INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 34 (2009) 615–627

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

The future of hydrogen – opportunities and challenges[☆]

Michael Ball[a,*], *Martin Wietschel*[b]

[a]*Shell International B.V., Carel van Bylandtlaan 23, 2596 HR The Hague, The Netherlands*
[b]*Fraunhofer Institute for Systems and Innovation Research (FhG ISI), Breslauer Straße 48, D-76139 Karlsruhe, Germany*

ARTICLE INFO

Article history:
Received 4 April 2008
Received in revised form
11 November 2008
Accepted 11 November 2008
Available online 16 December 2008

Keywords:
Hydrogen
Hydrogen energy system
Alternative fuels
Hydrogen infrastructure analysis
Global hydrogen scenarios
Fuel cells
Peak oil

ABSTRACT

The following article is reproduced from '*The Hydrogen Economy: Opportunities and Challenges*', edited by Michael Ball and Martin Wietschel, to be published by Cambridge University Press in June 2009. In the light of ever-increasing global energy use, the increasing cost of energy services, concerns over energy supply security, climate change and local air pollution, this book centres around the question of how growing energy demand for transport can be met in the long term. Given the sustained interest in and controversial discussion of the prospects of hydrogen, the authors highlight the opportunities and the challenges of introducing hydrogen as alternative fuel in the transport sector from an economic, technical and environmental point of view. Through its multi-disciplinary approach the book provides a broad range of researchers, decision makers and policy makers with a solid and wide-ranging knowledge base concerning the hydrogen economy.

1. Context – the energy challenge of the future

Today's energy and transport system, which is based mainly on fossil energy carriers, can in no way be evaluated as sustainable. Given the continued growth in the world's population as well as the progressive industrialisation of developing nations, particularly in Asia but also in South America, the global demand for energy is expected to continue to escalate in the coming decades – by more than 50% until 2030, according to the International Energy Agency (IEA) – with fossil fuels continuing to dominate global energy use.[1] At the same time, there is a growing global consensus that greenhouse gas (GHG) emissions, which keep rising, need to be managed in order to prevent dangerous anthropogenic interference with the climate system. Hence, security of supply and climate change represent two major concerns about the future of the energy sector which give rise to the challenge of finding the best way to rein in emissions while also providing the energy required to sustain economies. Concerns over energy supply security, climate change as well as local air pollution and the increasing prices of energy services are having a growing impact on policy making throughout the world.

☆ Disclaimer: This article represents the authors' views and not the views of any other person or organisation.

* *Corresponding author.*
E-mail address: michael.ball@shell.com (M. Ball).

[1] While this 'traditional' energy growth prognosis is a commonly accepted 'given' of other long term global energy scenarios as well, they generally fall short of discussing its actual dimension and impact on the planet, such as accompanying resource depletion and ecological consequences. Actual research works try to focus more on the energy resource problem and the influence on demand development.

doi:10.1016/j.ijhydene.2008.11.014

The transport sector today accounts for some 18% of primary energy use and some 17% of global CO_2 emissions, with the vast majority of emissions coming from road transport. Transport is also responsible for 20% of the projected increase in both global energy demand and greenhouse gas emissions until 2030. At present, oil is still the largest primary fuel with a share of more than one third in the global primary energy mix and more than 95% of transport energy demand. Any oil supply disruptions would therefore hit the transport sector hardest since, worldwide, it is almost entirely dependent on oil. Moreover, there is a high geographical concentration of oil as well as a growing import dependency on a few, often politically unstable countries (at least from the Western world's point of view). Mounting anxiety about the economic and geopolitical implications of possible shortages in the supply of oil as a pillar of our globalised world based on transportation and the need to reduce greenhouse gas emissions in the transport sector are triggering the search for alternative fuels.

1.1. *The challenge for road transport*

1.1.1. *Shortage of cheap oil – a driver for a paradigm shift in the transport sector?*

Oil and gas still make the world work; fossil fuels still account for about 80% of today's global primary energy supply. The worldwide demand for oil has reached new heights, led by China and other rapidly industrialising countries. The shrinking margin between oil production capacity and demand is largely responsible for the rapid rise in oil prices in recent years. Given the extent to which the industrialised world has come to depend on oil as a pillar of its economy, possible shortages in the supply of oil as a consequence of declining production are likely to result in abrupt and disruptive changes.

There will always be considerable uncertainty concerning how much oil still exists under the Earth's surface and how much can be recovered. There is a long history of failed forecasts regarding the peaking of oil production and experience shows that reserves are usually underestimated. However, there are compelling reasons why current projections can be taken to be more reliable than previous ones. For instance, global production has been exceeding new discoveries since the 1980s and the size of new discoveries is also decreasing.

The most recent world energy scenarios project that global oil demand will grow by more than one third until 2030. According to this projection, cumulative oil production will have to almost double to meet the rising demand. The analysis in this book reveals a mismatch between these growth scenarios and the remaining potential of conventional oil: if we continue with business as usual, we are likely to face shortcomings in the supply of oil in the coming decades. The analysis further suggests that conventional oil production will peak some time around 2010–2020. Moreover, the dependency on oil imports in all the major importing regions is projected to increase in the future, especially the reliance on OPEC countries since these hold around 75% of the known remaining reserves.

The analysis of resource potential vs. growth in oil demand clearly indicates that it is time to develop alternatives to oil as the main fuel for the transport sector. This leads to the question as to how the growing transport energy demand can be met in the long term when conventional (easy) oil runs out and crude prices remain high. Next to energy-saving strategies, what are the choices? The principal options being discussed include unconventional oil from oil sands or oil shale, synthetic liquid fuels (Fischer-Tropsch fuels) on the basis of gas or coal, biofuels, electricity as a fuel for battery electric vehicles (BEV) or plug-in hybrid electric vehicles (PHEV), and hydrogen.

1.1.2. *Climate change and other environmental impacts*

Transport systems perform vital societal functions, but in their present state cannot be considered 'sustainable'. Particular concerns in this respect include local air pollution (particulate matter, ozone), climate change, congestion, land use, accidents, and noise. Local air pollution, especially from road transport, is quickly becoming a major issue for urban air quality, particularly in the world's growing megacities. At a global level, greenhouse gas emissions from the transport sector and from fuel production represent another major problem and are increasingly subject to regulation around the world. Since the 1970s, GHG emissions from the transport sector have grown by more than 120% worldwide, and most scenarios predict that this trend will continue in the future.

The increasing global demand for fuel is one of the main reasons for the rise in greenhouse gas emissions. Emissions of CO_2, the main greenhouse gas from human activities, are the subject of a worldwide debate about energy sustainability and the stability of the global climate. Evidence that human activities are causing the planet to warm up is now unequivocal according to the Intergovernmental Panel on Climate Change (IPCC). To meet stringent climate change targets, such as stabilising CO_2 concentrations below 550 ppm, or limiting the global temperature rise to 2 °C above pre-industrial levels requires drastic CO_2 reductions of 60–80% in 2050 compared to 1990 emissions, which is a daunting challenge. This will require a portfolio of technologies and mitigation activities across all sectors such as improving energy efficiency, carbon capture and storage (CCS) and the use of renewable energies or nuclear power. Deep emissions' cuts will also be required in the transport sector. Implementing CO_2 emissions reduction measures in the transport sector is often accompanied by the co-benefits of reducing traffic congestion and/or improving air quality.

1.1.3. *The options*

Resolving the problems of road transport requires new solutions for transport energy use. The principal options are demand-side measures, more efficient vehicles and cleaner fuels. The former aim at reducing transport demand and using vehicles more efficiently, and include primarily transport demand management (TDM) like city taxes, road and parking pricing, a modal shift from private car use to public transport, park&ride, car sharing or promoting cycling and walking, but also improved freight logistics, shifting freight transport from roads to rail, tele-working as well as improved driving habits. In the near and medium term, smaller cars, more lightweight and aerodynamic construction and better drive train efficiency through improved conventional internal combustion engines (ICEs), hybridisation or dieselisation can all further improve the fuel economy of vehicles and help reduce fuel consumption and emissions. To give a theoretical example of what an improved fuel economy of vehicles could achieve: a dieselisation of the entire US light duty vehicles fleet or likewise replacing the current US gasoline fleet with more efficient EU-like gasoline vehicles would result in fuel savings of as much as 2–3 million barrels of oil per day. Longer term strategies must focus on developing alternative fuels and propulsion systems.

