Table 9
Centralised SMR option

| | |
|---|---|
| Investment cost centralised SMR facility (237 $H_2$ ton per day) (US$) | 220,000,000 |
| Natural gas fuel cost 5 US$/GJ (US$ per day) | 197,000 |
| Labour & other O&M (US$ per day) | 55,000 |
| Investment cost liquefaction plant (237 $H_2$ ton per day) (US$) | 153,000,000 |
| Electricity cost 0.09 US$/kWh (US$ per day) | 260,000 |
| Labour & other O&M (US$ per day) | 20,000 |
| Transport investment cost (4 ton $LH_2$ per truck) (US$ per truck) | 500,000 |
| Fuel cost (US$/l) | 0.8 |
| Fuel consumption (km/l) | 2.2 |
| Labour (US$/h) | 28 |
| Refuelling station (900 $H_2$ kg per day) | |
| Initial capital cost (storage tanks, pump and vaporiser, dispenser) (US$) | 575,000 |
| Final capital cost (10,000 units) (US$) | 133,200 |
| Electricity cost 0.12 US$/kWh (US$ per year) | 11,000 |
| Labour (US$ per year) | 265,000 |
| Other O&M (US$ per year) | 9,000 |

Table 10
On-site SMR option (900 $H_2$ kg per day)

| | |
|---|---|
| Initial capital cost: | |
| Reformer (US$) | 2,420,000 |
| Refuelling station (compressor, vessels, dispenser) (US$) | 1,254,000 |
| Final capital cost (up to 10,000 units) | |
| Reformer (US$) | 555,000 |
| Refuelling station (compressor, vessels, dispenser) (US$) | 290,000 |
| Natural gas fuel cost (US$/GJ) | 5.9 |
| (US$ per year) | 260,000 |
| Electricity cost (US$/kWh) | 0.12 |
| (US$ per year) | 110,000 |
| Labour (US$ per year) | 265,000 |
| Other O&M (US$ per year) | 15,000 |

Table 11
On-site electrolysis option (1170 $H_2$ kg per day)

| | |
|---|---|
| Initial capital cost | |
| Electrolyser plant (US$) | 5,030,000 |
| Filling station (compressor, vessels, dispenser) (US$) | 1,254,000 |
| Final capital cost (up to 10,000 units) | |
| Electrolyser plant (US$) | 1,430,000 |
| Refuelling station (compressor, vessels, dispenser) (US$) | 290,000 |
| Electricity cost 0.12 US$/kWh (US$ per year) | 2,000,000 |
| Labour (US$ per year) | 265,000 |
| Other O&M (US$ per year) | 15,000 |

In the case of on-site electrolysis the investment cost contributes only about 13% of the price of the hydrogen at the refuelling station, assuming mass production effects on small-scale polymer membrane electrolysers and on refuelling station equipment. The bulk of the cost is attributable to the cost of the electricity (74%) needed by the electrolysis process and for $H_2$ compression. Because of the major contribution of the cost of electricity, a sensitivity analysis has been performed to determine the effect of its variation on the cost of $H_2$ production (Fig. 3). Variations in the cost of electricity could depend on a variety of factors, such as market liberalisation effects, specific contractual agreements and purchase of electricity at particular times (e.g. off-peak).

In the case of on-site natural gas steam reforming the investment cost contributes about 21% of the cost of $H_2$ to the consumer, while about 32% is attributable to the cost of the natural gas feedstock. The natural gas price considered is that typical of medium industrial users, and a sensitivity analysis has been performed to investigate the effect of its variation on the cost of $H_2$ production (Fig. 4). Refuelling station equipment for $H_2$ compression, storage and dispensing is assumed to be the same as that for the on-site electrolysis plant.

