5.2. Environmental scope

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List of abbreviations

OE	oil equivalent energy consumption
IPCC	International Panel on Climate Change
GHGs	greenhouse gases
EOR	enhanced oil recovery
NG	natural gas
GWP	global warming potential
APUs	auxiliary power units
IEA	International Energy Agency

1. Introduction

In the third millennium "sustainability" is increasingly becoming a social, political, scientific, and engineering key issue. Indeed, there are growing signs of sustainability becoming a major new paradigm influencing the society of tomorrow and the engineering it requires. The sustainable development, which can be defined very simply as a process, in which it is tried not to take more from nature than nature can replenish, can be achieved without sacrificing the many benefits that modern technology has brought. The only problem is that technology respects the imposed constraints. Engineers are asked to do this by designing new processes and/or by modifying existing processes aiming at using less energy and renewable resources and producing by-products that can be safely returned to the earth.

Driving the global energy system on a sustainable path increasingly represents a major concern and policy objective [1, 2]. The emergence of a sustainable global energy system is a long-term process that will require a deep transformation of its current structure. In fact, energy resources play a major technical role in sustainable industrial development, and energy-related issues and hydrogen, its production, storage, transportation, and utilisation are key elements in a sustainable industrial development. Today, the world's economy is based on fossil fuel, as it covers around 80% of the world energy consumption, the remainder 6.5% and only 13.5% being met by nuclear and renewable resources, respectively [3]. Emissions from industry and fossil fuel energy use constitute the man-made part of the greenhouse gas emissions and result in heavy local and regional air pollution. The price to pay appears in the form of natural disasters, unreliable access to food, the spread of tropical diseases, and severe health and ecosystem impacts.

To remedy this situation, the ultimate goal must be to establish an energy system based on clean and renewable energy sources, such as solar, wind, hydro, geothermal, and bio. An integrated approach to meeting these demands is to find energy carriers that do not pollute during distribution or usage and, at the same time, ensure flexibility with regard to energy sources. Energy carriers with such characteristics are hydrogen, electricity, and thermal systems (such as district heating and cooling systems) as illustrated in Figure 1 [4]. Of the energy carriers, hydrogen is a newcomer in the scene and going to be by far the most important in the future. Hydrogen is not an energy source, but an energy carrier. Accordingly, it is not available in nature as it is, but must be produced from a raw material, transported, and finally utilised for the production of energy. Production and storage of hydrogen certainly are important in this chain, but the utilisation device, namely, the tool that transforms the chemical energy of hydrogen into electrical energy, plays a crucial role. This piece of equipment is a fuel cell and its efficiency and operating condition is of paramount importance in the hydrogen-based energy scenario.

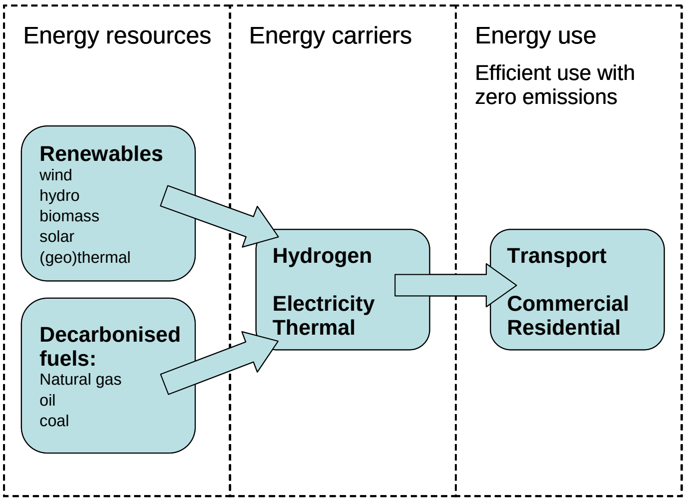

***Figure 1**: Vision of a clean energy chain in hydrogen society.*

The pollutants emitted by fossil energy systems (e.g. CO, CO_2, C_nH_m, SO_x, NO_x , radioactivity, heavy metals, ashes, etc.) are by far larger in quantity and more damaging than those that might be produced by a renewable hydrogen energy system. Worldwide reduction of CO_2 emission to limit the risk of climate change (e.g. greenhouse effect) requires a major restructuring of the energy system, and the use of hydrogen as an energy carrier is a long-term option to reduce CO_2 emissions.

In this chapter, environmental issues related to hydrogen technology will be presented and discussed briefly. Particular attention will be devoted to the benefits of the introduction of hydrogen technology for energy production. Direct positive effects of the production, storage, and utilisation of hydrogen are perceived immediately in terms of carbon dioxide emission reduction and, hence, the reduction of global warming. This, in turn, will result in a cascade of benefits to the climate, biodiversity, agriculture, and in general to the quality of life and world economy.