Incentives also need to be given to motivate car manufacturers to produce more low-fuel consumption and CO_2 efficient vehicles and to encourage people to buy cars with reduced fuel consumption. However, mobility is one of the major drivers of economic growth and societal development, so reducing energy demand and CO_2 emissions from transport, especially from personal transport, is a particular challenge.

1.2. Alternative fuels and propulsion systems

The present level of oil prices, growing concerns about whether world oil supplies will be able to meet increasing demand, especially from the developing economies of Asia, as well as the mounting number of countries experiencing declines in conventional oil production are prompting significant investments in oil sands and a renewed interest in oil shale, as well as in synthetic Fischer-Tropsch fuels from gas (gas-to-liquids (GTL)) and coal (coal-to-liquids (CTL)). There is also a significant push for biofuels taking place around the world. Interest in these alternatives is also motivated by energy security concerns which tend to stimulate a greater reliance on indigenous energy resources which often result in increased greenhouse gas emissions. Nevertheless, all these fuels have in common that they are simple to handle, have a high volumetric energy density, are easy to store on board a vehicle and can use the existing distribution and refuelling infrastructure.

Despite the considerable growth of the Canadian oil sands industry in recent years, there are still several difficulties that could impede the future development of this industry, for instance, the heavy reliance on natural gas and water, which are necessary for both the extraction of bitumen from oil sands and its upgrading to synthetic oil, as well as the associated high emissions of CO_2. For nearly a century, the oil shale in the western United States has been considered a possible substitute source for conventional crude oil. If a technology can be developed to economically recover oil from oil shale, the quantities would be in the range of today's conventional oil reserves. But the economics of shale oil production have persistently remained behind conventional oil. The prospects of oil shale development are uncertain and many issues related to technology performance, and environmental and socio-economic impacts remain unresolved. The potential resource base of these unconventionals is vast, but their extraction comes potentially at a much higher energy penalty and CO_2 intensity compared to conventional oil production – unless Carbon Capture and Storage (CCS) is applied – and may also result in detrimental environmental impacts, such as loss of biodiversity.

While synthetic fuels can be designed for optimal combustion in the engine and thus significantly reduce local emissions (e.g. due to low sulphur content and low particle emissions), the production of synthetic fuels from fossil energy sources is much more CO_2 intensive than conventional refining; in the case of CTL, more than ten times as intensive (without carbon management). Moreover, solely from a thermal process efficiency point of view, the syngas route favours the production of hydrogen rather than Fischer-Tropsch fuels (neglecting infrastructure build-up and vehicle availability), as this does not require Fischer-Tropsch synthesis, which itself has substantial hydrogen requirements, especially for the fuel synthesis on the basis of feedstocks with low hydrogen/carbon ratio such as coal and biomass. At present, the methanol route also has a low energy efficiency due to the energy consuming intermediate step of synthesis gas. If a catalyst were discovered which is capable of converting methane directly and easily to methanol, then this would also be a very attractive fuel for use in Direct Methanol Fuel Cells (DMFC). However, as things stand at present, hydrogen can be used as a secondary energy carrier in fuel cells without emitting any CO_2, so it does not make sense to convert hydrogen to methanol (another secondary energy carrier), which does emit CO_2 when used in a fuel cell.

Growth prospects for any unconventional oil source will depend to a large extent on the prices for conventional hydrocarbons and on environmental constraints. If the cost of producing unconventional oil becomes competitive with the cost of oil from conventional sources – either due to technological improvements or higher oil prices – and the environmental problems can be overcome, then unconventionals will find a place in the fossil fuel market in the future. If oil prices remain at relatively high levels, unconventionals production (incl. GTL and CTL) could reach between 7 and 15 Mb/day in 2030, i.e. between 6 and 13% of the total projected oil production at this time, of which around one third would come from oil sands. In the near and medium term, unconventional oil is not a silver bullet. Unconventionals may delay the mid depletion point of oil production for a short time, but the global decline of production cannot be prevented long term if demand continues to surge.

Today, due to policy support schemes, 'first-generation' biofuels (biodiesel and bioethanol) are gaining relevant market shares in some world regions like Europe or the US as a means to reduce transport-related GHG emissions and enhance supply security. However, there are various concerns associated with the supply of biofuels (particularly 'first-generation' biofuels), which challenge their overall sustainability and may constrain large-scale production: net reduction of GHG emissions, competition for water resources, use of pesticides and fertilizers, land use, impacts on biodiversity (such as loss of rainforest) as well as competition with food (crop) production for arable land availability, which may drive up food and fodder prices. As a consequence, biofuel mandates, especially in the EU, are being scrutinized and reviewed from a sustainability perspective. Moreover, biomass use for transportation fuels is increasingly in competition with stationary heat and power generation for feedstock availability. 'Second-generation' biofuels, such as ligno-cellulosic ethanol, could potentially extend the feedstock base and avoid interference with the food chain. However, more R&D is needed before these 'second-generation' biofuels become commercially available.

Tailpipe CO_2 emissions from biofuels are not much different from those for gasoline and diesel, but as the CO_2 released has previously been fixed by photosynthesis in the plants, biofuel combustion is generally considered to be CO_2 neutral. But the overall balance of GHG emissions over the entire supply chain of biofuels depends on several factors, such as crop type and yield, the amount and type of energy embedded in the fertilizer production and related emissions, the emissions impact of land use and land use change as well as the (fossil) energy used to harvest and transport the feedstock to the biorefinery and the energy intensity of the conversion process. In the case of biodiesel from palm oil from Indonesia for example, the GHG emissions are several times higher than is the case for conventional diesel production. Besides this, from the overall perspective of CO_2 reduction in the energy sector, the massive extension of biofuel production must be critically reflected as biomass can be used up to three times more efficiently in heating and combined heat and power than in producing the currently used biodiesel and bioethanol. While this also holds true for hydrogen, biomass yields more kilometres when used via hydrogen in fuel cell cars than liquid biofuels in ICE cars; moreover, as hydrogen is produced via gasification, it can be considered a second-generation biofuel.

Biofuels are appealing as, once produced, they require only limited changes in infrastructure and the performance and costs of a vehicle powered by biofuel are not substantially different from those of a fossil fuel powered vehicle. But biofuels alone cannot solve the dual problem of meeting a growing transport energy demand and reducing emissions. Biofuels (incl. bio-hydrogen) have only a limited ability to replace fossil fuels and should not be regarded as a 'silver bullet' solution to reducing transport emissions. Biomass availability, competition for end uses as well as socio-economic and environmental implications all place limits on biofuel use. At a global level, it is estimated that biomass-derived fuels could substitute a maximum of 20–30% of today's total vehicle fuel consumption.

Another alternative fuel already being used in many countries is (compressed) natural gas (CNG). Of all the alternative fuels (apart from hydrogen and electricity), natural gas achieves the greatest reduction of 20–25% in vehicle emissions of CO_2. The primary requirement for CNG is the implementation of new refuelling stations, as a natural gas distribution infrastructure is already largely in place in most countries. As an interim solution in response to the lack of a widespread availability of fuelling stations, bi-fuel vehicle concepts are being introduced. Nevertheless, the benefits of CNG, as well as LPG (Liquefied Petroleum Gas), are unlikely to offset the costs associated with further development of the refuelling infrastructure, vehicle conversions and safety issues. In addition, in the long term, natural gas will face the same resource-economic constraints as crude oil.

Triggered among others by the development of hybrid vehicles, there is renewed interest in electric vehicles as a means to reduce emissions and a lot of research is being done on the development of new battery types. It is possible to rank these vehicles by increasing battery involvement in the propulsion system and thus extended electric driving range as follows: hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), both of which incorporate an ICE (or maybe later on a fuel cell), and pure battery electric vehicles (BEV) without an ICE.

