Hydrogen – a truly sustainable transport fuel?

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Transport energy, particularly that derived from fossil fuels, is causing increasing problems worldwide. Hydrogen as a transport fuel offers solutions to many of these issues. Produced from renewable resources, hydrogen could cut greenhouse gas emissions to zero, and the use of some fossil sources could even reduce emissions. Air quality and noise problems would also be addressed. Although developments are underway, and many countries see hydrogen as part of a sustainable energy future, implementation is being hindered by social and economic considerations and immature technology. To ensure that expectations are met, support is needed from policy makers, industry, and the public.

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We are all familiar with the everyday downside of transportation, namely traffic jams and car accidents, as well as the fact that it is a primary contributor to greenhouse gas emissions and poor air quality around the world. Almost 99% of all transport fuel is derived from crude oil, making it one of the most homogeneous energy sectors in terms of fuel supply. Transport demands account for about 60% of total oil extraction worldwide (OECD 2000).

Greenhouse gases, local and regional pollutants, and the security of energy supplies have come to the forefront in the development of local, national, and international policy, including the expected final amendments to the California Zero Emission Vehicle mandate in 2003 and the use of force to protect oil supplies in the Arabian Gulf. Increasingly, interest has focused on improving technology and switching fuels as a way to help meet transport policy targets. More specifically, the use of hydrogen as a vehicle fuel, largely in conjunction with fuel cells, is being considered.

In February 2000, the US Department of Energy produced "A National Vision of America's Transition to a Hydrogen Economy – to 2030 and Beyond", a report that outlines the potential for using hydrogen in the energy system (USDOE 2002). President Bush went further in his 2003 State of the Union address, describing allocations of $1.2 billion in funding to hydrogen and fuel cell research. In Japan, the $2 billion World Energy Network (WE-NET) project, begun in 1993, aims to enable a transition to a hydrogen economy, with hydrogen usage possibly at 10% by 2020 (Chiba *et al*. 1998). The EU has announced both major research funding and the formation of a High Level Group on hydrogen; their task is to define a vision for a European hydrogen future (Meller 2002). Meanwhile, Germany is in the process of completing a Transportation Energy Strategy study; interim results clearly indicate that hydrogen is potentially the most sustainable transport fuel for the coming years (Heuer 2000). (In this context, "sustainable" refers to the promise of greenhouse gas reduction, air quality improvement, and reduced dependence on importation.) Iceland has announced its intention of becoming the world's first complete hydrogen economy, with all of the gas produced from renewable resources.

However, hydrogen energy technology is still in development, and while hydrogen vehicles could be used in many applications even now, there is still a long way to go on the path to a full hydrogen transport system. Many think that for this system to be fully effective, we will need fuel cell vehicles that run on hydrogen and atmospheric oxygen. These are currently still in prototype form. There is also the daunting task of moving from a sophisticated, economically viable infrastructure for the distribution of petroleum products to one in which hydrogen is transported. Although the shape of this new infrastructure is unknown, it is very unlikely to mimic the one developed over many decades for crude oil and its byproducts, so many opportunities exist for innovation and improvement.

Nevertheless, hydrogen offers the potential for substantial improvements in quality of life, while maintaining the mobility and access to services that have become an equally important part of the equation. Major achievements in production, storage, and end-use technologies have come about with the increased funding and interest seen in the past decade, and near-term applications are being demonstrated in many parts of the world. Costs are approaching competitive levels, and codes and standards are already being implemented to allow a more widespread deployment of hydrogen technologies.

In a nutshell:

- Use of hydrogen-based energy has the potential to lower greenhouse gas emissions and improve air quality and energy security
- Hydrogen is an energy carrier, not a source, so we must make sure that its production and use are actually beneficial
- Governments and companies are currently investing money and other resources in its development and deployment
- Clear policy support is required to help achieve these goals

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Some caveats remain, however. Hydrogen's status as an energy carrier, rather than an energy source, means that it must be produced and used in a sustainable fashion if it is not simply to be employed as a placebo. If its integration is mishandled, things could become worse instead of better.

