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International Journal of Hydrogen Energy 32 (2007) 1625–1637

www.elsevier.com/locate/ijhydene

Towards the hydrogen economy?

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Received 10 November 2006; received in revised form 21 December 2006; accepted 22 December 2006
Available online 2 February 2007

Abstract

The never ending debate on energy supply for a cleaner environment, recently associated with the worldwide effort to decrease global CO_2 emissions, has been revived by the steep increase in oil prices and the parallel controversy about the potential of nuclear energy, initiated in the mass media on the anniversary of the nuclear disaster of Chernobyl. Thus, now seems an appropriate time for the scientific community and energy producers to exchange their knowledge in this debate far away from the magic solutions provided by mass media prophets, in an attempt to arrive at realistic guidelines that may help society to understand the important issues involved in the move towards a cleaner energy system.

In this essay a description of the potential paths that may make it possible to change from the current energy sources to a cleaner energy production system is provided, the main focus being placed on how the so-called hydrogen economy might eventually be implemented. The milestones that the international agencies expect to emerge during the transition will be described, taking into account the issues of hydrogen production, distribution, storage and use. Additionally, the potential exploitation of the different hydrogen sources, both renewable and non-renewable, will be evaluated taking into account their availability and the efficiency of the processes used to transform them into hydrogen.

Keywords: Hydrogen; Economy; Biomass; Energy; Electricity

1. Four reasons to change

In 2004 primary worldwide energy consumption was about 11.7 Gtoe, whose distribution according to sources, transformation processes and network uses is plotted in Fig. 1 [1–5]. Eighty-two percent of this energy has been transformed into heat, electricity or movement by means of fossil fuel combustion processes, which has produced CO_2 emissions to the atmosphere equivalent to 7 Gton of carbon [6]. In a no-change scenario (base scenario of the International Energy Agency, IEA) CO_2 emissions in 2050 can be expected to reach 14 Gton of carbon [6]. Current CO_2 concentration in the atmosphere is 30% above the level of the pre-industrial era. The potential environmental effects derived from this continual increase in atmospheric CO_2 concentration, evaluated in a variable range depending on the predictive model used, has finally obliged the international community to act. As a consequence, the Kyoto protocol and other international agreements have been signed to secure an international commitment to reduce global CO_2 emissions. There is now a *political obligation derived from an environmental need* to reduce CO_2 emissions, which is the first step on the road to change in our energy system.

Added to this there is clearly a problem of *worldwide energy dependence*. Oil, which nowadays constitutes around 33% of primary world energy (Fig. 1), is produced in a small number of countries organized around OPEC (Organisation of the Petroleum Exporting Countries), characterized by political instability in their international relationships, at least from the western point of view. For this reason, the price of petroleum is subject to important fluctuations due to economic and political reasons. In the last few months, which have been dominated by the consequences of the Iraq war and the instability in Iran–USA relationships, the price of petroleum has increased to \$75/Brent bbl (1-May-2006), an unprecedented and exorbitant

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Abbreviations: CCS: CO_2 capture and storage; CHP: Combined heat and power; DMFC: Direct methanol fuel cell; DOE: Department of Energy (USA); FC: Fuel cell; ICE: Internal combustion engine; IEA: International Energy Agency; IGCC: Integrated gasification combined cycle; Lge: Litre of gasoline equivalent; LCH: Low calorific heat; OPEC: Organisation of the petroleum exporting countries; PEMFC: Proton exchange (polymer electrolyte) membrane fuel cell; SOFC: Solid oxide fuel cell

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doi:10.1016/j.ijhydene.2006.12.017

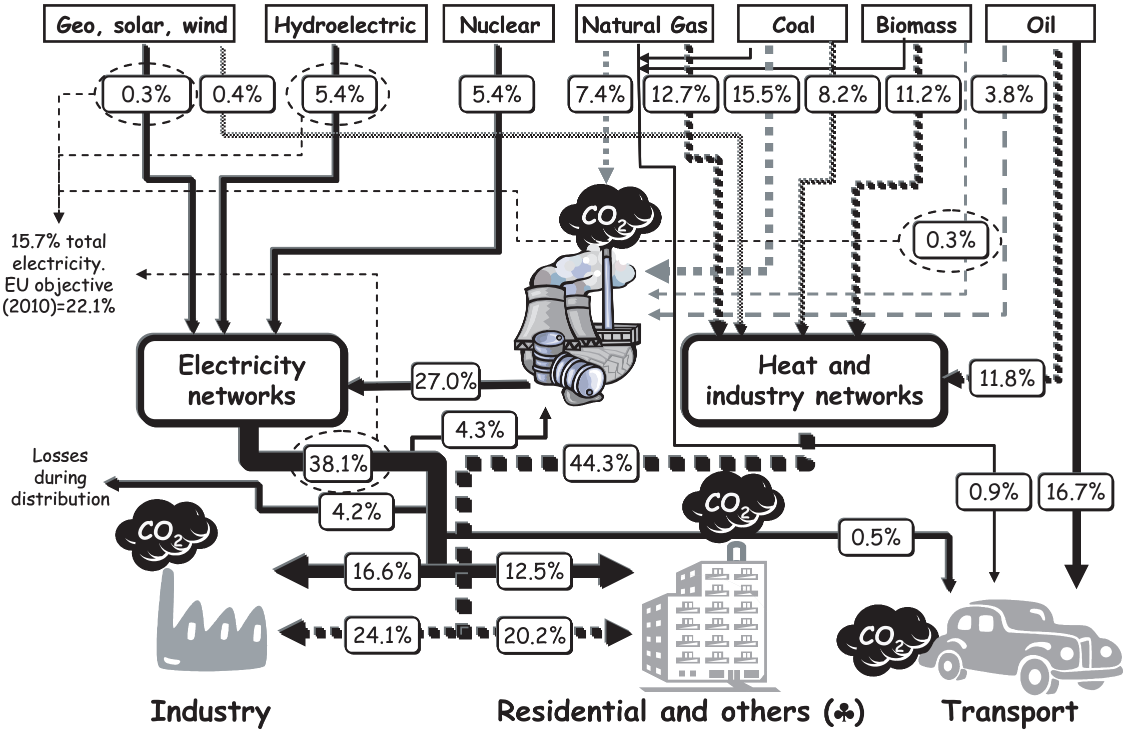


Fig. 1. Current energy scenario [1–5]. In the figure the distribution of the current energy sources consumption is indicated (basis 100%), including the transformation process and the final uses of the primary energy worldwide (38.1% electricity, 44.3% heat and industry consumption, 17.6% transport, excluding electricity vehicles. 4.2% of the primary energy is lost during electricity distribution (∼10% of the electricity generated). Worldwide primary energy in 2004: 11.7 Gtoe = 125,000 TWh = 496 Quad. ♣: includes agriculture, commerce, services and others not specified.

price for the developed countries that also restricts the progress of developing countries which depend on oil for their energy supply.

Furthermore, *oil is a scarce commodity*. Considering the linear extrapolations of the rate of growth of oil consumption and the rate of increase of known oil reserves it can be deduced that the end of the petroleum supply will probably take place around 2050 [2]. Natural gas appears as an alternative in the medium term, although a similar method of calculation predicts its total consumption will take place in 70–100 years. Of the fossil fuels used at present, only coal may retain its level of availability, considering its increasing rate of consumption, for another couple of centuries.