PHEV and BEV are major competitors for hydrogen fuel cell vehicles. When driven in the electric mode, they are zero-emission vehicles. Kilometres driven electrically are also lower in well-to-wheel CO_2 emissions compared to conventional fuels (even if the electricity is taken from new coal-fired power stations). This holds true even when taking upstream emissions into account. The switch to electricity also reduces the oil dependency of the transport sector by opening it up to the much wider portfolio of primary energy sources of the power sector. If renewable or carbon-neutral electricity is used for recharging, this is by far the cheapest option to reduce GHG emissions from road transport, taking only fuel costs into account. Like hydrogen, BEV and PHEV thus help reduce CO_2 emissions and local air pollution and alleviate energy security concerns, while at the same time offering a potential storage option for surplus electricity from intermittent renewable energies.

The main attraction of this option is that the ''fuel supply'' infrastructure, i.e. the electricity grid, already exists, although an extensive network of recharging stations would still need to be implemented, with all potential recharging options – slow charging, fast charging and battery swapping stations – having their own specific challenges, not least with respect to practicability and customer acceptance. In addition, the influence of large-scale electrification of the transport sector on the electricity system must be analysed and understood, such as resulting electricity demand and load profile, impacts on generation capacity as well as transmission and distribution capacity of the grid; for instance, if network extensions are necessary, this could be a major economic barrier.

BEV are apparently the most energy-efficient solution and superior to fuel cell vehicles as the high discharge rate of a battery is almost double the efficiency of a fuel cell, but major technical and economic breakthroughs for vehicle batteries will have to be realised first. The size and weight as well as the low energy density of existing batteries are at present a constraint on the range of battery-powered cars, limiting their suitability to largely urban operation. Currently long recharging times, the high cost of batteries – all the more if they should allow for extended driving ranges – and scarcity of some metals are further restrictions. BEV are actually already a promising option today for niche markets like small city cars, which have to fulfil strict environmental requirements in highly polluted urban areas. The most promising battery technology is the Lithium-Ion battery. But next to technical and economic issues, in particular the availability of Lithium resources also has to be analysed.

If battery performance was to improve markedly and at the same time costs could be reduced, BEV could represent a complete solution to decarbonising the transport sector, thus making the discussion about hydrogen largely obsolete. But given the above constraints, it seems likely that the major impact of batteries on the transport sector will be through PHEV, which have lower requirements on battery performance as they are only partly dependent on battery power. If developed with an electric range of 50–80 km, plug-in hybrids could "fuel" 60–80% of their energy demand from the power grid (as, on average, less than 20% of trips exceed 60 km in distance), thereby drastically reducing the liquid fuel demand of the vehicle. Even PHEVs with only a 30 km range would be a good match for urban driving patterns and could displace between one and two thirds of liquid fuel. However, in this case, there will still be the need for other types of fuels for "long-distance" drives and the long term necessity to develop alternatives as replacement for today's conventional liquid fuels.

Due to its chemical and physical properties oil is an excellent energy carrier in the transport sector, despite the associated environmental effects like the greenhouse gas emissions and local emissions released when burning it in combustion engines. But the total energy efficiency of this carrier is low (overall it is around 20%, and in this sense, today's vehicles are actually producing more heat than propulsion energy). However, the alternative fuels and drive systems available only seem to be viable on the mass market if the oil price stays above 60–70 $/bbl for a sustained period. Oil prices peaked above 140 $/bbl in summer 2008 and many experts believe that stable oil prices over 100 $/bbl could be reached in the next one or two decades. The higher the market prices of fossil fuels, the more competitive low-carbon alternatives will become. But higher priced conventional oil resources, on the other hand, can also be replaced by high carbon alternatives such as oil sands, oil shale or synthetic fuels from coal and gas, which also result in increasing GHG emissions unless production plants are equipped with carbon capture and storage (CCS).

A range of alternatives to today's conventional oil-based fuels exist which all exhibit constraints and drawbacks of some kind at present. No other fuel will ever be as easy (and cheap) to produce and handle as gasoline and diesel. While these fuels can be produced from crude oil with high efficiency, the production of any alternative fuel will generally incur higher conversion losses, and – in the case of gaseous fuels – be more difficult to handle and require a new distribution and refuelling infrastructure. Hydrogen and electricity even require new propulsion systems (fuel cells, batteries).

Among the various options, hydrogen seems especially promising at the current level of knowledge as it can contribute to the three most important targets with respect to transportation energy use which are being increasingly favoured by policy makers around the world: GHG emissions reduction, energy security and reduction of local air pollution. The major competitor to hydrogen in this respect is electricity, as it potentially offers the same benefits with respect to these energy policy objectives. Of all the alternatives, electric vehicles have the potential for the lowest fuel costs and GHG emissions due to their higher efficiency throughout the fuel supply chain and the vehicle's lower fuel consumption. From today's perspective, it seems to be a technology race between the battery and the fuel cell. While the challenges for batteries are technical and economic in nature, for fuel cells, they are rather economic. But even if purely electric vehicles fail, plug-in hybrids still have considerable potential to reduce the demand for liquid fuels and provide cleaner mobility. Nevertheless, there is unlikely to be a "silver bullet" in the coming decades and the transport sector will witness a much more diversified portfolio of fuels in the future.

1.3. *Why hydrogen?*

Neither the use of hydrogen as an energy vector nor the vision of a hydrogen economy is new. Until the 1960s, hydrogen was used in many countries in the form of town gas for street lighting as well as for home energy supply (cooking, heating, lighting), and the idea of a hydrogen-based energy system was already formulated in the aftermath of the oil crises in the 1970s. Moreover, hydrogen is an important chemical feedstock, for instance for the hydrogenation of crude oil or the synthesis of ammonia. The breakthroughs in fuel cell technology in the late 1990s are the main reason behind the revival of interest in hydrogen. While hydrogen can be utilized in different applications (mobile, stationary and portable), the transport sector is going to play the crucial role for the possible introduction of hydrogen, as outlined in the previous paragraphs. This is also where fuel cells can make the most of their high conversion efficiencies compared to the internal combustion engine.

Hydrogen offers a range of benefits as a clean energy carrier (if produced by "clean" sources), which are receiving ever greater attention as policy priorities. Creating a large market for hydrogen as an energy vector offers effective solutions to both emissions' control and the security of energy supply. Hydrogen is emission-free at the point of final use and thus avoids the transport-induced emissions of both CO_2 and air pollutants. Being a secondary energy carrier that can be produced from any (locally available) primary energy source (unlike other alternative fuels, except electricity), hydrogen can contribute to a diversification of automotive fuel sources and supplies and offers the long term possibility of being solely produced from renewable energies. Hydrogen could further be used as a storage medium for electricity from intermittent renewable energies such as wind power. Assuming that CCS is eventually realised on a large scale, clean power generation from fossil fuels would be possible via the production of hydrogen. Moreover, there is also the possibility to co-produce electricity and hydrogen in IGCC plants.

However, it is hard to justify the use of hydrogen solely from a climate policy perspective. It must be stressed that hydrogen is not an energy source in itself but a secondary energy carrier in the same way as electricity. Similar to electricity, as far as the security of supply or greenhouse gas emissions are concerned, any advantage from using hydrogen as a fuel depends on how the hydrogen is produced. If produced from coal, it augments the security of supply, but causes much higher CO_2 emissions (unless the CO_2 is captured and stored, a critical prerequisite for this pathway). If produced using non-fossil fuels (nuclear or renewable), it adds to the security of supply and reduces CO_2 emissions, but only in so far as the non-fossil fuel source is additional to what would otherwise be used in electricity generation. This means that any assessment of the virtues of switching to hydrogen as a transportation fuel involves a number of assumptions about long term future energy policy developments.