■ Background

Several publications cover the historical and current background of hydrogen as a vehicle fuel, in considerably more detail than this paper can (Hoffmann 1981; Hart 1997; Ogden 1999; Hoffmann 2001).

Hydrogen is a colorless, odorless, non-toxic, flammable gas, which can be used as a transport fuel in an internal combustion engine (ICE) or fuel cell vehicle. It has no local pollutant effects and is not a greenhouse gas, but is only found in useful quantities in compound forms, such as water or hydrocarbons (organic compounds containing carbon). As with electricity, a primary energy source must be used to produce hydrogen. The gas also has some characteristics that make it difficult to handle as a vehicle fuel; it is in gaseous form at standard temperature and pressure (0°C and 1 atm), and must be cooled to -253°C, only 20°C above absolute zero, to liquefy it. It is the lightest of the elements and has a very small molecular diameter, which allows it to slip through small spaces and diffuse through some materials. Storage vessels for hydrogen may therefore be bulky and/or heavy.

Hydrogen has been used as a fuel in ICEs since approximately the 1930s, though experiments were carried out well before then. Around WWII, the German engineer Rudolf Erren converted a wide variety of vehicles, including trucks, cars, locomotives, and ships, to run on hydrogen or hydrogen-rich fuel blends.

Hydrogen is also being used in the vast majority of fuel cell vehicles currently under development and in demonstration stages. It is the ideal fuel for the type of fuel cell – the proton exchange membrane – used in almost all road transport applications under consideration. It reacts quickly with oxygen in the air to produce electrical power to drive a motor. The only byproduct is water vapor, and the drive cycle efficiency can be double that of the equivalent ICE, or up to 50% better than a hybrid electric vehicle (Thomas *et al.* 1998).

■ Drivers for use in transport

Historically, the most substantial drivers for fundamental changes in fuel use have been technological and economic. The development of the steam engine substantially increased the demand for coal, the internal combustion engine fed on newly discovered oil sources, and gas turbines and uses for the natural gas found in oil fields developed in tandem (Yergin 1991; Grübler *et al.* 1999). The discovery of electricity and its many applications also had a profound effect on fuels and technology – in the late 1890s and early 1900s, electric vehicles were actually more common than those fitted with internal combustion engines.

However, the primary drivers for using hydrogen as a transport fuel – climate change, air quality, and energy supply security – are different. The technology option may come in the form of the fuel cell, but appears to be less of a driver. Each of the primary drivers are of varying importance in different parts of the world. Others, such as noise reduction, biodiversity protection, and regional acidification, are also considered, but often only as an afterthought.

In the US, supply security and import dependence is paramount, with California leading the way in addressing air quality concerns, and only a marginal interest shown in greenhouse gas emissions. In Europe, the focus is on greenhouse gases, while in Japan interest is divided between climate change and security of supply. The reasons behind these are obvious when considered in a geopolitical context.