As a final remark on this energy scenario it is necessary to underline the importance of the *incorporation of developing countries*, many of them with an enormous population which is constantly growing, to the group of countries that waste energy. Since these countries show a value of consumption per capita far below that of the developed countries, their rate of consumption can be expected to be much faster. Additionally it is necessary to remember that the highest rate of population growth in the next few decades is going to take place precisely in these developing countries. China is typically considered as the most representative example of these emerging energy wasting countries, as can be seen from the increase in its coal consumption from 22% of the total world consumption in 2000 to 35% in 2004 [2]. In this country it is expected that the total number of cars in 2010 will be 90 times as many as those in 1990. However, we should try to retain a balanced picture; CO_2 emissions per capita in China are below 3 ton CO_2 compared to around 20 tons per American citizen [7].

The so-called hydrogen economy is a long-term project that can be defined as an effort to change the current energy system to one which attempts to combine the cleanliness of hydrogen as an energy carrier with the efficiency of fuel cells (FCs) as devices to transform energy into electricity and heat. As an energy carrier, hydrogen must be obtained from other energy sources, in processes that, at least in the long term, avoid or minimize CO_2 emissions. For the future of the worldwide energy supply three goals must be fulfilled: security in the energy supply, environmental protection and the utilization of energy sources that promote the economic growth of societies.

Considering our bleak starting point (Fig. 1) and the abundance of economic interests involved we can expect the transition to this hydrogen economy to last for decades. In the following paragraphs we will discuss the key points that affect the fulfilment of these goals.

2. Why hydrogen?

The amount of energy produced during hydrogen combustion is higher than that released by any other fuel on a mass basis, with a low heating value (LHV) 2.4, 2.8 and 4 times higher than that of methane, gasoline and coal, respectively. Currently, the annual production of H_2 is about 0.1 Gton, 98% coming from the reforming of fossil fuels. H_2 is mainly employed in oil refining and ammonia and methanol production. As a fuel it is only employed in spaceship propulsion systems and ground vehicle prototypes for demonstration purposes.

Hydrogen as energy carrier exhibits both positive and negative aspects. Science and technology should try to derive the maximum benefit from all the positive aspects while minimizing the negative ones in the long and turbulent transition that can be expected. The main advantage of hydrogen as a fuel is the absence of CO_2 emissions, as well as other pollutant emissions (thermal NO_x) if it is employed in low temperature FCs. This is especially important for the transport sector, which is responsible for ∼18% consumption of primary energy worldwide (Fig. 1). Apart from the economic–political interests involved in the substitution of oil-derived fuels, which are scarce and subject to continuous price fluctuations, vehicles are highly dispersed CO_2 emission sources in which it is difficult and expensive to install CO_2 capture and storage (CCS) systems. The two alternatives currently under consideration are hydrogen (and its derivative bio-methanol) and bio-fuels (bio-ethanol and bio-diesel), whose participation in the future world energy economy will be one of coexistence or competition.

Additionally hydrogen can be expected to allow the integration of some renewable energy sources, of an intermittent character, in the current energy system. Thus, we can envisage a photovoltaic solar panel (or a windmill) linked to a reversible FC, which uses a part of the electricity to produce H_2 during the day (or in windy conditions), and consumes the hydrogen during the night (or in the absence of wind) to produce electricity. In spite of the undeniable lack in efficiency of this system, it is clear that it would provide an uninterrupted supply of electricity.

However, as mentioned before, hydrogen is not an energy source, but a carrier and consequently it will be as clean as the method employed for its production. Moreover, today its transport and storage is expensive and difficult due to its low energy density on a volume basis (gasoline density is 0.7 kg/L whilst H_2 density is 0.03, 0.06 and 0.07 kg/L at 350 atm, 700 atm and liquefied (20 K), respectively). As it is highly inflammable, H_2 is a dangerous gas in confined spaces, although it is safe in the open since it diffuses quickly into the atmosphere. Hopefully, the search for new storage media and the establishment of codes and standards for use will enable some of these negative aspects to be overcome in the future.

Some countries are undertaking major commitments to hydrogen. Canada, Japan, the United States and Germany have led the way with new hydrogen technologies and are gradually increasing their efforts to implement hydrogen niches in their energy systems. Japan, a nation with few fossil fuel resources, has a major ongoing program to develop a global hydrogen system with new technologies for power plants, cars, buses, planes, ships and rockets, all fuelled with renewable hydrogen. The European Union decidedly supported the change to a Hydrogen Economy in 2002 when a group of experts drew up the document “Hydrogen energy and fuel cells—A vision of our future” [8] which is regarded as the basis of future research and development activities. It is evident then that the interest of developed countries in the implementation of hydrogen as the future energy carrier is growing and hence the need to illuminate the paths leading to a hydrogen society.

3. The goal: the hydrogen society

It is difficult to predict the long-term panorama (for instance beyond 2050) due to the uncertainty about the future of the energy system. To reach our goal we first need to overcome a number of social obstacles (the development of codes and worldwide standards, consumer reticence, lack of public support for scientific research, etc.) macroeconomic difficulties (developing countries need to be incorporated into the welfare state in a sustainable way, with the aid of developed countries and in a CO_2 emissions market promoted by the Kyoto protocol) and technological challenges (mainly related to the development and implementation of clean and efficiency production systems and to the decrease of cost of hydrogen storage systems and FCs).

If these difficulties are overcome, beyond 2050, when the world is expected to consume more than 25 Gtoe of primary energy [9], the energy supply and transformation will be managed as indicated in Fig. 2 [10]. Oil will not be an energy source any longer, but it will still be used for the synthesis of chemical products. A wide range of energy sources will be available and the energy mix will be selected in each locality depending on its needs and resources. In the following sections the main features of Fig. 2 will be described in detail.

3.1. Centralization

It is clear that beyond 2050 two energy distribution networks will be operating: the electric network(s) and the hydrogen network(s). The structure of both networks goes beyond the classical concept of a centralized distribution system. In fact, they will be constituted by a multiplicity of interconnected production sources, with a lower capacity but more flexibility than the current production sources. These sources will be organized into small sub-networks that could be connected to the global network depending on the needs of the population and geographical location. Thus, the integration of renewable energy sources, which are highly delocalized, could be carried out in an optimal way. In this system the production points would be closer to the points of final consumption and consequently the losses of electricity during distribution, currently estimated to be around 10% of total electricity production (4.2% of primary sources; Fig. 1), would decrease.

3.2. The electricity network

The traditional electricity network will be partially fed with natural gas and coal as it is nowadays, although their contribution will decrease. These fuels will be transformed in cogeneration thermal plants to produce H_2 and electricity (for instance in IGCC plants; integrated gasification in combined cycle) provided with CO_2 separation systems (sorbents, membranes, etc.). CO_2 will be safely confined inside underground

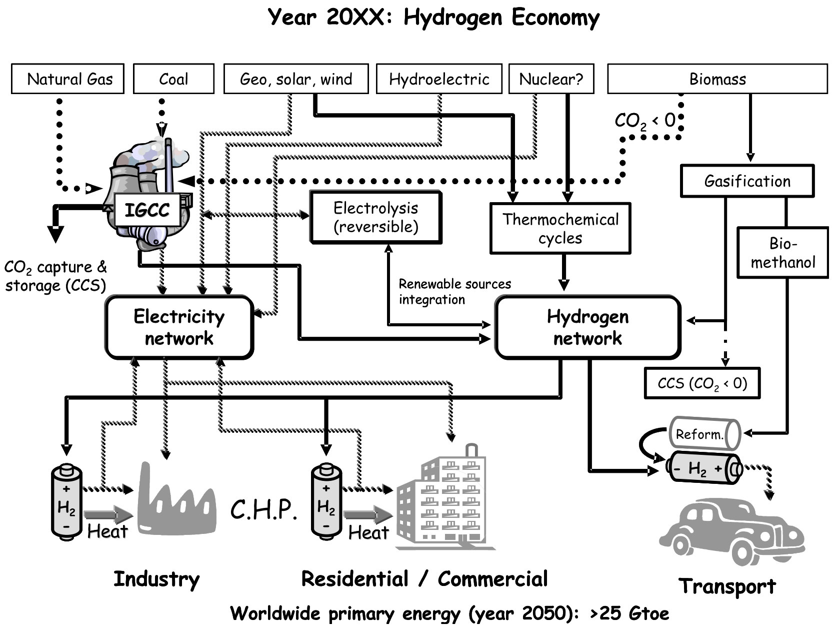


Fig. 2. Expectative for the hydrogen society in the distant future. Renewable energies are intensified and fuel cells-hydrogen binomial is employed to achieve higher efficiencies.