Local air emissions, responsible for particulate matter, ozone and acid rain, as well as noise could be significantly reduced by the introduction of hydrogen fuel cell vehicles. Emissions of NO_x, SO_2, and particulates can be reduced by 70–80% compared to a case without hydrogen. Especially in densely populated areas this is one major benefit of hydrogen, which is often underestimated. As there are a growing number of megacities worldwide, the importance of improving urban air quality is also increasing. A calculation shows that the CO_2, local emissions, and noise benefits of a fuel cell vehicle can reduce the average external cost of a vehicle by 1000–1500 US$ compared to a conventional vehicle.

1.4. *The role of fuel cells*

In fuel cells, electricity and water are usually produced from hydrogen and oxygen in an electrochemical reaction which also releases heat. In contrast to conventional electricity generation, which takes place in a three-stage conversion process (chemical energy – thermal energy – mechanical energy – electricity), in a fuel cell, chemical energy is directly converted into electrical energy. A fascinating point is the potential theoretical efficiency of fuel cells.

A lot of different fuel cell types exist which do not require hydrogen as fuel. Therefore fuel cells could enter the market independently of hydrogen production or infrastructure build-up. This is especially valid for portable applications and stationary applications. Stationary (high temperature) fuel cells – and hence distributed heat and power generation – are not necessarily a market for hydrogen because they can use, e.g. natural gas from the gas mains directly; conversion to hydrogen would only reduce their overall efficiency. The situation is different for mobile applications, where the dominant fuel cell type is the Proton Exchange Membrane (PEM) fuel cell, which only functions with pure hydrogen.

On the other hand, it makes no sense to introduce hydrogen in the transport sector without fuel cells in the long run because of the high electricity to heat ratio and the high overall conversion efficiency of fuel cells powered by hydrogen: today, the efficiency of the fuel cell system for passenger cars is around 40% (in the future maybe 50%) compared to 25–30% for the gasoline/diesel powered internal combustion engine under real driving conditions. Fuel cell systems have a higher efficiency at partial load than full load which also suggests their suitability for application in motor vehicles, which are usually operated at partial load, e.g. during urban driving. In addition, the fuel cells exhaust produces zero emissions when fuelled by hydrogen. Road transport noise in urban areas would also be significantly reduced. Furthermore, fuel cell vehicles could possibly even act as distributed electricity generators when parked at homes and offices and connected to a supplemental fuel supply. From this perspective, the use of hydrogen in internal combustion engines can only be an interim solution.

Today, the powertrain costs of fuel cell vehicles are still far from being cost-competitive. They have the largest influence on the economic efficiency of hydrogen use in the transport sector and the greatest challenge is to drastically reduce fuel cell costs from currently more than $2000/kW to less than 100 $/kW for passenger cars. On the other hand, fuel cell drive systems offer totally new design opportunities for vehicles: because they have fewer mechanical and hydraulic subsystems compared with combustion engines, they provide greater design flexibility, potentially fewer vehicle platforms and hence more efficient manufacturing approaches which may lead to additional cost reductions. Nevertheless, this cost reduction potential has to be realised first and is in a continuous interplay with the requirements for efficiency and lifetime. This is the major source of uncertainty for the market success of fuel cell vehicles. Additional technical challenges like hydrogen storage and safety issues have to be solved as well.

To achieve a relevant market success, it is essential to meet the fuel cell targets set for costs, lifetime and reliability. These technology developments obviously always take longer than planned by industry. However, preparation for the structural changes in industry is just as important as the technical optimisation of fuel cells. Qualified service technicians and skilled workers must be available to ensure that the introduction of fuel cell technology is managed as smoothly as possible. The success of hydrogen in the transport sector will crucially depend on the development and commercialisation of competitive fuel cell vehicles.

1.5. *Hydrogen storage*

Hydrogen storage is regarded as one of the most critical issues, which must be solved before a technically and economically viable hydrogen fuel system can be established. In fact, without effective storage systems, a hydrogen economy will be difficult to achieve.

Considerable progress has been achieved over the past few years concerning hydrogen-propelled vehicles. Most of the development efforts concentrated on the propulsion system and its vehicle integration. At present, there is a general agreement in the automotive industry that the on-board storage of hydrogen is one of the critical bottleneck technologies for future car fleets. Still, no approach exists as yet which is able to comply with the technical requirements for a range greater than 500 km while meeting all the performance parameters regardless of costs. The physical limits for the storage density of compressed and liquid hydrogen have more or less been reached, while there is still potential in the development of solid materials for hydrogen storage, such as systems involving metal hydrides.

1.6. *Supply of hydrogen*

1.6.1. *Hydrogen production*

Hydrogen occurs naturally in the form of chemical compounds, most frequently in water and hydrocarbons. Hydrogen can be produced from fossil fuels, nuclear and renewable energy sources by a number of processes such as water electrolysis, natural gas reforming, gasification of coal and biomass, water splitting by high temperature heat, photoelectrolysis and biological processes. Global hydrogen production today amounts to around 700 billion Nm^3 (enough to fuel more than 600 million fuel cell cars) and is based almost exclusively on fossil fuels: roughly half on natural gas and close to one third on crude oil fractions in refineries. Most of this hydrogen is produced on-site for captive uses. The largest use of hydrogen is as a reactant in the chemical and petroleum industries: ammonia production has a share of around 50%, followed by crude oil processing with slightly less than 40%.

Natural gas reforming, coal gasification and water electrolysis are proven technologies for hydrogen production today and are applied on an industrial scale all over the world. Steam reforming of natural gas is the most used process in the chemical and petro-chemical industries; it is currently the cheapest production method and has the lowest CO_2 emissions of all fossil production routes. Electrolysis is more expensive and only applied if high-purity hydrogen is required. With an assumed increase in natural gas prices, coal gasification becomes the most economical option from around 2030 onwards. Biomass gasification for hydrogen production, still at an early stage today, is expected to become the cheapest renewable hydrogen supply option in the coming decades although biomass has restricted potential and competes with other biofuels as well as heat and power generation. Biomass gasification is applied in small decentralised plants during the early phase of infrastructure rollout and in centralised plants in later periods. Steam reformers and electrolysers can also be scaled down and implemented on-site at fuelling stations (although still more expensive), while coal gasification or nuclear energy are for large-scale, central production only and therefore restricted to later phases with high hydrogen demand.

In the medium to long term, hydrogen may be produced by natural gas reforming or coal gasification in centralised plants with CCS. CCS is essential in order to avoid an overall increase in CO_2 emissions through fossil hydrogen production, primarily from coal. The (additional) costs of CO_2 capture in connection with hydrogen production from natural gas or coal are mainly the costs for CO_2 drying and compression since CO_2 and hydrogen are already separated as part of the hydrogen production process (even if the CO_2 is not captured). Taking the costs for CO_2 transport and storage into account, total hydrogen production costs increase by about 3–5% in the case of natural gas reforming and 10–15% in the case of coal gasification.

Hydrogen also occurs as a by-product of the chemical industry (for instance chlorine-alkali electrolysis) and is already being used thermally. This represents another (cheap) option (where available), because it can be substituted by natural gas although investments in purification might be necessary. This option is relevant for supplying hydrogen during the initial start-up phase in areas where user centres are nearby.

Nuclear power plants dedicated to hydrogen production are an option for later phases with high hydrogen demand. Thermo-chemical cycles based on nuclear energy or solar energy are a long term option for hydrogen production with new nuclear technology (for instance the sulphur–iodine cycle) or in countries with favourable climatic conditions. However, nuclear hydrogen production is likely to face the same public acceptance concerns as nuclear power generation. The production of hydrogen from photo-electrolysis (photolysis) and from biological production processes is still at the level of basic research.

Generally, the hydrogen production mix is very sensitive to the country-specific context and strongly influenced by the assumed feedstock prices; resource availability and policy support also play a role, in particular for hydrogen from renewable and nuclear energy. The fossil hydrogen production option dominates the first two decades while infrastructure is being developed and also later periods if only economic criteria are applied: initially on the basis of natural gas, subsequently with increasing gas prices more and more on the basis of coal. Renewable hydrogen is mainly an economic option in countries with a large renewable resource base and/or a lack of fossil resources, for remote and sparsely populated areas (such as islands) or for storing surplus electricity from intermittent renewable energies. Otherwise renewable hydrogen needs to be incentivised or mandated.