The total capital cost of supplying hydrogen from on-site SMR (US$ 0.5/kg $H_2$) appears to be significantly lower to that of electrolysis (US$ 0.8/kg $H_2$), furthermore the variable

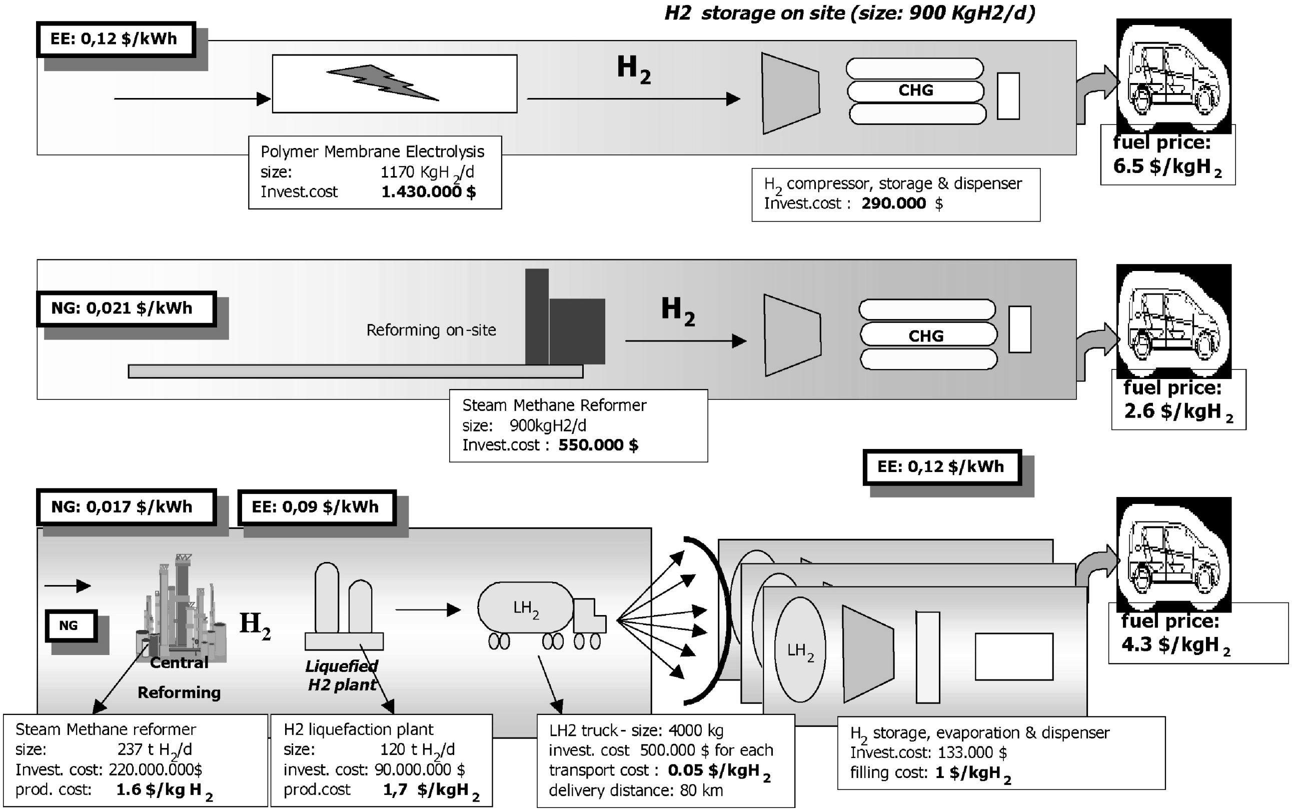

Fig. 2. Different possible hydrogen supply options and cost contributions.