formations. The concept of high-capacity power plants based on coal will be maintained since this fuel is not appropriate for energy generation (electricity or hydrogen) at a smaller scale. These power plants will also be suitable for the processing of energetic biomass, either alone or in combination with coal. This biomass will be mainly made up of the short-rotation crops and organic wastes that are not destined to be employed in the reformers or bio-refineries for the production of hydrogen and bio-fuels (Fig. 2). With appropriate CCS systems the use of biomass will lead to a reduction in the concentration of CO_2 in the atmosphere (net CO_2 emissions below zero).

If everything goes according to plan, the renewable energy sources (biomass, hydraulic, solar, geothermal, wind, sea tides, etc.) will play a preponderant role in the generation of electricity in 2050. The European Union expects that by 2010 these renewable sources will contribute 22% to the total amount of electricity generated (Fig. 1). The percentage of renewable energies in electricity production will probably be high, although the amount will vary depending on availability in each geographic location. A model to imitate is that of Norway, which currently produces 100% of its electricity by means of hydroelectric power plants.

The role of nuclear energy in the generation of electricity is still unknown. This is going to depend on the outcome of social, political and economical discussions that are currently taking place. Nuclear energy permits the centralized generation of large electricity fluxes from the uranium mineral available in the earth without the emission of greenhouse gases. However, from the values of known and suspected reserves of uranium in the earth, 17 Mton [11] it seems likely that current nuclear energy systems would be able to provide the total amount of energy consumption worldwide for only a few years, failing to live up to its image as a never ending source of energy that is sometimes projected. Consequently, regardless of other safety considerations, the massive implantation of nuclear power plants is not very likely unless a great advance in the extraction of the huge amount of uranium in the sea (4000 Mton [11]) takes place. This does not seem feasible in the short term considering the enormous amount of sea water that would need to be processed for extracting the highly diluted uranium. Additionally, the unresolved problem of management of radioactive wastes and the possibility of terrorist attacks on the nuclear plants has turned public opinion against the massive exploitation of nuclear resources.

3.3. The hydrogen network

On the basis of the most optimistic hypotheses, hydrogen and FCs will be able to provide the global energy demand in transport far beyond 2050. In order to supply hydrogen to areas far from the general network it will be necessary to build refuelling stations able to generate hydrogen *in situ*, by means of electrolysers fed by renewable energies (such as photovoltaic solar panels or windmills) or biomass reformers. However, most of the supply will be provided by a network of refuelling stations in which hydrogen will be supplied by a piping system connected to large scale production plants. These H_2 production plants will use a mix of the primary energy sources most suited to each region. A general scheme of the centralized hydrogen production systems is given in Fig. 3. In this scheme the IGCC plants are designed to cogenerate hydrogen and electricity. The processes shown in this figure and which will be analysed in depth below, are those considered best placed in the race towards hydrogen.

As mentioned above, nuclear energy is an uncertain option. Its contribution to global hydrogen production will take place,

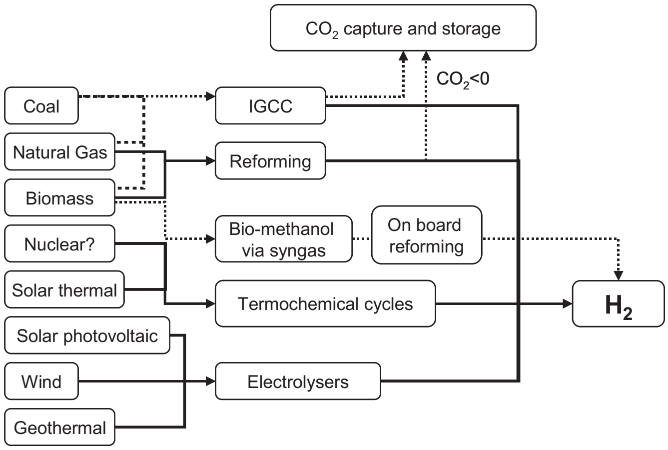


Fig. 3. Energy sources mix and H_2 production processes in a hydrogen society.

in any case, by means of thermochemical cycles that are more efficient than electrolytic processes.

There are other options that are currently in an incipient development stage that could produce important economic and environmental benefits, if they were successfully developed [10]. As an example, photo-electrolysis uses semiconductor catalysts in contact with water which by solar light activation produce the rupture of water molecules into H_2 and O_2 [12,13]. Currently there are no ideal photocatalysts in terms of efficiency and stability so the feasibility of this option will depend on the future development of new materials.

There is also great interest in the production of hydrogen in bio-reactors from photosynthetic processes with microscopic algae. For instance, cyanobacteria and green algae can produce hydrogen from solar light, water and hydrogenase as enzyme [14]. This is a technology currently under research and development, with estimated solar to hydrogen conversion efficiencies of around 27% under ideal conditions [15,16]. More than 400 varieties of plants have been identified as candidates for the production of hydrogen.

Hydrogen produced in large centralized plants will be distributed to final consumption points by means of pipes. Alternatively, hydrogen will be supplied *in situ* in small plants of decentralized production (production and refuelling stations). To store large quantities of hydrogen over long periods of time the best option is the subterranean deposit, where hydrogen is compressed and injected into aquifers or subterranean caverns. There are three types of formations for underground storage: natural gas fields (and associated aquifers), caverns or cavities in saline formations, and depleted mines. The storage costs in caverns will vary depending on the type of geological formation, but they can be expected to be low. In fact this storage method is already being employed in some areas. As an example the German city of Kiel has had a subterranean deposit of $32,000\,\mathrm{m}^3$ of city gas at 80–100 atm with a hydrogen content of 60–65% since 1971 [17]. ICI, the company that patented the method of methanol synthesis at low pressure has hydrogen deposits in England at 50 atm in subterranean caverns. For smaller scale storage at production points, similar systems to those employed in vehicles could be applied (pressure tanks, liquid hydrogen tanks, hydrides, etc.).

3.4. Hydrogen uses

In the hydrogen society, the main use of this fuel will be to feed the polymeric electrolyte membrane (or proton exchange membrane) fuel cells (PEMFC) onboard vehicles (road, marine and aerial transport). Under favourable conditions hydrogen will supply 100% of the energy demands of transport. To achieve this goal, the price of the vehicles based on FCs will need to decrease substantially, and so technological improvements in the FC and storage system will be required.

H_2 will be supplied to the vehicles via a worldwide grid of refuelling stations. For the success of the hydrogen economy secure and cheap H_2 storage systems will be needed in vehicles. It does not seem likely that the cost of compressing and liquefying hydrogen can be decreased to the level of cost required for massive use, so other more predictable solutions include the development of solid deposits based on rechargeable hydrides (AlH_3, NH_4BH_4, $NaAlH_4$, etc.) operating at pressures and temperatures of formation/decomposition between 1–10 atm and 25–100 °C. An alternative option which will probably coexist with direct hydrogen storage is the onboard reforming of bio-methanol to produce the hydrogen that feeds the FC. Bio-methanol synthesized from biomass (Fig. 3) can be easily stored onboard, thus avoiding the high cost associated with hydrogen deposits.