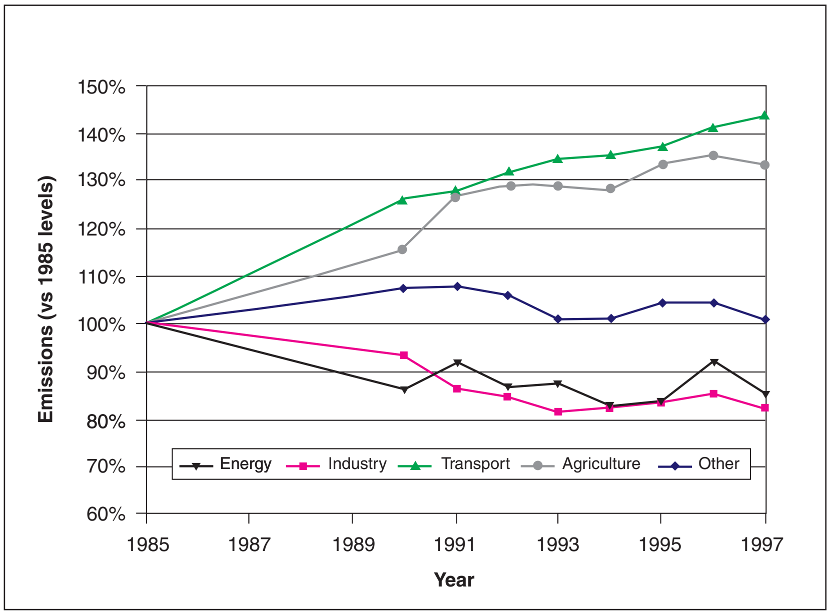
US policy drivers

The drivers for hydrogen energy development in the US are well summarized in the USDOE paper mentioned above. These apply also to other countries and regions, and are summarized in Table 1. The clear message from the paper and other government communications is that energy security is the main driver for investigating the use of hydrogen in the transport sector. Petroleum consumption became greater than domestic supply in the US around 1949, and by 1998 even net imports exceeded domestic supply (EIA 2001).

Table 1. Key drivers affecting hydrogen energy development

Supports	Inhibits	Both supports and inhibits
National security and the need to reduce oil imports	Inability to build and sustain national consensus on energy policy priorities	Rapid pace of technological change in hydrogen and competing energy sources and technologies
Global climate change and the need to reduce greenhouse gas emissions and pollution	Lack of hydrogen infrastructure and substantial costs of building one	Current availability of relatively low-cost fossil fuels, but the inevitable depletion of these resources
Global population and economic growth and the need for clean energy supplies at affordable prices	Lack of commercially available, low-cost hydrogen production, storage, and conversion devices, such as fuel cells	Simultaneous consumer preferences for a clean environment and affordable energy supplies
Air quality and the need to reduce emissions from vehicles and power plants	Hydrogen safety issues	

Courtesy of US Department of Energy (2002)



Courtesy of Eurostat

Figure 1. *Changes in CO_2 emissions from different EU sectors from 1985–97, showing the great increase in relative emissions from transport. While agriculture also looks like a problem sector in this representation, its absolute emissions are one-sixteenth that of transport, so its impact is far smaller.*

Policy drivers in other countries

Both Japan and Germany are almost completely reliant on petroleum products produced elsewhere (BP 2001). This extreme dependency is partly responsible for the move towards hydrogen as a vehicle fuel, although climate change has also had a major influence. Both countries have ratified the Kyoto Protocol and have undertaken to reduce emissions in comparison with 1990 baselines (Germany by 8% and Japan by 6%) (United Nations 1998). As the transport sector typically contributes around 30% to the CO_2 emissions of a developed country (OECD 2000), and since that sector is growing in all parts of the world, it is a substantial target. Figure 1 summarizes the problem by showing the change in contribution of CO_2 emissions from different sectors in the EU over a 13-year period. Relative emissions from transport have increased by 45%, and the trend is set to continue.

Demand-side drivers

Demand-side drivers are the result of increasing awareness of the disadvantages of fossil fuel use and traditional combustion technologies, and the policies introduced to combat some of these issues. In addition, demand for new technologies such as fuel cells, and new industry or market opportunities, will each play a part in creating demand. The list of drivers includes:

- Growing demand for low carbon fuels in response to climate change issues
- Demand for low pollution fuels, based on local air quality problems and regional pollution such as acidification
- Demand for resource diversification, based both on security of energy supply and resource scarcity
- Demand for fuel cells, many of which operate best on hydrogen
- Energy market liberalization, which carries the danger of deterring new investment, but which is encouraging novel solutions to local problems and innovation within the energy sector
- Hydrogen as a possible energy vector for the use of renewable fuels in transport
- Desirability of electric traction increasing automotive companies' interest in fuel cells

The supply side of hydrogen energy development, especially the technological aspect, has also contributed to the recent interest in hydrogen energy. The economics of hydrogen technologies are improving, with increased research and development effort, both in the public and private sectors.