It is evident that hydrogen needs to be produced in the long term from processes that avoid or minimize CO_2 emissions. Renewable hydrogen (made via electrolysis from wind or solar-generated electricity or via biomass gasification) is surely the ultimate vision (particularly from the viewpoint of mitigating climate change), but not the precondition for introducing hydrogen as an energy vector. Until this goal is reached, hydrogen from fossil fuels will prevail, but the capture and storage of the produced CO_2 then becomes an indispensable condition if hydrogen is to contribute to an overall CO_2 reduction in the transport sector. The expected dominance of fossil hydrogen during the introduction phase (the period until around 2030) is reflected in the various hydrogen roadmaps as is the later role of renewable energies. With the exception of biomass, the specific costs of hydrogen production from renewable energies are not considered to be competitive with most other options during this period.

Hydrogen production costs depend to a very large extent on the assumed feedstock prices. The typical range until 2030 is between 8 and 12 ct/kW h (2.6–4 $/kg). In the long term until 2050, with an expected increase in feedstock prices (fossil fuels) and CO_2 prices, hydrogen production costs will increase as well.

1.6.2. *Hydrogen distribution*

Different options are available for hydrogen transport and distribution: delivery of compressed gaseous and liquid hydrogen by trucks and of gaseous hydrogen by pipelines. Pipelines have been used to transport hydrogen for more than 50 years, and today, there are about 16,000 km of hydrogen pipelines around the world that supply hydrogen to refineries and chemical plants; dense networks exist for example between Belgium, France and the Netherlands, in the Ruhr area in Germany or along the Gulf coast in the United States.

The technical and economic competitiveness of each transport option depend on transport volumes and delivery distances. Pipelines are the preferred option for large quantities and long distances. Liquid hydrogen trailers are for smaller volumes and long distances, and compressed gaseous hydrogen trailers are suitable for small quantities over short distances. Pipelines are characterised by a very low operating cost, mainly for compressor power, but high capital costs. Liquid hydrogen has a high operating cost due to the electricity needed for liquefaction (which accounts for 30–60% of the total liquefaction costs and may also represent a significant CO_2 footprint), but lower capital costs depending on the quantity of hydrogen and the delivery distance. Distance is also the deciding factor between liquid and gaseous trailers. Hydrogen transport costs are typically in the range of 1–4 ct/kW h (0.3–1.3 $/kg).

Because of the specific physical and chemical properties of hydrogen, pipelines must be made of non-porous, high-quality materials such as stainless steel; therefore the investments in a hydrogen pipeline for a given diameter are up to two times higher than those for natural gas pipelines. The costs could be considerably reduced if the natural gas infrastructure could be adapted to hydrogen. As hydrogen can diffuse quickly through most materials and seals and can cause severe degradation of steels, mainly due to hydrogen embrittlement, the use of existing natural gas pipelines could be problematic and has to be investigated on a case by case basis. Coating or lining the pipelines internally, or adding minor amounts of oxygen could solve the problems in using existing long-distance transmission pipelines made from steel. Next to embrittlement, hydrogen diffusion would prohibit the transport of hydrogen in low-pressure, natural gas distribution pipelines, which are often made of plastic materials. In addition, valves, manifolds, and in particular compressors would need to be modified, as they are optimised to work under a certain range of conditions, such as gas composition. Another possibility could be to blend hydrogen with natural gas up to a certain extent and either separate the two at the delivery point, or use the mixture, e.g. in stationary combustion applications. However, to which extent this is feasible and reasonable is still a matter of debate, given that hydrogen is an expensive and valuable commodity, and because admixture to and extraction from natural gas is no solution for fuel cell vehicle owners. To conclude, the introduction of hydrogen would largely require a new dedicated pipeline transportation and distribution infrastructure.

1.7. *Hydrogen infrastructure build-up*

How the hydrogen supply infrastructure would develop and what this would look like depends heavily on country-specific conditions such as the available feedstock (like renewable energies), population density, geographic factors and policy support, and must therefore be assessed on a country-by-country basis. Nevertheless, based on the hydrogen infrastructure analysis presented in this book it is possible to derive some robust strategies and cross-national communalities for the introduction of hydrogen in the transport sector. It is important to bear in mind that the technical and economic challenges concerning fuel cells and hydrogen storage are assumed to have been resolved and that fuel cell vehicles are cost-competitive with conventional vehicles.

For the introduction of hydrogen, two broad phases can be distinguished: the infrastructure build-up phase (2015–2030) and the hydrogen diffusion phase (2030–2050). The former can further be subdivided into an early implementation phase (2015–2020) and the transition phase (2020–2030). Scenario results generally show the greatest differences during the transition phase, when the initial infrastructure is being developed, but tend to converge in later periods.

Hydrogen use will take off predominantly in densely populated areas/urban environments with favourable support policies and, during the transition phase, will then gradually expand outwards into rural areas. As buses and fleet vehicles such as delivery vans operate locally to a large extent, run on short, regular routes and return to a central depot for refuelling and maintenance, they are ideal candidates for hydrogen during the early implementation phase as they do not need an extensive network of refuelling stations. Hydrogen ICE vehicles with bi-fuel conversions are advantageous during the early phase as well, as they avoid the necessity of having an area-wide coverage of refuelling stations in place right from the beginning. Strong policy measures, such as zero-emission mandates or tax incentives are essential to encourage the early adoption of hydrogen vehicles.

The introduction of a hydrogen fuel system is best accomplished initially through the distributed production of hydrogen, mainly on-site at the fuelling stations. This is the most economic approach, as it avoids constructing an extensive and costly transport and distribution infrastructure, which accompanies centralised production. This could be deferred until the demand for hydrogen is large enough. A distributed production system during the transition phase can be installed rapidly as the demand for hydrogen expands, thus allowing hydrogen production to grow at a pace, which is reasonably matched to hydrogen demand. This approach gives the market time to develop and diminishes the risks for investors, as it avoids fixing large amounts of capital in underused large-scale production and distribution facilities, while it is still unclear how hydrogen demand will develop. The preferred technology is small-scale natural gas reforming (using the existing natural gas pipeline network), followed to a lesser extent by gasification of biomass, on-site electrolysis (from grid electricity or wind or solar energy) and by-product hydrogen.

On-site hydrogen production at the fuelling station is not only the preferred option during the early implementation phase (first decade), but also in areas where demand is too low for more centralised schemes (in later periods). On-site production becomes less preferable once a distribution infrastructure has gradually been built up and demand for hydrogen has risen and there is therefore a trend towards centralised production in later phases. In remote areas with a high energy demand, however, it is possible that they may be able to exploit local energy resources by manufacturing hydrogen to meet local transport energy demands.

Due to the dominant on-site production, there is little need for hydrogen to be transported during the first decade. If this takes place, it is mainly by liquid hydrogen trailers, but also by compressed gaseous trailers under specific circumstances. Liquid hydrogen plays an important role during the transition phase (until 2030) and in connecting outlying areas, such as along motorways or in rural areas. A pipeline network is constructed during this period and pipelines clearly dominate hydrogen transport in the diffusion phase (after 2030).

Transport options are exposed to many sensitivities (e.g. distances, volumes, fuelling station utilisation, demand for liquid hydrogen, energy prices, density of fuelling stations in a region) and there is no ''ultimate best strategy'' as each of the options can play a role under specific conditions. The distance to be covered has the strongest impact on transport costs which influence the total supply costs of hydrogen to a much larger extent than is the case for today's liquid fuels.

As transport is so expensive, hydrogen should be produced close to the user centres. The primary optimisation goal is therefore to minimize the average hydrogen transport distances through well planned siting of the production plants.