Finally, hydrogen will also be able to supply a fraction of the electricity and heat requirements in residential and industrial sectors. By means of solid oxide fuel cells (SOFC) which operate at high temperatures with high efficiency, it is possible to cogenerate the electricity and heat required for domestic use. Small capacity units of 4–300 kW will be employed to supply energy to family residences and apartment blocks. Medium capacity systems (<10 MW) will be able to provide electricity in residential, service and industrial areas. The balance between the use of H_2 and electricity from the conventional network for satisfying demand will be established by the law of supply and demand in the different sectors. Finally, the integration of cogeneration FCs in the conventional electric network will permit the sale of energy excess to the network. Where the system is not integrated in the electricity network (i.e. single-family residences) small excesses of electricity generated in situations of low energy demand could be stored by lead-acid conventional batteries for use in situations of high demand.

This can be considered a brief description of what is pursued by those who believe in a hydrogen-based future. The transition towards this ideal touches on many different issues that will be outlined in the following sections.

4. From now to 2015. Hydrogen popularization. Decentralized production units

4.1. Public funds and initial market niches

Unfortunately the previous picture is far from reflecting the real situation. If expectations are to be fulfilled, immediate action is required worldwide on the part of public and private organizations. Many public and private initiatives involving the energy organisms of EU, USA and Japan have already been taken to make the hydrogen based society a reality. Some of these initiatives are listed below:

Year 1977—IEA. "Hydrogen Implementing Agreement" (12 countries and the European Commission). http://www.ieahia.org/

Year 2002—Japan. "JHFC: Japan Hydrogen & Fuel Cell Demonstration Project" (2010: 50,000 FC cars; 2020: 5,000,000 FC cars). http://www.jhfc.jp/e/

Year 2003—EEUU. "The International Partnership for a Hydrogen Economy" (1,700 M$ investment in 5 years). http://www.hydrogen.energy.gov/

Year 2003—EEUU. "FreedomCAR and Fuel Partnership" (DOE, the United States Council for Automotive Research, Ford Motor Company, DaimlerChrysler and General Motors). http://www.hydrogen.energy.gov/freedomcar_partnership.html

Year 2004—EU. Hydrogen and Fuel Cells Technology Platform. http://www.hfpeurope.org/

Year 2007—2013 (7th Framework Program EU). The investment in Energy + Environment + Transport: 8,280 M€ (15.5% of the total). http://www.cordis.lu/fp7/

Parallel to the efforts being made in research and development and the establishment of codes and standards for the production, distribution, storage and use of H_2, measures should be taken to make hydrogen energy acceptable to potential users. This can be achieved by the introduction of early markets, in which the importance of popularizing the product to a reluctant public should outweigh that of economic benefit. Of these, the most important market is that of mobile devices (phones and laptops) with hydrogen-fed PEMFC or direct methanol fuel cells (DMFC). Such batteries will permit a higher degree of autonomy than that offered by current Li-ion batteries, although they still need to be improved in terms of cost, weight and social acceptance.

4.2. Reformers

In the first stage, hydrogen production will be performed in small decentralized systems, by means of electrolysers (which consume water and electricity provided by the network or generated by small solar panel modules) and reformers (in which water and natural gas react at high temperature to produce H_2 and CO_2) without a distribution network (as they will be distributed in pressurized cylinders by ship and road) and without CCS systems [9].

The reforming of natural gas is a well known technology by means of which it is possible to achieve energy conversion efficiencies of between 65–75% (LHV) for small decentralized units and up to 85% for large centralized systems. The current H_2 price from the reforming of natural gas in decentralized systems is around \$1.6/Lge (litre of gasoline equivalent; currently the price of gasoline before taxes is around \$0.2–0.3/L) [10]. In the short term (2010) the goal is to reduce the price to below \$0.5/Lge. For decentralized systems the investment costs (\$1300/car per day for stations with a capacity of over 300 cars daily) are 3 times higher than those of large centralized systems [10].

4.3. Electrolysers

Today the efficiency of conventional electrolysers is around 40–50% [18]. Other sources suggest a somewhat higher efficiency value that may be explained by differences between working and test conditions [10]. There are two main groups of electrolysers depending on production capacity: those that obtain H_2 from electrical energy from the network, that are able to produce fuel to feed 1–2 cars (house systems); and electrolysers that are able to feed more than 100 vehicles (refuelling stations). With these systems, the cost of H_2 production, including investment, electricity and compression costs is quite high (\$2.7/Lge in house systems and \$0.9/Lge for refuelling stations) although these prices can be expected to decrease to \$0.9/Lge and \$0.6/Lge, respectively, by 2030 [10]. An important aspect in the development of this kind of system is the expected reduction in the price of PEMFC, since an electrolyser is just a FC operating in reverse mode [19]. Thus the price of electrolysers can be expected to vary from the current \$5800 per car and per day to around \$725 for a refuelling station able to feed more than 100 cars/day [10]. It can also be assumed that the increase in capacity of reformers and electrolysers will lead to a further decrease in their cost and an increase in their efficiency to values close to the theoretical ones.

4.4. Refuelling stations

There are currently 227 H_2 refuelling stations operating around the world (May 2006). These are generally based on reformers or electrolysers that are employed to fuel fleets of urban buses with internal combustion engines (ICEs) based on H_2 (ICE-H_2) or FCs. As an example, in Spain there are two stations in operation, one in Madrid where H_2 is produced by a methane reforming system, and the other in Barcelona, where solar panels produce clean electricity to feed the electrolyser. These stations which fuel six DaimlerChrysler Citaro buses equipped with FCs were built within the framework of international projects such as the CUTE European project, the aim of which is to analyse the operation of different technologies in real operating conditions. Updated information about H_2 refuelling stations can be found in http://www.h2stations.org/

4.5. Storage

Storage is another key issue for the popularization of H_2 in transport. Currently there are pressurized tanks at 350 and 700 atm that permit the storage of H_2 up to weight percentages (H_2 + tank) of 5.5 and 11 wt% [DOE objective: 6 wt% [20]] for a 400 km autonomy. These tanks which are built of carbon fibre are used in the bus fleet mentioned above and in some car prototypes such as Ford Focus C-Max with ICE-H_2. Compression energy is around 10% of the LHV of H_2, which is an acceptable value. However, the fabrication cost is around \$3000/kg H_2 while the DOE objective for 2015 for the storage of H_2 in vehicles is \$67/kg H_2 [20]. Considering that the high cost is essentially related to the tank material (carbon fibre) it is not foreseeable that any future reduction in cost will comply with the requirements established. An alternative to these pressurized tanks is cryogenic storage (20K) in a double insulating chamber tank. These tanks are less voluminous and are able to store a higher amount of hydrogen (equivalent to compression at 845 atm) but they are heavier and consequently the H_2 weight percentage is similar to the percentage obtained after pressurizing at 350 atm (∼5 wt%). In addition, the fabrication costs are high and the liquefaction energy is equivalent to 30% LHV. It is clear then that any future solution must involve an alternative type of storage, at least for private vehicles.