Barriers

Despite all the drivers listed above, hydrogen is rarely used as a fuel today. Specific obstacles include:

- The typically high cost of the gas (owing to the fact that it is produced for specialist chemical uses rather than as a fuel)
- Hydrogen's physical properties make it difficult and costly to store and transport, although recent advances in materials and processes are helping to reduce this problem
- Entrenched interests in the industrial and energy fields have had no reason to shift from the fossil fuel-based status quo
- Hydrogen has different chemical and physical properties from other fuels, and needs to be handled differently to ensure safety
- Standards for hydrogen energy use (such as accurate, repeatable, low-cost methods of sensing hydrogen and measuring flow rates) are only now being developed, which has hindered demonstrations and the development of applications
- Hydrogen fueling stations have only recently been introduced, and require a substantial investment in order to achieve cost reduction, production engineering and standardization

The successful future integration of hydrogen as a transport fuel will depend as much on overcoming these barriers as on capitalizing on the drivers. Technology development and deployment is a highly critical area that requires attention.

■ Current technologies

Like electricity, hydrogen is an energy carrier, not an energy source. This gives great flexibility to its use, in that it can be produced from locally appropriate energy sources, including solar, wind, biomass, natural gas, or even nuclear power. This also means that the gas will always be more expensive per unit of energy than those primary sources. However, the end-use cost depends on many other factors, and if hydrogen use is both clean and efficient, then it may be given economic breaks, which will help it to compete with conventional fuels.

An important consideration in terms of cleanliness and efficiency is the full fuel chain of hydrogen production, transport, and end use. Hydrogen from wind electrolysis or nuclear electrolysis may have the same local end-use impacts, but upstream, the production effects will be dramatically different. Hydrogen produced from natural gas, on the other hand, will have a different emissions and efficiency profile than that produced from coal. Some of these effects are discussed later in this paper, but to understand them it is useful to look briefly at hydrogen energy technologies from production to end use.

Hydrogen production

Hydrogen is produced from a wide range of primary resources, employing a similarly wide range of technologies. Table 2 lists those in general use and development. Most hydrogen currently in use around the world is produced via the large-scale steam reforming of methane (Suresh *et al.* 2001). Some is created as a byproduct of industrial chemical processes, such as chlor-alkali production, and off-peak electricity is also used for electrolysis in places where this is economically feasible. More esoteric means of production include harvesting the respiration products of certain strains of algae, direct thermal decomposition (splitting water into H_2 and O_2 by heating to very high temperatures), and direct photolysis (chemical decomposition induced by radiant energy such as light), but these are all currently just at the research and development stage (Cammack *et al.* 2001).

Table 2. Hydrogen production methods

Resource	Production Method
Hydrocarbon-rich gas	Steam reforming
Oil/heavy liquid hydrocarbons	Partial oxidation
Coal	Partial oxidation
Woody biomass	Partial oxidation
Wet biomass	Digestion
Electricity (including renewable)	Electrolysis

Storage

Hydrogen is the lightest and smallest molecule, making it difficult to store in compact or light systems. Common storage methods include compression, liquid, and solid-state systems. Compression systems involving steel tanks can store about 3% by system weight (including tanks, valves, regulators, etc), while advanced composite tanks, either made of aluminum liners and carbon fiber wrap or entirely of composites, can store up to 13% by weight, at pressures of up to 70 MPa. Metal hydride systems typically operate at around 2%, though high-temperature hydrides can store up to 6–7%. Hydrogen liquefies at -253°C, so liquid hydrogen systems require expensive and complex insulating tanks – vacuum-wrapped, multi-layered, even magnetically suspended to minimize losses – but these can store around 8% hydrogen.

Internal combustion engines

Hydrogen can be burned in a standard ICE with minimal modification. If it is burned in a dedicated hydrogen engine, then performance may be better than with a comparable gasoline engine. Hydrogen has a high flame speed and flame temperature, meaning that alterations to input and timing are required for its use in conventional engines, but it burns well. Emissions are very low. NOx (oxides of nitrogen emissions) arise from the high-temperature combustion process, although these can be reduced using lean-burn engines and catalysts, and there may be trace hydrocarbons from the lubricating oil used in the engine. There are no other on-board (ie tailpipe) emissions.