Projected hydrogen supply costs are highly sensitive to the underlying assumptions about the development of feedstock prices, as these have a decisive impact on production costs; uncertainty therefore increases significantly with longer term projections. Being representative for both the European Union and North America, at around 12–14 ct/kW h (4–4.6 $/kg), the specific hydrogen supply costs in the early phase are high due to the required overcapacity of the supply and refuelling infrastructure and the higher initial costs for new technologies because of the early phase of technology learning. Around 2030, hydrogen costs range from 10 to 16 ct/kW h (3.6–5.3 $/kg) in above mentioned regions, mainly depending on the feedstock. In the long term until 2050, hydrogen supply costs stabilise around this level, but with an upward trend due to the assumed increase in energy prices and CO_2 certificate prices. Also while fossil hydrogen costs will rise in accordance with the expected increase in fossil fuel prices, at the same time costs for renewable hydrogen will go down, ultimately reaching a break-even point.

With a share of 60–80%, hydrogen production dominates total supply costs. The installation of refuelling stations makes up about 10%, the remainder is for transport and liquefaction. At these supply costs, hydrogen becomes competitive in the long run at crude oil prices above 80–100 $/barrel (no taxes, no vehicle costs included). The specific investments for implementing a complete hydrogen supply infrastructure (production plants, transport infrastructure (pipelines) and refuelling stations) vary between 150 and 190 M$/PJ until 2050 across the various scenarios, with a tendency towards higher numbers in later periods due to higher feedstock prices.

1.8. Hydrogen and the electricity sector

If hydrogen production on a large scale is to be integrated into the energy system, a more holistic view needs to be applied to its interactions with the electricity sector. Alongside the option of producing hydrogen from electricity via electrolysers, there are other direct links between hydrogen and the power sector. These concern for instance the ensuing competition for renewable energies, as in the long term, only hydrogen production from renewable energy sources can reduce the dependency on fossil fuels and enhance the security of supply. Hydrogen can also be used as a storage medium for electricity from intermittent renewables, such as wind energy. Finally, the co-production of electricity and hydrogen in IGCC plants (with CCS) is potentially a promising option for the future.

The uses of renewable energies will face increasing competition with respect to feedstock availability for electricity generation and fuel production, and in the case of biomass also for food production. Today, since renewable energy supplies are still limited in most countries, the question is where they are best employed in order to achieve the largest CO_2 reduction for the energy system as a whole: in the power sector or the transport sector? New renewable energy sources will reduce CO_2 emissions to a greater extent if they are used to generate power which displaces grid-mix electricity, than if applied to producing vehicle fuels like hydrogen (or other renewable fuels) and thus substituting conventional fuels. This reduction will be even greater if there is a high share of fossil fuels in the power mix. Moreover, if produced by renewable energies, hydrogen supplements the security of supply and reduces CO_2 emissions only to the extent that the renewable energy source is additional to what would otherwise be used for power generation. This picture may change if electricity from fluctuating renewable sources such as wind or solar has to be stored. Hence, from the overall perspective of CO_2 reduction, renewable energies should only enter the transport sector after they have achieved significant penetration in the power sector.

As for the competition between hydrogen and electricity from renewable energies in the transport sector, it is clear that the use of renewable electricity in battery electric vehicles is by far the most efficient application and yields a much higher CO_2 reduction than hydrogen fuel cell vehicles due to the high discharge rate of batteries. Battery vehicles still face significant technical hurdles, but even if battery and/or fuel cell technology cannot be sufficiently developed, plug-in hybrids that significantly reduce the demand for liquid fuels and CO_2 emissions from transport would still achieve a more sustainable energy system.

A rapid build-up is expected in wind power but also photovoltaic and solar thermal electricity generating capacities. Despite some clear advantages – renewable and CO_2 free – the intermittency of wind- and solar-generated electricity poses a challenge with regard to load levelling when capacity grows. Hydrogen could be one solution to this problem, as it offers the chance to store and transport the energy. Especially for mobile applications, where energy has to be stored anyway, this could be a more promising option than storage and re-electrification for stationary applications. Hydrogen production could also be an attractive option for remote areas such as low populated islands without access to the main grid and for exploiting large renewable resources, which are far away from user centres (so-called stranded resources).

Using hydrogen to produce electrical energy from fossil fuels in large centralised plants will contribute to achieving significant reductions of CO_2 emissions if combined with CO_2 capture and storage. Such plants will also help to increase the diversification of resources since a variety of fossil feedstocks can be used, including resources such as coal and waste that otherwise cause major impacts on the environment, as well as biomass. In addition, it is possible to co-produce hydrogen and electricity in these plants, which can contribute to load levelling. For instance, IGCC plants can be used to produce more electricity during peak periods, and to produce more hydrogen during off-peak periods. This demonstrates the important advantage of IGCC plants: they can deliver to two markets, the electricity market as well as the transport market, depending on the price signals.

As already mentioned, the high temperatures of the exhaust gases produced from the high temperature (stationary) molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) are ideal for co-generation and combined cycle power plants, reaching an overall system efficiency of up to 90%, or for providing heat for space and hot water heating. But since they can be fuelled directly by hydrocarbons because of their high operating temperatures, natural gas or biogas would be the fuel of choice here rather than hydrogen.

1.9. International competitiveness and economic impacts

The transport sector is of high economic relevance for some world regions, for instance in Europe and the US, where it contributed between 4 and 6.5% to employment, and between 6 and 10% to production in 2002. Roughly 40% of these figures are attributable to vehicle production. Therefore the international competitiveness of the transport sector is also of high political relevance to some regions. Looking at hydrogen, the structure of the necessary investments in hydrogen as an energy vector is clearly dominated by the expenditures on hydrogen vehicles. If a hydrogen vehicle is imported, it is very likely that this involves the whole vehicle, not just the hydrogen drive system. Therefore the structure of the domestic vehicle industry is one of the key factors for the development in employment and Gross Domestic Product (GDP).

The macro-economic analysis for Europe revealed that the introduction of hydrogen results in positive effects for long term employment – assuming a similar degree of competitiveness as today's for the non-hydrogen technologies which will be substituted by hydrogen technologies. The development of new technologies requires a higher qualification level, needs more workers due to a lower automation level, and is a barrier to off-shoring production. The overall impact on economic growth (GDP) from introducing hydrogen into the energy system is small. Besides the fact that net changes in expenditure patterns are small, the fact that hydrogen is introduced in only part of the energy system also helps to explain the relatively small impacts on GDP. Overall however, the economic development proves to be positive, among others due to an increase in investments. This increase in investments is due to several reasons: first, additional investments in hydrogen production and fuelling infrastructure as well as in the additional renewable capacities required to produce 'renewable' hydrogen (both funded by revenues from selling hydrogen as a fuel), and second, the wider economic effects following these additional investments, i.e. increased employment and income resulting in higher GDP which leads to increased demand and hence more investment in the second round.

It should be pointed out that the economic analysis is based on the assumption that, after an initial period of support, hydrogen technologies show cost advantages compared to conventional technologies. In addition, the above conclusions are all based on the assumption that there are no shifts in exports/imports (e.g. same market share of fuel cell vehicles for European car manufactures as today for conventional vehicles). However, midterm employment effects in automotive sectors could be drastic if the assumption of similar competitiveness is rejected for hydrogen technologies. Therefore the following dilemma can be identified for the major car-making countries: on the one hand, job losses could be drastic if these countries lose market shares due to late market entry. On the other hand, there are uncertainties regarding the market success of hydrogen cars and the potential risk of losing several billion dollars due to investments in premature hydrogen infrastructure and hydrogen car development. Compared with these countries, the economic risks of a hydrogen economy are much smaller for countries without a large domestic automotive industry and promise significant increases in employment here if the right strategy is pursued. Similar conclusions, but with lower total effects can be drawn for the plant and equipment branches.

Replacing conventional vehicles by fuel cell vehicles induces a sectoral employment shift away from traditional automobile manufacturing to the fabricated metal, electrical, machinery and rubber/plastic sectors among others. Because of the required gradual build-up of manufacturing capacity and a skilled labour force, preparing for expected mass production makes early political action essential.