4.6. Hydrogen vehicles

H_2 PEMFC may become the engine of the future due to its obvious advantages over the ICE, i.e. its efficiency (∼50% average over the whole range with the possibility of achieving 60% vs. ∼20–38% in the case of ICEs), the absence of pollutant emissions and its silent operation. However its high cost (∼$1800/kW in the case of the FC of ∼100 kW [10]) demands for the mid/short-term a more available though less efficient system, with the objective to speed up the introduction of hydrogen as an alternative motor vehicle fuel. This system is the hydrogen internal combustion engine (ICE-H_2) which is very similar to the classic four-cylinder petrol engine except for some adjustments to the air mixture and other mechanical features. In the initial hydrogen popularization step, ICE-H_2 will permit the creation of a network of H_2 refuelling stations and become a bridge to FC vehicles, the mass marketing of which is not expected before 2030. During this transition to FC vehicles some hybrid concepts will be put on the market to optimize the energetic efficiency of the vehicle. The IEA forecast is that the hybrid vehicle will be the ICE-H_2/electric engine [10]. In this hybrid vehicle a Li-ion battery will be used to activate the electric engine. A computer will decide which motor should be activated in a given situation. When the ICE-H_2 is employed, it works with the maximum degree of efficiency. If the engine generates more energy than is needed, the excess is used to charge the battery, and the electric engine acts as a generator. Otherwise only the electric engine works, this being fed by the energy of the battery. The energetic efficiency of the vehicle is increased by the addition of a system to recover the heat from the brakes which is also employed to charge the battery.

4.7. Domestic energy

During this period we will see the beginning of the popularization of the cogeneration systems to provide electricity and heat to houses as a substitute for diesel generators or conventional fossil fuel and electricity networks. At the present time the most appropriate fuel cells for this use are the SOFC which are fitted with non-porous ceramic electrolytes. As they operate at high temperatures (800–1000 °C) it is not necessary to use expensive catalysts or pre-reforming processes. In fact, they are able to operate on different fuels ranging from methane to H_2 including CO/H_2 mixtures, which makes them an ideal system for the transition from methane to H_2. Additionally the high temperatures needed for their operation gives rise to residual heat which can be used in heating systems (combined heat and power system) so they become integrated systems for the supply of heat and electricity to houses. Initially small power systems (∼4 kWe) will be produced for supplying single houses, whereas medium power systems (∼200 kWe) will supply energy to apartment blocks and small industries. These systems will be fed by natural gas ("non-clean" energy) until the transition to hydrogen takes place. Such systems have a greater efficiency than the traditional systems; 45% in electricity, which can be expected to reach 60–70%, compared with the 38% efficiency in conventional CHP systems [10]. However, the main obstacle for the massive implantation of these systems is their price (€5000/kW compared to €1000/kW for the conventional systems), although a reduction in cost to €1000/kW can be expected by the year 2030, with an increase in electric efficiency of up to 55%. The expectations for 2007 in USA are 130 MWe, approximately 33,000 houses [21].

5. Beyond 2015. The slow path to decarbonization and renewable energies

By 2015 there will be decentralized units for H_2 production (essentially refuelling stations for small fleets of urban buses) from methane and electricity (with CO_2 emissions) and a small percentage of industries and houses with a slightly cleaner but also somewhat more expensive supply of heat and electricity (SOFC fed with methane). However, this panorama could only arise in the economically advanced societies (USA, Canada, Europe, Japan and maybe China). In the subsequent decades we should be moving towards the hydrogen economy, on a path signalled by the following developments.

5.1. Mid-term production of electricity

From 2015 onwards systems for CCS must be installed in power plants, especially in new plants that will permit the co-processing of biomass and fossil fuels (coal and natural gas) and the co-generation of electricity and hydrogen as in IGCC (Fig. 2). Today the worldwide capacity of coal gasifiers in operation is 46 GW [10] (currently the total electricity capacity worldwide is around 4000 GW, the final electricity production being equivalent to the uninterrupted use of around 2000 GW). Moreover, renewable energies (biomass, hydraulic, wind power, etc.) will start to be preponderant in the electricity market, with a share of over 25% in EU by 2015. These renewable energy sources will be integrated into the electricity and hydrogen networks taking into account environmental benefits, regional availability and energy efficiency.

5.2. Selection of energy sources and transformation processes

On the path towards widescale hydrogen production we should be careful to choose the appropriate energy sources and

Table 1
Primary Energy consumption, reserves and maximum capacities estimated from the *non-renewable* energy sources

Primary energy source	Availability			H_2 production (efficiency%)[e]	Needs for H2AT2050
	Primary energy 2004 (Mtoe/y)[a,b,c,d]	Proven reserves 2004 (Mtoe)[b]	Electricity production 2004 (TWh/y)[a,b]		From primary energy (Mtoe/y) (global efficiency%)[f]
Nuclear	624.3	45,000–195,000[g]	2752.2	Electrolysis (>50%)	15,100 (18%)
				Thermochemical cycles (> 40%)	6750 (40%)
Coal	2778.2	448,000.5	6939.4	Reforming (44%)[h]	6250 (44%)
Natural Gas	2420.4	161,000.6	3350.0	Reforming (83%)[h]	3250 (83%)
Oil	3767.1	162,000.1	1148.6	Reforming (70%)[h]	3900 (70%)

The last column shows an estimation of the amount of primary energy needed to generate 1 Gton of H_2, an amount that is enough to supply all transport by 2050, if the implantation of fuel cell vehicles is 100% (H2AT2050=H_2 for all transport in 2050). Electric energy consumed in 2004: 17,350 TWh. Estimation of electric energy needed in 2050 (excluding transport): 38,000 TWh. Heat consumption estimation: 10 Gtoe. Efficiency of the FC: 50%. Efficiency of the ICE: 30%.

[a] Ref. [21].

[b] Ref. [2].

[c] Ref. [3].

[d] Ref. [4].

[e] Ref. [23].

[f] Global efficiency: 100×Primary E (Mtoe)/[1000 Mton H_2× 2.7 Mtoe/Mton H_2].

[g] These amounts are equivalent to 3.9 Mton (conventional reserves) and 17.1 Mton (conventional + speculative reserves) of natural uranium [1 kg uranium = 50 MWh, 36% efficiency]. (Ref. [11]).

[h] Ref. [27].

transformation processes on the basis of availability, cleanliness, energy efficiency and cost. Taking into account the forecasted need for 25 Gtoe of primary energy in 2050 [9], of which 18% will be used in transport (current ratio), in addition to an expected improvement in the efficiency of hydrogen engines, the consumption of H_2 when this fuel has totally replaced diesel and petrol will be ∼1 Gton. In this estimation, a conservative difference in efficiency between ICE (30%) and FCs (50%) is assumed. Using similar criteria the worldwide electricity consumption for 2050 can be expected to be approximately 38,000 TWh, while heating consumption will be around ∼10 Gtoe. The total amount of electricity needed worldwide could be obtained by means of 2.3 Gton of H_2 in SOFC which would also generate around 2.5 Gtoe of heat.

5.2.1. *The role of decarbonized renewable energies*

Tables 1and 2 [22–29] contain a list of the available energy sources worldwide, the total amount of each one consumed during 2004, estimations of the reserves or annual maximum production capacities and the consumption needed to obtain 1 Gton of H_2 by the different processes associated with each energy source (H2AT2050: H_2 needed to supply all transport needs in 2050). The processes considered suitable for converting primary energy to hydrogen are indicated in Fig. 3 with the exception of IGCC whose place has been taken by coal or oil reforming (the latter included for the sake of comparison). The production of bio-fuels (bio-ethanol and bio-diesel) from biomass, for direct use in ICEs, and bio-methanol for on-board reforming has also been included.