Fuel cells

Hydrogen can be used more efficiently in fuel cells than in ICEs. A fuel cell is a device for directly converting the chemical energy of a fuel into electrical energy in a constant temperature process – like a battery, but with a continuous supply of fuel. Unlike ICEs, fuel cells are not limited by the difference in temperature between input and output (called the Carnot efficiency), and they can therefore be considerably more efficient. Many detailed descriptions of fuel cell engines have been published, including Appleby and Foulkes (1993); Blomen and Mugerwa (1993); Kordesch and Simader (1996); Hart and Bauen (1997); Larminie and Dicks (2000).

In practical terms, these characteristics give fuel cell vehicles several potential advantages over ICEs. Their primary disadvantage at present is cost, although their reliability has yet to be proven, and there is also the problem of availability. Fuel cell vehicles have the potential to be at least twice as efficient as conventional vehicles over a standard drive cycle (including urban and highway driving) (Friedlmeier *et al.* 2000). Some of this advantage is diminished in comparison to a hybrid (gas–electric) drivetrain, but the other advantages remain. Polluting emission levels from a hydrogen fuel cell vehicle are zero, which is

Courtesy of DaimlerChrysler

Figure 2. *Fuel cell-powered NEBUS (New Electric Bus) in Stuttgart-Möhringen, Germany*

impossible to achieve with any combustion technology. Noise levels are extremely low, as a fuel cell produces no noise in operation (though some will be produced by auxiliary components such as compressors and pumps). Also, a fuel cell can generate considerable amounts of electrical power, above what is needed to turn the wheels; this could be used for anything from more efficient air conditioning to on-board electrical systems. Further into the future, it may well be possible to use this extra resource to supply power to buildings, for example when the car is not being driven. Taking hydrogen from a local source and converting it at a high efficiency to electricity for local use could solve some problems associated with developing new grid infrastructure and building new power plants (Kempton and Letendre 1997; Kempton *et al.* 2001).

Hydrogen transport demonstrations

Current deployment of hydrogen energy technology is very limited, and is primarily in the form of demonstration systems in the US, Canada, Japan, and Germany. In recent years, more and more such systems have been built, and many others are planned or under construction. Government investment has also increased, with the US aiming to increase its spending by 30%, bringing it to $40 million in fiscal year 2003 on research and development alone, and Japan is planning to spend approximately the same amount. In October 2002, the EU announced the creation of a High Level Group of major corporate and other institutions to develop a hydrogen economy plan for Europe, and has set aside significant monies for hydrogen in its 6th Framework Program of research and development funding, to run from 2003–07.

Despite the low level of actual usage, hydrogen transport demonstrations are becoming widespread. Leaving aside test stations built within industrial or automotive industry premises, at least three hydrogen fueling stations currently exist in California, and several more are being built. Four exist in Japan, with six more due for completion in 2003; two have been built in Germany, and three are currently under construction; and at least 15 more are planned for Europe, Australia, and Southeast Asia. The main funding is coming from industrial entities such as BP, Shell, and Air Products, with major support from the governments of the EU, US, Canada, and Japan. As part of the EU-funded Clean Urban Transport for Europe (CUTE) project, hydrogen fuel cell buses and fueling stations will be introduced into nine European cities (Figure 2). DaimlerChrysler announced in October 2002 that it would put 60 "F-Cell" versions of its A-class car into demonstrations worldwide in 2003. General Motors, Toyota, and other auto manufacturers are similarly optimistic. To enable comparison between costs, development issues, and other factors, the hydrogen for these different demonstrations comes from different sources, including the steam reforming of natural gas, PV electrolysis from solar photovoltaic power, reformation of liquified petroleum gas and methanol, trucked-in liquid hydrogen, and grid electrolysis.