1.10. Global hydrogen scenarios

The extent to which hydrogen is considered to play a role in the global energy system in the future ranges widely across the various world energy scenarios. Hydrogen is not included as an important energy carrier in the official reference scenarios. Hydrogen penetration is only assumed in scenarios with a strict climate policy, high oil and gas prices, and moreover, a technology breakthrough in fuel cells and hydrogen storage. Under the most favourable assumptions, hydrogen vehicles are projected to reach shares of 30–70% of the global (light duty) vehicle stock by 2050, resulting in a hydrogen demand of around 7 EJ and 16 EJ, respectively, with the vast majority split to largely equal parts among Europe, North America and China. The resulting reduction of oil consumption would be in the range of 7–16 million barrels per day.

For an average investment of 170 M$/PJ needed to implement a complete hydrogen supply infrastructure (i.e. production plants, transport pipelines, refuelling stations etc.), the (cumulative) investments required to put the necessary supply capacity in place by 2050 would add up to around US$ 1200 billion and 2700 billion respectively for the above demand scenarios; this is equivalent to up to $75 billion per year (only around 6% of worldwide armament expenditure in 2006). Although these estimates harbour considerable uncertainties and should only be interpreted as indicative orders of magnitude, they should be considered in the context of the overall global investments required in the energy sector. According to the IEA, these are estimated to already amount to around US$ 20,000 billion in the period up to 2030. The cumulative investments required in the oil and gas sectors alone total $4300 billion and $3900 billion, respectively in this period. The transition to hydrogen in the transport sector would represent a maximum of 1.7% of the projected GDP growth until 2050. While the investments for introducing hydrogen would add substantially to the ones already required for the energy system, they should not be considered an insurmountable barrier to implementing a hydrogen fuel system. Moreover, to the extent that hydrogen would substitute oil-based transport fuels, the investments foreseen in the oil sector would be diminished.

The global hydrogen mix in 2050 is hard to predict. In the scenario where the cumulative hydrogen demand until 2050 is met by one primary energy source alone – which reflects the maximum impact on resources – it can be concluded that the impact on the depletion of fossil resources would be marginal (up to 4% of the current natural gas reserves and up to 2% of hard coal reserves). In contrast, a significant expansion of renewable energies dedicated to hydrogen production would be required: up to a 40 fold increase of the current global installed wind capacity and up to six times the current global biomass use. It is not possible to conclude any preference for hydrogen (from fossil fuels) over oil sands and oil shale from a resource point of view, because the primary energy expended for their production – although significantly higher than for the recovery of conventional oil – yields more "mobility" than when it is used for hydrogen production.

To get an idea of the potential CO_2 reduction achievable in the transport sector from the introduction of hydrogen vehicles, CO_2 emissions from hydrogen supply have to be compared on a well-to-wheel (WTW) basis (i.e. taking into account the entire supply chain) with conventional gasoline/diesel fuels. Generally, close to 90% of total CO_2 emissions of the hydrogen supply chain result from hydrogen production. Assuming average WTW emissions for conventional passenger cars of 160 g CO_2/km, hydrogen fuel cell vehicles achieve – *without* CCS – a CO_2 emissions reduction of around 35% for hydrogen from natural gas, 90% for biomass and almost 100% for wind energy. Under this scenario, hydrogen from coal results in a 25% increase in CO_2 emissions (which would even exceed WTW emissions from fuels derived from oil sands). If CCS is applied, CO_2 emissions for fossil hydrogen can be reduced by up to 80%. For hydrogen ICE cars, WTW emissions are in any case 60–80% higher due to the lower efficiency of the combustion engine compared to the fuel cell; their application should therefore be largely constrained to the transition phase.

While hydrogen is emission-free at final use, it is evident that if hydrogen is produced from coal without CCS, no overall CO_2 reduction in the energy system is achievable. Given that coal will become the most economic feedstock in the medium to long term as natural gas prices increase, CCS becomes an inevitable prerequisite for the supply of hydrogen.

Both the production of hydrogen from coal as well as the production of oil from unconventional resources (oil sands, oil shale, CTL, GTL) result in high CO_2 emissions and substantially increase the carbon footprint of fuel supply unless the CO_2 is captured and stored. While the capture of CO_2 at a central point source is equally possible for unconventionals and centralised hydrogen production, in the case of hydrogen, a CO_2 reduced fuel results, unlike liquid hydrocarbon fuels. This is all the more important as around 80% of the WTW CO_2 emissions result from the fuel use in the vehicles. If CCS were applied to hydrogen production from biomass, a net CO_2 sequestration would even be achievable.

1.11. *Perspectives*

It has taken more than a century for the existing transportation system to evolve, which today still relies almost entirely on one energy source, crude oil. Recently, the growing anxiety about energy security against the background of increasing import dependency has been shaping the discussion about the future supply of energy and in particular the supply of fuels. To what extent the decline in (conventional) oil production will become a problem largely depends on to what extent it is possible to substitute oil by other energy carriers in due time. In this respect, industry and policy makers are increasingly being challenged to develop alternatives to oil. It will only be possible to manage shortages in the supply of oil and realise the necessary transition to alternative fuels by setting the direction at an early stage as any change in the energy system will take a long time.

Hydrogen offers the possibility to respond to all the major energy policy objectives in the transport sector at the same time, i.e. GHG emissions reduction, energy security and reduction of local air pollution and noise. Hydrogen could provide the link between renewable energy and the transport sector, transforming biomass, wind and solar energy into transport fuel and reducing oil dependence as well as CO_2 emissions. Moreover, hydrogen could play an important role as a means to store surplus electricity from intermittent renewable energies. Nevertheless, for hydrogen from fossil fuels, especially coal, CCS is a critical prerequisite if overall CO_2 reduction over the entire supply chain is to be achieved. Moreover, if CCS is deployed on a large scale, fossil fuels could be decarbonised via the production of hydrogen, which could then be used as a clean fuel for power generation.

Energy systems and technologies evolve slowly – the combustion engine took more than a century to be developed and improved. Hydrogen and fuel cells will be no different, and it will take several decades for the build-up of a hydrogen infrastructure and for hydrogen to make a significant contribution to the fuel mix. Threats such as dwindling energy resources or climate change may lead to a faster market penetration of hydrogen vehicles than anticipated in general.

Hydrogen should not be evaluated in isolation, but benchmarked against its main competitors, as assessing its potential without taking competing options into account would result in misleading conclusions. The introduction of hydrogen should also be analysed in the context of the development of the energy system as a whole. In the transport sector, in a long term perspective, alongside hydrogen, only electricity seems to have the potential to fulfil all the above transport energy requirements, too.

The widespread introduction of hydrogen as a vehicle fuel faces three major technical challenges: developing cost-competitive and efficient fuel cells for vehicles, designing safe tanks to store hydrogen onboard with an acceptable driving range and developing an infrastructure for hydrogen production, distribution and refuelling. Both the supply side (the technologies and resources that produce hydrogen) and the demand side (the hydrogen conversion technologies) must simultaneously undergo a fundamental transformation, as one will not work without the other. However, shifting transport to hydrogen is not only a technical issue. It would also induce structural economic changes through the build-up of manufacturing capability and the development of a large-scale industry producing and distributing hydrogen. In addition, there would be trade-flow changes due to reduced trade in fossil fuels and increased trade in feedstocks for hydrogen production, and changes in employment opportunities.

Technology breakthroughs that substantially reduce the costs of the whole supply chain are essential for the successful take-off of a hydrogen market. But it has been shown that the introduction of hydrogen in the transport sector seems feasible from an economic viewpoint; for instance the cumulative capital needed to develop hydrogen infrastructure should not be considered a deterrent when considered relative to the estimated investments required over the next decades in the energy sector in general and in the oil sector in particular to keep up production levels. Hydrogen production and infrastructure costs are not an economic barrier at today's prices of conventional energy carriers. The critical element is the cost development of the fuel cell propulsion system, whose forecasts are a major source of uncertainty here.