Using only electrolysis to produce all the hydrogen needed for transport in 2050 would require an amount of electricity that would be almost double the quantity consumed that year by the rest of the sectors (67,000 vs. 38,000 TWh). As indicated in Table 3, such a huge amount could not be covered independently by on-shore wind energy (125% of the total estimated capacity would be needed). Only solar photovoltaic and nuclear energies would have enough potential capacity (the latter only for a limited period of time between 3 and 13 years). For example, in order to meet the production target mentioned above with only one energy source, either the installed nuclear energy would need to be increased by a factor of 25, wind energy by a factor of 900 (as indicated the actual demand would be higher than the estimated total capacity) or photovoltaic solar energy by a factor of 21,000.

It is obvious that a mix of energy sources, including hydroelectricity and geothermal energy could supply electricity to electrolysers to obtain 1 Gton of H_2, even without the need for nuclear energy, by an appropriate increase in the power already installed. However, the high installation costs of these systems, which would affect the final cost of H_2 production (Fig. 4) as well as the low global efficiency of H_2 produced from electrolysis compared to the other processes (last column in Tables 1 and 2) seems to favour the use of electrolysers only in cases where other cheaper and equally clean processes are not available (for instance in isolated areas without biomass, such as desert areas). Thus, the use of decarbonized renewable energy sources, which excludes biomass, should be reserved for the production of electricity for direct consumption and not for the widescale production of H_2.

5.2.2. *Fossil fuels*

As already pointed out, fossil fuels will continue to form an important part of the worldwide energy economy in the transition towards hydrogen. Hydrogen and electricity could be cogenerated in large coal gasifiers equipped with CCS systems. Currently the cost of production of hydrogen in centralized

Table 2
Primary Energy consumption, reserves and maximum capacities estimated from the *renewable* energy sources

Primary energy source	Availability				H_2 production (efficiency%)^{e}	Needs for H2AT2050
	Primary energy 2004 (Mtoe/y)^{a,b,c,d}	Maximum estimated energy production (Mtoe/y)	Electricity production 2004 (TWh/y)^{a,b}	Maximum estimated electricity production (TWh/y)		From primary energy (Mtoe/y) (global efficiency%)^{f}
Hydraulic	634.4		2853.8	10,000^{e}	Electrolysis (> 50%)	15,000 (18%)
Wind on shore	29.8	—	81.5	50,000^{g} Spain: 70–100^{e} or 2285^{h}		25,000 (11%)
Geothermal	6.3	—	54.7	2000–11,000^{i}		7400 (36%)
Solar (photoV)	2.0	—	3.2	Spain: 100,000 km^2 direct insolation 26,000^{e}		42,000 (6.4%)
Solar (thermoch.)	49.4	Spain:100,000 km^2 direct insolation 5000^{e}			Thermo-chemical cycles (> 40%)	22,000 (12%)
Biomass	1350.0	12,700–9400^{j}	164.2	18,000–13,500^{j}	Bio-ethanol Bio-diesel (35%)^{k,l} Bio-methanol from syngas (65%)^{m} Reforming (73%)^{m}	12,900 (21%) (Motor ICE) 4600 (59%) (on-board autothermal reforming: 87%)^{n} 3750 (73%)

The last column shows an estimation of the amount of primary energy needed to generate 1 Gton of H_2, an amount that is enough to supply all transport by 2050, if the implantation of fuel cell vehicles is 100% (H2AT2050 = H_2 for all transport in 2050). Electric energy consumed in 2004: 17,350 TWh. Estimation of electric energy needed in 2050 (excluding transport): 38,000 TWh. Heat consumption estimation: 10 Gtoe. Efficiency of the FC: 50%. Efficiency of the ICE: 30%.

[a] Ref. [21].
[b] Ref. [2].
[c] Ref. [3].
[d] Ref. [4].
[e] Ref. [23].
[f] Global efficiency: 100 × Primary E (Mtoe)/[1000 Mton H_2 × 2.7 Mtoe/Mton H_2].
[g] Ref. [25].
[h] Ref. [24].
[i] Identified sources—non identified sources rank Ref. [22].
[j] Maximum estimated for 2050 (4100–12,700 Mtoe) and 2100 (3000–9400 Mtoe), respectively Ref. [20].
[k] Biofuels production efficiency from biomass Ref. [22].
[l] A production of 75% bio-ethanol and 25% bio-diesel (~70% LHV of petrol) is assumed.
[m] Ref. [26].
[n] Ref. [27].

coal gasifier systems (without CCS) is more expensive than the cost of H_2 from centralized natural gas reforming systems ($0.22/Lge vs. $0.13/Lge) [10]. If CCS systems are added the cost will increase up to ~$0.3/Lge. Moreover, in coal gasification plants of the future with cogeneration systems and global efficiencies around 50%, the price of H_2 can be expected to fall to ~$0.22/Lge (Fig. 4). In Fig. 4 the equivalence in litres of gasoline is considered in terms of absolute energy content without taking into account the higher efficiency of the systems in which H_2 would be used (FCs). Thus when comparing the prices of H_2 and gasoline *per kilometre* we should multiply the former by an approximate factor of $\frac{3}{5}$.

Added to the small natural gas reformers installed in the previous stage (before 2015) CCS systems will allow the installation of natural gas reforming plants to reach capacities of over 50,000 cars per day, since the CO_2 produced will be appropriately confined. These large plants will be then integrated in a centralized hydrogen network.

Although clearly the best solution to the negative effects of energy consumption is to continue to decrease the use of fossil fuels, their use on a large scale for electricity generation and H_2 production is guaranteed at least for several decades. For instance H_2 production for transport by coal reforming, if we consider the rate of consumption expected in 2050 (1 Gton H_2/year) will be guaranteed for 70 years if electricity and heat are produced from other energy sources (Table 3). With the projected cogeneration plants based on coal, equipped with CO_2 separation membranes and CCS [31], considering the rate of consumption for 2050 we should be able to produce electricity for 40 years and H_2 for 60 years (a period of time that would be considerably lower if the H_2 so formed were employed to generate synthetic fuels instead of being directly used in vehicles). The utilization of natural gas could duplicate these values, although we would have to reduce them again if we take into account the parallel supply of heat. In any case we are talking about a limited period of time—a few decades—when

Table 3
Utilization values of energy sources to produce enough H_2 to supply transport needs based totally on fuel cell vehicles in 2050 (1 Gton H_2) by means of the processes listed in Tables 1 and 2

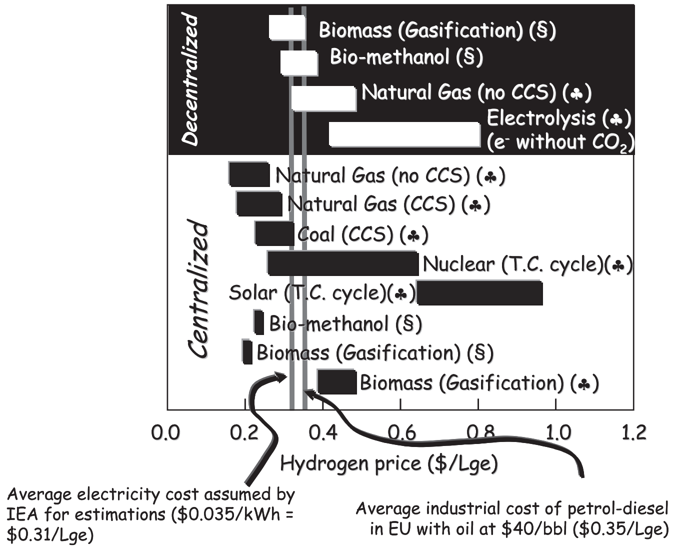
Energy source (H_2 production method)[a]	Multiplying factor in 2050 compared to 2004	Consumption in 2050 (percentage of maximum capacity)	Years to extinction at the consumption rate of 2050
Solar photovoltaic (e)[b]	21,000	—	—
Geothermal (e)	1250	3000–600[c]	—
On-shore wind (e)	900	125	—
Solar thermal (tcc)[b]	500	—	—
Hydraulic (e)	25	625	—
Nuclear (e)	25	34–8[c]	3–13[c]
Nuclear (tcc)	11	16–4[c]	6–30[c]
Biomass (bio-ethanol/diesel-ICE)	7.0	104	—
Biomass (bio-methanol/on board reforming fuel cell engine)	2.5	37	—
Biomass (r)[b]	2.1	28	—
Coal (r)	2.3	1.4	72
Natural gas (r)	1.4	2.0	50
Oil (petrol-ICE)	1.3	2.8	36
Oil (r)	1.0	2.4	42

To consider total energy consumption, 38,000 TWh/y should be added for electricity consumption and 10 Gtoe for heat consumption.