Future deployment

Although the widespread introduction of hydrogen energy systems in any sector will clearly take a long time, specific plans are emerging. The Japanese Millennium Project, funded by the Ministry of Economy, Trade and Industry, aims to have 50 000 hydrogen fuel cell vehicles on the roads by 2010, while the US Department of Energy is planning 5000 in a similar timeframe. Whether these and other targets can be achieved depends on several factors, including government policy (local, national, and international on CO_2 emissions, local pollutants, energy diversity, and

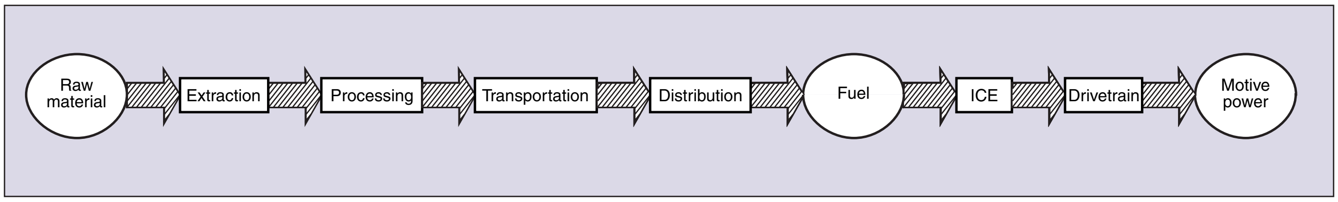


Figure 3. *Schematic fuel chain*

security); automotive companies achieving desired performance, lifetime (about 5000 operating hours), and cost targets for hydrogen vehicles; and the development of an infrastructure for the provision of the gas.

Some scenarios suggest that hydrogen could achieve significant penetration into the energy sector in general by 2050 (SIGBE 2001; Barreto *et al.* 2002). In developing these scenarios, the environmental drivers have been assumed to be a strong influence.

■ Possible benefits

Hydrogen transport systems can be completely carbon free, assuming either renewable- or nuclear-generated hydrogen or full carbon capture and sequestration from fossil fuel generation. On the other hand, hydrogen produced from coal without sequestration can increase CO_2 emissions in comparison to conventional generation. Specific greenhouse gas reductions depend on the fuel chain of the specific method of production. Of course, greenhouse gases are not the only concern. Local pollutants and other environmental impacts may also guide the choice of primary energy. In the long term, many people view renewable hydrogen as the only sustainable option.

Greenhouse gas emissions

When comparing fuel emissions, the entire fuel chain (Figure 3) must be taken into account, including production, distribution, and end use. While the effects of some emissions will depend on their location (for example, particulates will cause more health damage in highly populated areas), greenhouse gases have a global impact, and so emissions from any part of the chain are equally important. Hydrogen generates no CO_2 emissions from its end use, but its production may entail substantial greenhouse gas emissions.

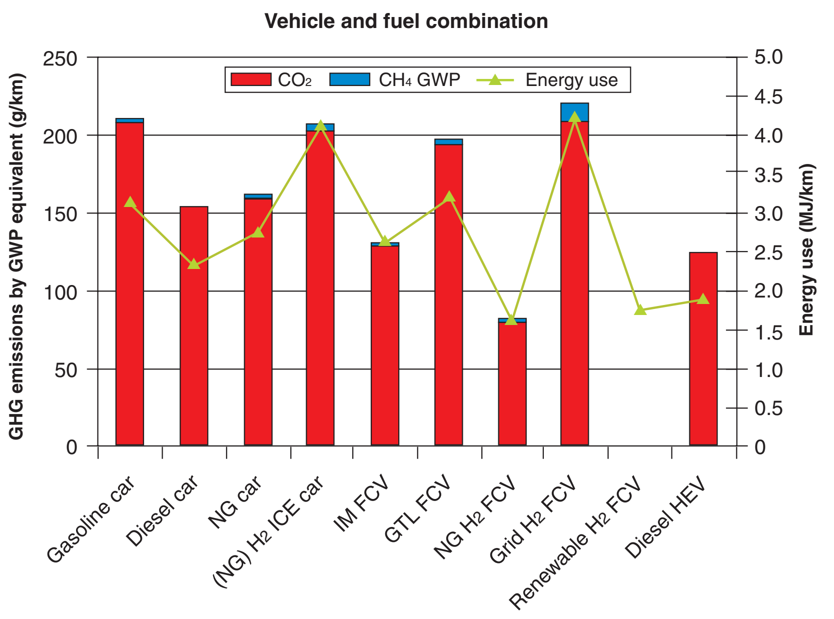
Figure 4 shows the results of modeling carried out using UK data (Hart 2002), building on work of Hart and Hörmandinger (1998) and Bauen and Hart (2000). Many similar analyses have been carried out, with similar results (Thomas *et al.* 2000; GMC *et al.* 2001, 2002; Weiss *et al.* 2003). These suggest that significant reductions can be made in CO_2 emissions from the transport sector by the introduction of hydrogen.