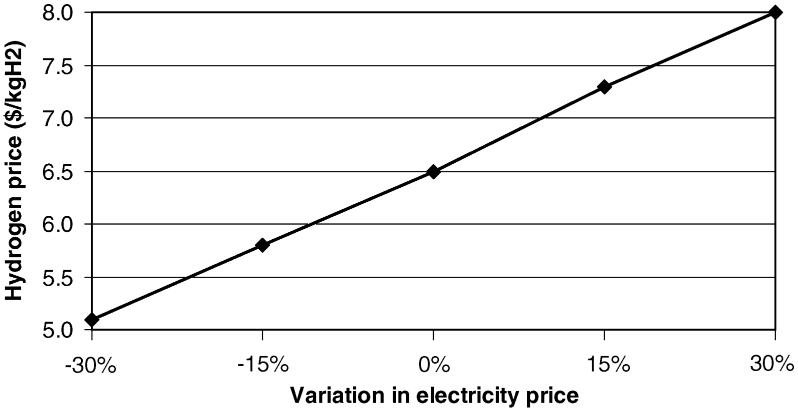

Fig. 3. Sensitivity of on-site electrolytic $H_2$ production to the cost of electricity (capacity 900 kg $H_2$ per day).

costs associated with natural gas inputs are also significantly lower than those associated with electricity inputs for the production of hydrogen.

In the case of centralised liquid $H_2$ production from natural gas steam reforming and $H_2$ liquefaction, the technologies are assumed to be mature and a progress ratio has been applied only to the refuelling station as per the previous cases. A range of liquefaction plant sizes (from 6 to 237 ton per day $H_2$) has been considered, to accommodate the fact that only part of the hydrogen may not be exported from the plant for the transport market (there may be some complementary use for electricity production or refining of fuels) and to allow for flexibility in meeting the requirements of a potentially growing $H_2$ fuel market. For example, a 6 ton per day $H_2$ liquefaction plant would be enough to supply about six refuelling stations of the size considered. A delivery distance of 80 km has been considered as representative of a regional $H_2$ fuel market, with hydrogen assumed to be stored as a liquid at the refuelling site and then vaporised and compressed to refuel vehicles.

The costs of natural gas and electricity at the production site are typical of large industrial users and lower than those for the on-site production facilities. $H_2$ liquefaction has an important impact on the cost of $H_2$ and its energy consumption is estimated at about 35% of the energy content (LHV) of the $H_2$ produced. The liquefaction stage is characterised by high investment costs and variable costs in the form of electricity costs. Fig. 5 illustrates the cost of $H_2$, as a function of the liquefaction plant size (for a fixed steam reformer unit of 237 ton $H_2$ per day) and for a range of natural gas and electricity prices for a refuelling station of 900 kg $H_2$ per day.

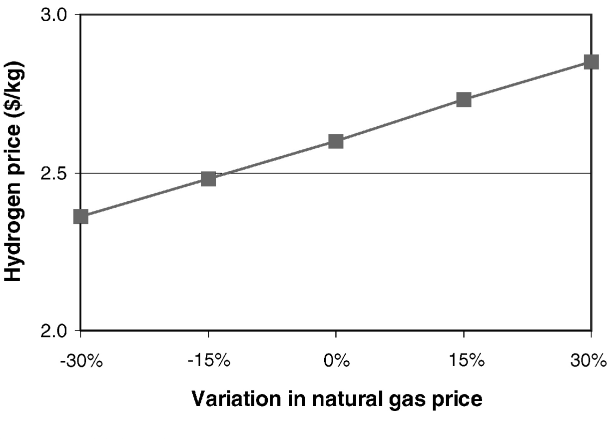

Fig. 4. Sensitivity of on-site SMR $H_2$ production to the cost of natural gas.

It can be seen that there are significant reductions in liquid $H_2$ production costs associated with economies of scale in the liquefaction plant. The cost of $H_2$ fuel is also highly sensitive to the cost of the natural gas feedstock and to the cost of the electricity used for liquefaction. This is because of their large contribution to the cost of $H_2$ as illustrated in Fig. 3.