[a] For biomass and oil, the consumption needed to produce bio-fuels and petrol is also given.

[b] e: electrolyser; tcc: thermochemical cycle; r: reformer.

[c] Identified sources—(identified + non-identified sources). Sea uranium is excluded.



Average electricity cost assumed by IEA for estimations ($0.035/kWh = $0.31/Lge)

Average industrial cost of petrol-diesel in EU with oil at $40/bbl ($0.35/Lge)

Fig. 4. Cost estimations in the future production of H_2 (♣ Ref. [10], § Ref. [30]).

biomass should be increasingly replacing fossil fuels, allowing us to continue using thermal power plants to generate electricity and hydrogen in a clean way.

5.2.3. Biomass

Biomass is a clean and available future energy source since it contributes to net CO_2 emissions only in the small amount of fossil fuels used in the transformation processes to H_2 or bio-fuels. Biomass comes from energy crops, such as corn and sugar cane (bio-ethanol precursors), sunflower and rapeseed (bio-diesel precursors) and sawmill residues (sawdust that produces bio-alcohols and Fischer–Tropsch diesel), agricultural residues (straw, animal wastes and manure to produce bio-alcohol and bio-gas) and the organic fraction of domestic and industrial wastes (to produce bio-gas and bio-methanol). However, if we take a look at the 1200–1500 Mtoe of biomass consumed in 2004 [4] almost half was wood burnt in the tropical developing countries (in Africa almost 90% of the primary energy consumed was provided by wood). In the transition to a hydrogen economy, biomass can be employed as a clean form of energy mainly through the three conversion processes (Table 2) described below:

Process 1: Transformation to bio-fuels (bio-ethanol and bio-diesel) that are directly burnt in the ICE. Today the main producers of bio-ethanol are the USA (from corn) and Brazil (from sugar cane). Brazil is far ahead of the other producers since biomass constitutes around 13% of its energy demand [32]. Spain is the leader in bio-ethanol production in EU, while Germany and France are the biggest European producers of bio-diesel.

Process 2: Transformation to bio-methanol through syngas ($CO+H_2$) produced in the biomass gasification process. Liquid bio-methanol is stored in vehicles provided with a reformer in which the fuel reacts with water to produce H_2 that is fed to the FC engine [33]. This option largely increases energetic efficiency compared with bio-fuels. Thus, an ideal autothermal process would produce hydrogen with a 104% of the energy existing in the reacted methanol.

Process 3: Direct transformation of biomass to H_2. This option is employed in centralized reforming systems or in

H_2-electricity cogeneration systems (i.e. IGCC). The gasification or reforming process produces a mixture of H_2, CO and CO_2. CO is further reacted with water to produce CO_2 and more H_2 (water gas shift reaction). The environmental benefit of this procedure is that it allows carbon capture and storage and consequently the net CO_2 emissions are below zero.

The future of the first option (bio-fuels) as a substitute for petrol in transport [22] is uncertain for several reasons. Apart from the production costs and the use of a small amount of fossil fuels in bio-fuel production (thus detracting from the real concept of "bio") there is controversy about the use of crops such as corn or sugar beet for energy production rather than for alimentary purposes. The controversy centres around the limited availability of cultivable land so the production of biomass for one application will have a negative impact on the other. Biomass to generate bio-fuels will receive a better response when the massive implantation of short-rotation crops of lignocellulosic varieties occurs. Lignocellulosic crops do not compete with alimentary crops since they can be implanted in any land (including forests). Moreover their own lignin can be used as fuel in the cellulose-to-bio-fuel transformation process, thus eliminating the use of fossil fuels. To achieve this, however, it will be necessary to optimize and reduce the cost of the cellulose-to-bio-ethanol process.

For the optimal situation, from an analysis of Tables 1–3 it is evident that the total energy demand of transport can hardly be covered by bio-fuels alone (process 1) since the entire worldwide biomass capacity would have to be employed. This is due to the low energetic yield of this biomass conversion option (~20%) compared to the other two options (direct transformation into hydrogen or methanol; ~60–70%). However, the first process is the best alternative to allow a gradual decrease in the consumption of gasoline in the short-term, since bio-fuels can be mixed with standard gasoline or used alone with only minor modifications to the current combustion engines.

Processes 2 and 3 which employ gasification to obtain bio-methanol or hydrogen are more favourable from an energetic point of view and consume less biomass (they only require 37% and 28%, respectively, of the annual maximum capacity of biomass production to be able to meet the needs of transport; Table 3). Thus in the medium and long-term they must be considered the more reasonable alternatives. The state of the technology of H_2 storage will be determinant in selecting one of these two options. The use of hydrogen as fuel is slightly more efficient (Table 2) if the storage cost is not included, and would allow the combination of the large reforming plants with CCS systems, which would lead to negative net CO_2 emissions (or the removal of a part of CO_2 from the atmosphere). However, the bio-methanol option has the advantage of not requiring the storage of H_2, and would allow the use of the existing liquid fuel distribution network. These advantages make bio-methanol an option to be considered in the future hydrogen economy, although to our surprise the IEA *considers that it is an expensive option and a technological challenge* [10]. However, in our opinion the benefits of bio-methanol should be stressed: (i) biomass availability for bio-methanol production is guaranteed (Tables 2 and 3); (ii) hydrogen storage options are likely to be more expensive and currently suffer from a lower state of development than onboard reforming; (iii) a deposit with 33 kg of methanol and 14 kg of water (54 L) is sufficient to produce 5 kg of H_2 (reformer efficiency: 87%) which is enough to drive the FC car 400 km; (iv) world methanol production needs to be multiplied by a factor of just ~200 from current production, which by the year 2050 would imply one standard bio-methanol plant (1 Mton/year) per 1,300,000 habitants and (v) bio-methanol is considered to be among the cheapest sources of hydrogen (Fig. 4).

The use of biomass on a large scale for centralized energy production will lead to the creation of a transport and distribution network in order to guarantee the supply of biomass to regions with a deficit in production by means of an import/export market. Of course this will increase the price of biomass but will contribute to the incorporation of the developing countries to the club of developed countries, given that their economic biomass potential is considerably higher than those of developed countries which will exchange money and conversion technology for raw materials [22] in a market that will be fairer and more reasonable than the current oil market.

5.2.4. *Thermochemical cycles*

The high energy consumption of electrolysers makes it necessary to find sources other than electricity for the production of hydrogen, such as nuclear or solar thermal power. The direct thermal splitting of water is technically challenging, since it occurs at a very high temperature (~2500 °C). However, the use of two parallel thermal cycles in which H_2 and O_2 are produced separately, allows H_2 to be obtained at a considerably lower temperature (<1000 °C). The use of heat generated directly by solar or nuclear energy sources makes for a more globally efficient conversion process than that obtained by an electrolyser (almost two times, see Tables 1 and 2). Many cycles are currently under study, the most popular being the S–I cycle (sulphur–iodine) which is based on the following reactions:

Sulphur cycle:

$I_2 + SO_2 + 2H_2O \rightarrow H_2SO_4 + 2HI$ (common reaction at 120 °C. Afterwards the two products are separated),

$H_2SO_4 \rightarrow SO_2 + H_2O + 1/2O_2$ (at 850 °C; the O_2 is separated and the SO_2 is recycled).