Figure 4 also shows the differences in emissions between hydrogen used in ICEs and fuel cells, and hydrogen from different sources. Clearly, renewable hydrogen used in any application results in zero greenhouse gas emissions. Hydrogen from natural gas also has low emissions, but it is still a fossil fuel and, in the longer term, is unlikely to be sustainable. The poor performance of the ICE in comparison to the fuel cell vehicle is due to its lower efficiency and therefore greater fuel requirement.

Other environmental impacts

Regulated pollutant emissions

The vast majority of hydrogen transport applications will have next to no polluting emissions. Emissions are lim-



NG – natural gas
Grid H_2 – hydrogen from electrolysis using UK grid electricity
H_2 IE car – hydrogen internal combustion engine
NG H_2 – hydrogen from steam-reformed natural gas
IM – indirect methanol (on-board reformer)
FCV – fuel cell vehicle
GTL – gas-to-liquid synthetic fuel (on board reformer)

Figure 4. *Full fuel cycle greenhouse gas emissions and energy use from different fuel chains*

ited to water vapor and NO_x formed from high-temperature combustion in ICEs, and which can be easily removed. The production of hydrogen can give rise to local and regional pollutant emissions such as NO_x. These are typically very low in comparison to combustion processes. Studies suggest that over a full fuel chain, the total emissions of regulated and other pollutants can be up to an order of magnitude lower for hydrogen systems (Wang 1996; Ogden *et al.* 1999; Thomas *et al.* 2000).

Noise

Hydrogen ICEs are based on spark ignition, and are thus quieter than diesel engine systems and comparable to compressed natural gas engines. Hydrogen fuel cells are very quiet – typically one or two orders of magnitude quieter than combustion engines under normal circumstances.

Site impact

Hydrogen is nontoxic and dissipates rapidly into the air. It does not build up in the environment, and cannot pollute groundwater or soil.

Safety

Engineering studies suggest that the use of hydrogen presents a danger level similar to that of gasoline, natural gas, or other common energy carriers. It has different characteristics and must be handled differently, but standards are being put in place to ensure that this is done safely. However, to date hydrogen use has rested primarily with trained personnel in industrial environments, and its widespread use by the public will require careful introduction and development. In addition, public perception issues must be addressed, though studies suggest that hydrogen has a low public profile, rather than a negative one (LBST 1997).

■ What does the future hold?

The ultimate transport fuel system would use hydrogen produced renewably, either directly from biomass or from electrolysis. Until enough renewable capacity has been built, it may be possible to use hydrogen from fossil fuels to help the transition – even going as far as using CO_2 capture and sequestration once the technology is proven. Hydrogen from nuclear power is also seriously being considered as a carbon-free source, particularly in the US, but nuclear power has formidable economic and public acceptance barriers to overcome.

Despite the many apparent advantages to the introduction of hydrogen, public policy strategies are required to overcome some of the barriers. Furthermore, the use of hydrogen can bring significant increases in pollution and greenhouse gas emissions if it is not done well – for example, using electrolytic hydrogen from coal-fired power plants without carbon sequestration. Until the gas becomes plentiful, renewable electricity may be a better way to reduce emissions from fossil-fuel power stations, although biomass may also be an excellent fuel source (Eyre *et al.* 2002). Policy makers therefore need to take care, not in terms of what they wish for, but how they set about achieving it.

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