### 3.1. Assessing the options and addressing transitional aspects of hydrogen infrastructure development

The costs of hydrogen from different options could change significantly as a $H_2$ fuel infrastructure develops (Fig. 6). The analysis shows that costs for on-site $H_2$ production options can be reduced significantly as the market for $H_2$ fuel becomes established, with on-site steam reforming potentially the lowest cost $H_2$ fuel production option. This is likely to be the case, especially if significant price differentials between gas and electricity persist. However, hydrogen from large-scale SMR plants appears to be a cost effective option in the very short-term. The greatest dilemma remains the development of a hydrogen refuelling infrastructure in the short- to medium-term. For early $H_2$ FCV demonstration programmes and fleets of a few vehicles, electrolysis may represent the most easily implemented on-site solution offering suitable operating flexibility. However, liquid hydrogen imported from large-scale production plants may represent the most economic solution, possibly to be challenged soon by the on-site SMR option. Also, although electrolysis appears to be the most expensive option, it may be a very interesting one

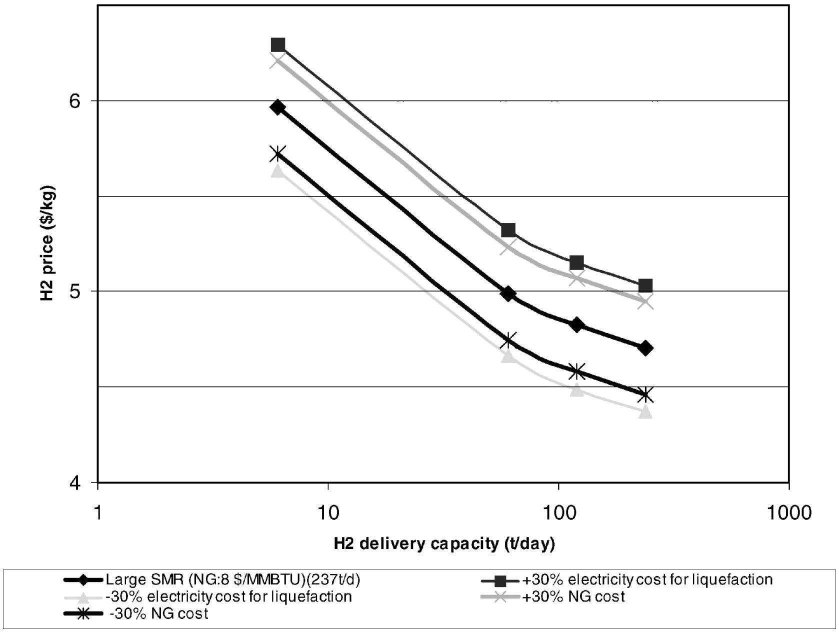

Fig. 5. Delivered $H_2$ cost at a 900 kg per day $H_2$ refuelling station for the centralised production option, as a function of liquefaction plant scale and natural gas and electricity prices.

long-term, in particular in relation to producing $H_2$ from renewable electricity (possibly even directly on-board the vehicle).

One plausible evolution of a hydrogen infrastructure is described below.

### 3.1.1. Short-term

Electrolysis at small scale offers an interesting option, more readily available and flexible in operation than small-scale steam reforming. Furthermore, electricity generators interested in the potential market for $H_2$ fuel production may become involved early on offering electricity at special rates. In addition, bulk $H_2$ from large-scale SMR plants operated by industrial gas companies and from a variety of industrial processes, such as refineries and chlor alkali plants, may be competitive.

### 3.1.2. Medium-term

On-site SMR establishes itself as the most viable option where gas is available. $H_2$ supply from large-scale SMR