Iodine cycle:

$I_2 + SO_2 + 2H_2O \rightarrow H_2SO_4 + 2HI$ (120 °C),

$2HI \rightarrow I_2 + H_2$ (at 450 °C; the H_2 is separated and the I_2 is recycled).

As Table 3 shows, to produce by this process all the hydrogen needed to satisfy our transport needs in 2050 (H2AT2050) we will have to increase the capacity of currently installed thermal solar collectors by 400 times or our nuclear capacity by 9 times (in the latter case new designs such as the "very high temperature reactor" [10] will be needed since conventional designs cannot achieve the required temperature of ~950 °C). If nuclear energy were used to produce all the hydrogen necessary for transport in 2050 (H2AT2050) uranium would be exhausted within ~40 years (Table 3).

Although these processes are technologically feasible they are still under development and there are not as yet any viable commercial solutions. Before they can be applied, it will be necessary to overcome some technological and social barriers. The technological barriers include the cost, the development of economic and appropriate materials for the experimental conditions (separation membranes and heat exchangers) and an increase in thermal efficiency of over 50%. The main social obstacle to be overcome is again negative public opinion towards nuclear energy. In any case this option could not be applied before 2030 [10].

5.3. Hydrogen distribution network

Centralized hydrogen production in thermal cogeneration power plants equipped with CCS and scaled up reformers and electrolysers will lead to the creation of a hydrogen distribution grid for transferring hydrogen from the production points to the consumption points (refuelling stations and residential CHP systems). Today there are ~16, 000 km of H_2 pipelines around the world that supply H_2 to refineries and chemical plants. These pipes have a diameter of 25–30 cm and operate at 10–20 atm, although they could operate at pressures of up to 100 atm. Considering that H_2 pipes must be produced with non-porous materials such as steel, their cost for a given diameter is around twice that of pipes used for conducting natural gas. Moreover, as the volumetric density of hydrogen is a fourth that of natural gas the cost of a H_2 pipe is about six times higher than that of a natural gas pipe. Estimations by IEA consider the investment cost for new pipes would be $1.4/Lge [10]. This is equivalent to a worldwide investment of about 5000 billion dollars per 1 Gton of H_2. We also need to include ~300 billion dollars to cover the cost of the refuelling stations in a centralized network. The cost would be considerably reduced if the natural gas infrastructure could be adapted to H_2. A decentralized network of refuelling stations would cost more than twice this estimate [10]. Although the cost of distribution would be avoided, the global production cost of H_2 would be much higher. If we assume that the creation of a centralized network could take as long as 60 years, the annual cost would be ~80 billion dollars. This is only about 8% of worldwide armament expenditure in 2004 [34].

5.4. Storage in vehicles and FCs

As mentioned above a key step on the road to a hydrogen society must be to reduce the cost of H_2 storage systems and FCs in motorized vehicles. Due to the uncertainty about whether pressurized and liquid hydrogen tanks can be made at a lower cost the future seems to lie in storage in solid materials. These systems require less energy to store H_2 in similar amounts to gaseous or liquid systems, at a lower volume and at lower pressures. However their weight is considerably higher (50 L/200 kg for solid systems vs. 100 L/50 kg for H_2 compressed and liquid). Porous carbon was at one time considered an interesting material for hydrogen adsorption. However, the failed expectations of carbon nanotubes, whose initial results of 30–60 wt% of stored hydrogen are now considered to have been an experimental error, has to some extent undermined research on these materials [35,36]. Other porous materials such as zeolites or (metal organic frameworks), MOF, with really high values of surface area are still in need of further development. They are capable of storing considerable amounts of hydrogen at cryogenic temperature but their adsorption capacities at ambient temperature are still quite low. Rechargeable metallic hydrides, including their alloys, seem to be in a better starting position for winning the storage race, with an estimated value of 8 wt% (DOE objective: 6 wt%) at 10–60 atm.

The current cost of FC vehicles is about $2000/kW (a standard car will need a fuel cell stack of ~100 kW). Future previsions indicate that this cost could be reduced to $100/kW, although a further reduction to ~$50/kW will be needed to make them completely competitive [10]. Such a reduction cannot be achieved with the current technology, so new FC concepts are required. Currently PEMFC use conducting Nafion membranes as electrolytes, which operate at low temperature (80 °C). As a consequence, the amount of Pt needed as catalysts in the electrodes for the electrochemical conversion of H_2 and O_2 into water needs to be very high (1.4 g/kW). Two ways to reduce the amount of Pt would be either to increase the reaction temperature over 100 °C, which would imply the development of new membranes, or to resort to more active catalysts, such as platinum alloys with cobalt or chromium [37] supported on electrodes with a higher surface area. The high temperature FC would additionally allow the bio-methanol reforming system to be integrated more easily in the vehicle if the development of this technology is finally achieved.

Beyond 2015 an exponential increase in the use of H_2 can be expected for transport in market niches where the engine and storage tank price is not critical (i.e. buses, trucks and planes). The design and operation of SOFCs for the cogeneration of electricity and heating in homes must be improved (at present the start-up is too slow due to the high operation temperature) but they will gradually become an integral part of society over the next few decades.

6. Future expectations

Two simultaneous conditions must be met for a society based on a hydrogen economy. First international organizations must be strong enough to guarantee the fulfilment of the international agreements on global reductions in CO_2 emissions. This problem can be expressed in numbers via the worldwide CO_2 emission market, in which an estimated cost of $50/ton would seem to be enough to force the energy companies along the path of implementing carbon-free energy sources. If this condition is not met, fossil fuels will continue to form the base of the energy scenario for decades. In this situation, when the oil is used up, synthetic fuels produced from coal and natural gas by Fischer–Tropsch synthesis (SASOL process) will be employed in transport, with drastic consequences for climate change and with society left wondering why its predecessors were so selfish and unconscientious in their attitude to the energy crisis. However, this is not the only condition that needs to be accomplished for the success of a hydrogen-based society. Technological development must bring about a reduction in the costs of H_2 production, distribution, storage and utilisation (FCs). Even in the case of failure, provided the first condition is met, the energy system might also be a clean one if society uses renewable energy as electricity source and employs hybrid systems based on conventional lithium batteries and bio-fuels to power its cars.

IEA has analysed several scenarios of political and technological evolution that have been named ESTEC [10] from the dimensions employed to quantify the different hypotheses (Environment, Security supply, Technological progress, Economic conditions and Competing options). In the most favourable situation for the development of a hydrogen economy (ESTEC D) in 2050 30% of the cars will be powered by hydrogen feed FCs and there will be a capacity of 200–300 GW in installed FCs to cogenerate heat and electricity in the residential sector. By then the collective impact of hydrogen and other clean technologies (CCS, electricity from renewable energies, etc.) will help to stabilize CO_2 emissions to the atmosphere and create a diversified network of energy sources, thereby reducing our dependency on oil. But *videre est credere*.

Acknowledgements

The authors wish to thank Dr. J.C. Abanades for his fruitful suggestions and comments to improve the quality of this work. TVS acknowledges CSIC-ESF for the award of an I3P postdoctoral contract. The financial support for this research provided by the Spanish MCyT (MAT2005-00262) and FICYT Regional Project (IB05-001) is gratefully acknowledged.

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