Hydrogen and fuel cells are unlikely to emerge in future energy markets without decisive and favourable policy support and incentives. Measures need to be put in place and upheld long enough to create public awareness and stimulate consumer acceptance of hydrogen and to guarantee investment security for entrepreneurs since significant industry investments are required for vehicle manufacturing and infrastructure build-up well in advance of market forces. Moreover, regulations, codes and standards (RCS) are required for the production, distribution, storage and use of hydrogen (especially with regard to vehicle and on-board storage system safety). International cooperation will also be crucial to establish transboundary hydrogen infrastructures because vehicles are driven, imported and exported across country borders. Last, but not least, the public will need to be trained and educated in the use of hydrogen technologies, for instance the refuelling of hydrogen cars.

Hydrogen will probably mainly replace oil-based fuels in the transport sector while other energy carriers like electricity will continue to play a role. Using the term 'hydrogen economy' therefore may be misleading. Via renewable energies and CCS, hydrogen has the potential to solve some of our energy problems, but improving energy efficiency also plays a vital role in tackling climate change as well as contributing to the security of energy supply.

The discussion about the sense and non-sense of hydrogen as an energy carrier has been controversial in the past and this is likely to continue in the foreseeable future, as will be the case for any of the alternative fuels. A lot of this controversial dispute can be explained by the fact that the parameters and assumptions for the evaluation are often not laid down clearly. The evaluation of hydrogen worldwide is positive if:

- the oil price remains above 80–90 $/barrel in the medium and long term and other conventional energy carrier prices are also high,
- renewable energies and CCS are deployed on a large scale,
- the transport sector has to reduce greenhouse gas emissions significantly,
- there is no major technological breakthrough in vehicle batteries.

This book has considered in detail the potential for and costs of technologies and measures to introduce hydrogen, recognising that this is subject to significant uncertainties. These include the difficulties of estimating the costs of technologies several decades into the future, as well as of how fossil fuel prices will evolve in the future. It is also difficult to predict what the public acceptance of hydrogen will be.

The analysis presented here does not attempt to give a definitive answer. Instead, this book aims to shed some light on the challenges and opportunities that lie ahead for countries seeking to develop hydrogen energy policies. However, the authors would like to stress that hydrogen should not be seen as the all-encompassing solution to the world's energy problems and in particular not as the one and only response to the challenges faced by the transport sector. It is also highly unlikely that any single technology/fuel has the potential to be this "silver bullet", able to meet the energy challenge and all the other criteria for improving energy security and mitigating the effects of climate change and other harmful environmental impacts, because all the options are subject to constraints of some kind. The transport sector will probably witness a much more diversified portfolio of fuels in the future, with the share of electric mobility in its broadest sense, i.e. electric-drive vehicles powered by a fuel cell, battery, or a hybrid drivetrain, expected to increase markedly.

Today, there are a growing number of public-private partnerships aimed at accelerating the commercialisation of hydrogen and fuel cell technologies as well as hydrogen demonstration projects around the globe. The critical question is whether these partnerships will be able to pave the way for the commercial introduction of hydrogen vehicles. Will hydrogen remain the fuel of the future? The coming decade will provide the answer.

FURTHER READING

[1] Ball M, Wietschel M, Rentz O. Integration of a hydrogen economy into the German energy system: an optimising modelling approach. International Journal of Hydrogen Energy 2006;32(10–11):1355–68.
[2] Chiesa P, Consonni S, Kreutz T, Williams R. Co-production of hydrogen, electricity and CO_2 from coal with commercially ready technology: part A: performance and emissions. International Journal of Hydrogen Energy 2005;30(7):747–67.
[3] Dunn S. Hydrogen futures: toward a sustainable energy system. International Journal of Hydrogen Energy 2001;27(3):235–64.
[4] Ewan BCR, Allen RWK. A figure of merit assessment of the routes to hydrogen. International Journal of Hydrogen Energy 2005;30(8):809–19.
[5] Forsberg P, Karlström M. On optimal investment strategies for a hydrogen filling station. International Journal of Hydrogen Energy 2006;32(5):647–60.
[6] Hijikata T. Research and development of international clean energy network using hydrogen energy (WE-NET). International Journal of Hydrogen Energy 2002;27(2):115–29.
[7] Hodson M, Marvin S, Hewitson A. Constructing a typology of H2 in cities and regions: an international review. International Journal of Hydrogen Energy 2008;33(6):1619–29.
[8] Hugo A, Rutter P, Pistikopoulos S, Amorelli A, Zoia G. Hydrogen infrastructure strategic planning using multi-objective optimisation. International Journal of Hydrogen Energy 2005;30(15):1523–34.
[9] Karlsson K, Meibom P. Optimal investment paths for future renewable based energy systems – using the optimisation model Balmorel. International Journal of Hydrogen Energy 2008;33(7):1777–87.

[10] Kim J, Moon I. Strategic design of hydrogen infrastructure considering cost and safety using multiobjective optimisation. International Journal of Hydrogen Energy 2008; 33(21):5887–96.
[11] Kreutz T, Williams R, Consonni S, Chiesa P. Co-production of hydrogen, electricity and CO_2 from coal with commercially ready technology: part B: economic analysis. International Journal of Hydrogen Energy 2005;30(7):769–84.
[12] Lin Z, Chen C-W, Ogden J, Fan Y. The least-cost hydrogen for Southern California. International Journal of Hydrogen Energy 2008;33(12):3009–14.
[13] Márban G, Valdés-Solís T. Towards the hydrogen economy? International Journal of Hydrogen Energy 2007;32(12):1625–37.
[14] Melaina MW. Initiating hydrogen infrastructures: preliminary analysis of a sufficient number of initial hydrogen stations in the US. International Journal of Hydrogen Energy 2003;28(7):743–55.
[15] Nazim Z Muradov, Veziroğlu TN. "Green" path from fossil-based to hydrogen economy: an overview of carbon-neutral technologies. International Journal of Hydrogen Energy, in press.
[16] Ricci M, Bellaby P, Flynn R. What do we know about public perceptions and acceptance of hydrogen? A critical review and new case study evidence. International Journal of Hydrogen Energy 2008;33(21):5868–80.
[17] Schoots K, Ferioli F, Kramer GJ, van der Zwaan BCC. Learning curves for hydrogen production technology: an assessment of observed cost reductions. International Journal of Hydrogen Energy 2008;33(11):2630–45.
[18] Schulte I, Hart D, van der Vorst R. Issues affecting the acceptance of hydrogen fuel. International Journal of Hydrogen Energy 2004;29(7):677–85.
[19] Steinberger-Wilckens R. Not cost minimisation but added value maximization. International Journal of Hydrogen Energy 2003;28(7):763–70.
[20] Smit R, Weeda M, de Groot A. Hydrogen infrastructure development in the Netherlands. International Journal of Hydrogen Energy 2007;32(10–11):1387–95.
[21] Starr F, Tzimas E, Peteves S. Critical factors in the design, operation and economics of coal gasification plants: the case of the flexible co-production of hydrogen and electricity. International Journal of Hydrogen Energy 2007;32(10–11): 1477–85.
[22] Stiller C, Seydel P, Bünger U, Wietschel M. Early hydrogen user centres and corridors as part of the European hydrogen energy roadmap (HyWays). International Journal of Hydrogen Energy 2008;33(16):4193–208.
[23] Tzimas E, Castello P, Peteves S. The evolution of size and cost of a hydrogen delivery infrastructure in Europe in the medium and long term. International Journal of Hydrogen Energy 2007;32(10–11):1369–80.
[24] Winter C-J. Electricity, hydrogen – competitors, partners? International Journal of Hydrogen Energy 2005;30(13–14): 1371–4.
[25] Winter C-J. Energy efficiency, no: it's exergy efficiency! International Journal of Hydrogen Energy 2007;32(17):4109–11.
[26] Yang C, Ogden J. Determining the lowest-cost hydrogen delivery mode. International Journal of Hydrogen Energy 2007;32(2):268–86.
[27] Yang C. Hydrogen and electricity: parallels, interactions, and convergence. International Journal of Hydrogen Energy 2008; 33(8):1977–94.