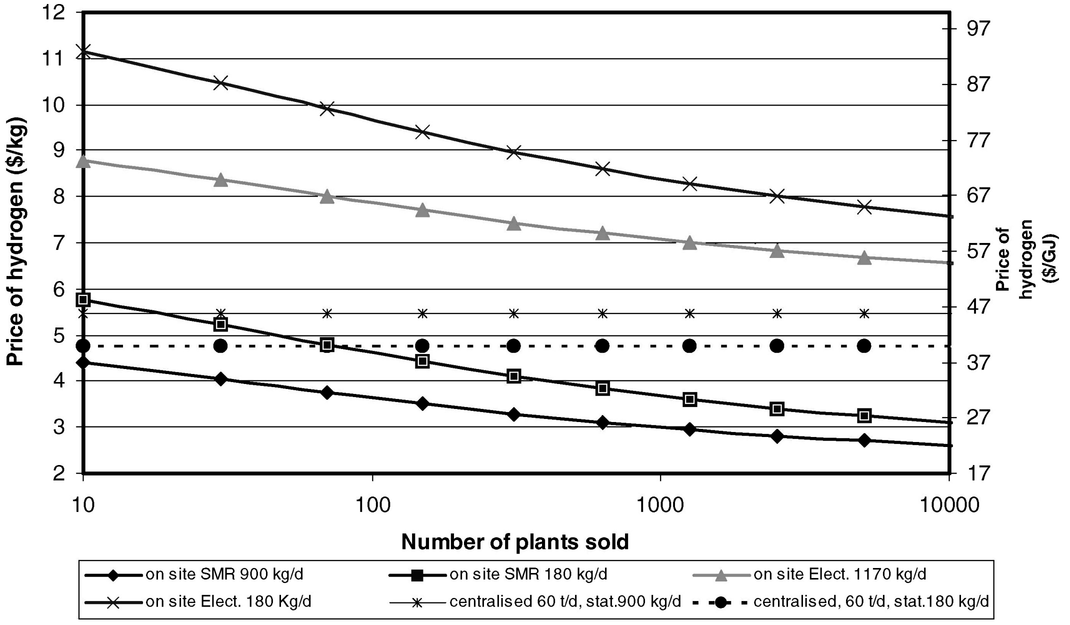

Fig. 6. Comparison of delivered hydrogen cost for different production options and as a function of learning curves.

Table 12
Fuel consumption and fuel consumption costs for ICE and FC vehicles

| | Fuel consumption (MJ/km) | Fuel related cost (US$/km) |
|---|---|---|
| Diesel bus | 13 | 0.117 |
| Gasoline car | 2.6 | 0.0247 |
| $H_2$ FC bus | 6.8 | 0.147 |
| $H_2$ FC car | 1.2 | 0.0258 |

where on-site SMR not viable because of demand (low) or location (no gas grid connection).

### *3.1.3. Long-term*

A mix of steam reforming and electrolysis options at different scales are used, with electrolysis possibly an increasingly interesting option if hydrogen can be produced at relatively low cost from renewable electricity (perhaps including incentives, such as carbon taxes, arising from environmental concerns) or other competitive clean electricity sources.

## *3.2. The cost of $H_2$ to the consumer*

To provide a useful indication of the cost of $H_2$ to the consumer, it has been expressed in US$/km driven by a FC bus and car, and compared to equivalent costs for diesel buses and gasoline cars (based both on taxed and untaxed diesel and gasoline costs). Table 12, Figs. 7 and 8 provide the energy consumption assumptions for FC, diesel and gasoline buses and cars assumed to have similar performance requirements and a fuel cost comparison. The cost of $H_2$ (US$ 2.6/kg $H_2$) is based on the on-site SMR option (900 kg $H_2$ per day) for a cumulative production of over 10,000 units.

The private cost comparisons above show $H_2$ FCV fuel costs could be competitive with current ICE fuel costs, based on untaxed costs of diesel and gasoline, on a per distance travelled basis.

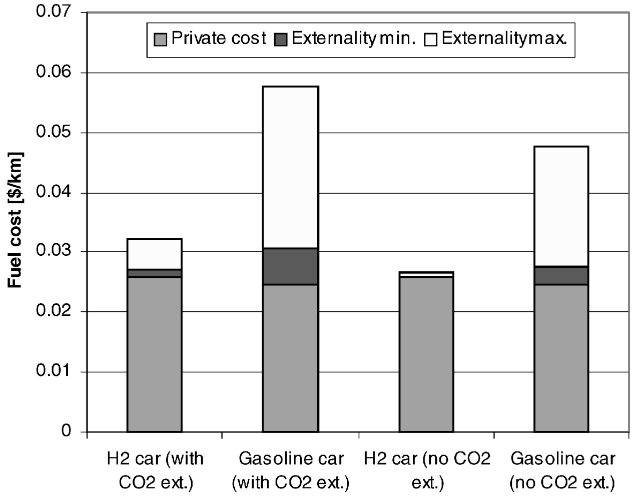

Fig. 7. Fuel cost comparison (cars).

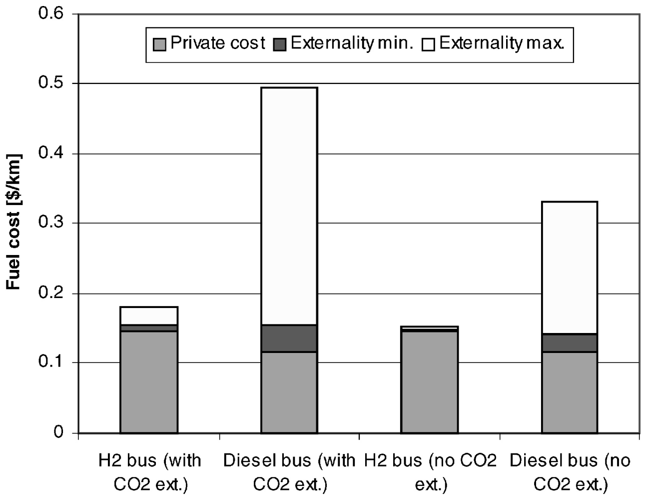

Fig. 8. Fuel cost comparison (buses).

## *3.3. Accounting for externalities*

The taxation levels of diesel and gasoline fuels are generally not meant to reflect the external costs associated with their use, although environmental concerns have been part of the rationale for increasing fuel taxes in some countries. Possible reductions in externalities associated with cleaner fuel consumption for transport could be a powerful argument for the introduction of $H_2$ fuel. The potential economic benefits associated with the substitution of conventional fuels with hydrogen could effectively be translated into price signals favouring $H_2$.

Figs. 7 and 8 provide an indication of the fuel cost, including a range of externality costs (see Table 6), for diesel, gasoline and $H_2$ in the case of buses and cars. The inclusion of externalities could significantly improve the economic viability of $H_2$ fuel. In the case of gasoline cars and diesel buses, the external costs appear to be larger than the private cost per unit distance travelled differential between these fuels and hydrogen. Thus, on a social cost basis $H_2$ would appear to be a competitive fuel.

## **4. Conclusion**

There seems to be some potential for $H_2$ FCVs in Italy. FCVs could help meet a number of consumer demands, in particular an increasing demand for environmental quality. In fact, reducing urban pollution from transport could be one of the main initial drivers behind the uptake of FCVs. Due to issues of logistics and economics, fuel cells are likely to be introduced first in buses and other fleet vehicles, which allow for centralised refuelling and possibly more favourable economics than private cars over the lifetime of the vehicle. In Italy, a number of FCV demonstration projects are planned and, under favourable conditions, FC cars could represent over 60% of cars on Italian roads in 2030. However, even under optimistic conditions, uptake will be gradual and at the most a 6% FC car penetration (2 million cars) could be expected for around the year 2015. $H_2$ fuel costs need not be a barrier in the long-term as it has been shown that on a distance travelled basis, $H_2$ fuel costs, based on mature on-site SMR $H_2$ production technologies, would only be slightly higher than those of untaxed gasoline or diesel for ICE vehicles. Also, a preliminary analysis of externalities associated with gasoline, diesel and hydrogen fuels, appears to indicate that the social benefit of introducing $H_2$ as a fuel could largely outweigh the higher private costs. The benefits that could be derived from the use of $H_2$ fuel, and its potential for long-term economic competitiveness with gasoline and diesel could justify incentives aimed at facilitating its introduction, together with FCVs, in the early stages where cost reductions need to be achieved.

All $H_2$ supply options appear to have future market potential. In the case of Italy in particular, large-scale SMR could supply a significant part of the short-term $H_2$ fuel demand and capture part of the long-term market. However, based on Italian energy market conditions and widespread gas infrastructure, on-site SMR appears to be the most interesting option to supply a FCV mass market. $H_2$ supply from electrolysis plants is likely to remain marginal in the medium-term, but could become an increasingly interesting long-term option if it can be achieved at relatively low cost from renewable electricity.

## Acknowledgements

We would like to thank Vittorio Meda of EniTecnologie for helpful discussions on some of the technical and economic aspects of this paper.

## References

[1] Ministero dell'Ambiente Relazione sullo Stato dell'Ambiente, 2001, p. 298. www.miniambiente.it/sito/pubblicazioni/pubblicazioni.asp

[2] Ministero dell'Ambiente, Relazione sullo Stato dell'Ambiente, 2001, p. 56.

[3] IEA, $CO_2$ emissions from fuel combustion 1971–1998, International Energy Agency, Paris, 2000.

[4] ENEA, Rapporto Energia e Ambiente, 2000, p. 93.

[5] Ministero dell'Ambiente, Relazione sullo Stato dell'Ambiente, 2001, p. 53.

[6] ENEA, Rapporto Energia e Ambiente, 2000, p. 99.

[7] L.D. Franklin Jr., B.D. James, G.N. Baum, C.E. (Sandy) Thomas, Detailed Manufacturing Cost Estimates for Polymer Electrolyte Membrane (PEM) Fuel Cells for Light Duty Vehicles, Directed Technologies, Inc., Arlington, 1997.

[8] www.h2forum.org

[9] K. Pehr, Aspects of safety and acceptance of $LH_2$ tank system in passenger cars, Int. J. Hydrogen Energy 21 (5) (1996) 387–395.

[10] Ford Motor Company, Direct hydrogen fuelled PEM Fuel cell system for trasportation applications: hydrogen vehicle safety report, DOE/CE/50389-502, US Department of Energy.

[11] J.M. Ogden, Developing an infrastructure for hydrogen vehicle: a Southern California case study, Int. J. Hydrogen Energy 24 (8) (1999) 709–730.

[12] Automobile Club Italia, Autoritratto 1999, www.aci.it.

[13] Staffetta Quotidiana 7/04/2001.

[14] Staffetta Quotidiana 28/07/2001.

[15] Associazione Transporti ASSTRA (Ed.), Trasporti pubblici, Aprile 2001, www.asstra.it/stampa/rivista_tp.asp, www.gasoliobianco.com

[16] Staffetta quotidiana 5/07/2001, 18/07/2001.

[17] EnergiaBlu, n. 2, March 2001.

[18] Staffetta quotidiana 3/03/2001.

[19] M. Ronchetti and A. Iacobazzi, Celle a combustibile, ENEA, 2000.

[20] www.comune.torino.it.

[21] www.aem.it, www.ecotrasporti.it/bmw/idrogeno.htm, Conference Tecnologia e unificazione delle prestazioni e dei requisiti di sicurezza per le motorizzazione a FC, Milan, 1/6/2001.

[22] www.firenze.net.

[23] D. Hart, A. Bauen, R. Fouquet, M. Leach, P. Pearson, D. Anderson, Hydrogen supply for SPFC vehicles ETSU F/02/00176/REP, 2000.

[24] A. Bauen, D. Hart, Assessment of the environmental benefit of transport and stationary fuel cell, J. Power Sources, 86 (1/2) (2000) 482–494.

[25] G.D. Berry, Hydrogen as a transportation fuel: Costs and benefits, UCRL-ID-123465, Lawrence Livermore National Lab. CA (United States), 1996.

[26] Autorità per l'Energia, Report Stato dei servizi: settore gas ed elettrico (tav. 3.5/2.16) (2001).

[27] C.E. Thomas, B.D. James, F.D. Lomax Jr., I.F. Kuhn Jr., Fuel options for the fuel cell vehicle: hydrogen, methanol or gasoline?, International Journal of Hydrogen Energy, 25 (6) (2000) 551–567.

[28] Commission of the European Communities (CEC), DG, XII Edition, 1998a, Final Reports of ExternE Phase III (preliminary versions available at http://ExternE.jrc.es), in press.

[29] R. Friedrich, P. Bickel (Eds.), Environmental External Costs of Transport, Springer, Berlin, 2001.