The chapter will start by illustrating the issue of global warming and its relation with carbon dioxide handling. In particular, current figures summarising the impact of carbon dioxide emission on climate changes and on ecosystem changes shall be reported and strategies will be discussed to reduce the carbon dioxide emissions. Subsequently, issues related to hydrogen and the energy market shall be presented in order to depict some possible scenarios for the future. The state of the art of hydrogen production and utilisation industries and devices will be highlighted. In the end, some conclusions will be drawn in line with many researchers and scientists, who agree that the future in energy production is hydrogen [4-8]. The question is not whether, but only when this will happen. And we all hope that this will be soon.

2. Global warming and CO_2 handling

2.1 Current figures

Global primary energy consumption amounted to 10.54 billion tons of oil equivalent (OE) in 2005 and is projected to increase by 1.3% per year for the industrialised countries and by up to 9.2% per year for the developing countries [9]. With such a large oil consumption predicted, great care should be given to oil reserves, but this issue definitively is one of the most controversial aspects of the discussion for several reasons: (i) there is no universally accepted definition of reserves, nearly everybody has his own version, (ii) most reserve estimates are unverifiable, as they tend to be state secrets, and (iii) reserves reported in open publications tend to increase with time in spite of extensive production. Despite this uncertainty in determining the amount of oil available for energy production, fossil energy will remain the number-one energy source until far into this century.

Since 1751, roughly 305 billion tons of carbon have been released into the atmosphere from the consumption of fossil fuels and cement production. Half of these emissions have occurred since the mid-1970s. The 2003 global fossil fuel carbon dioxide emission estimate - 7303 million tons of carbon - represents an all-time high and a 4.5% increase compared to 2002 [10]. Globally, liquid and solid fuels accounted for 76.7% of the emissions from fossil fuel burning in 2003. Combustion of gas fuels (e.g., natural gas) accounted for 19.2% (1402 million tons of carbon) of the total emissions from fossil fuels in 2003 and reflects a gradually increasing global utilisation of natural gas. Emissions from cement production (275 million tons of carbon in 2003) have more than doubled since the mid-1970s and now make up 3.8% of global CO_2 release. On the other hand, gas flaring which accounted for roughly 2% of global emissions during the 1970s now accounts for less than 1% [10].

Preliminary figures calculated in compliance with the International Panel on Climate Change (IPCC) directives show that the amount of carbon dioxide, the most common of the greenhouse gases (GHGs), emitted in 2005 was 177 billion kg, a reduction by 4 billion kg (2%) compared to 2004. Other greenhouse gas emissions remained stable or decreased [11].

The most remarkable CO_2 emission reduction was reported in the energy sector. In electricity production the emission of CO_2 caused by combustion of fossil fuels was reduced by approximately 3 billion kg. The use of natural gas and coal, for example, was cut by 3% and 7%, respectively. In spite of the reduction, the amount of electrical energy available remained on the same level due to the promotion of renewable energy sources and extra imports of electricity. The use of renewable energy sources increased by approximately 40% in 2005 compared to the previous year; net imports increased by 13% [11].

Despite the good news of a minor reduction or stabilisation of CO_2 emissions, it is estimated that continued use of fossil energy will lead to an increase of the average global temperature in the next century by up to 3.4 °C [12]. On 2th February 2007, the fourth assessment report of IPCC [13] was presented, where this prediction has been updated to a more dramatic value of 4.0 °C as the best estimate corresponding to an interval of 2.4 – 6.4 °C as a likely range in the next 100 years. In the same report this temperature increase is said to correspond to an average sea level rise of 0.26 to 0.59 m.

2.2 Impact of CO_2 emissions

The most important impact of carbon dioxide emission will be on the **climate**. Alhough the forecasts of future CO_2 emissions from fossil energy use as well as the magnitude of their influence on global warming are much disputed and there is much dissent on the climatic consequences of global warming, the impact of CO_2 emissions on global warming itself is widely admitted.

On 29th August 2005, the hurricane Katrina ravaged New Orleans, Louisiana, and Mississippi, leaving a trail of destruction in its wake. It will take some time until the full toll of this hurricane can be assessed, but the devastating human and environmental impacts are already obvious. If Earth's climate will warm steadily in coming decades, as many scientists predict, heavy smog and extreme weather events could increase health risks around the world. Warmer temperatures could bring increased rainfall to some regions as well as heat waves and drought. The possible reduction in cleansing cold fronts is based on known aspects of the interconnected global climate. Low-pressure systems transfer heat from the tropics and bring cold air away from the poles. If the planet warms, the poles are expected to warm more quickly. This would decrease the temperature difference between the poles and the equator and the atmospheric "engine" that moves heat around would slow down. A report in the Journal of Medical Entomology warned that a warmer climate would bring increased mosquito populations and also allow for disease-spreading pests to propagate into new terrain. Most of the increase in diseases is due to numerous environmental factors (including infectious microbes, pollution by chemicals and biological wastes, and shortages of food and nutrients) and global warming will only make matters worse [14].

The fourth assessment report of IPCC [13] says that warming is expected to be greatest over land and at highest northern latitudes and least over the Southern Ocean and parts of the North Atlantic ocean. Snow cover is projected to contract and widespread increases in thaw depth are foreseen for most permafrost regions. Sea ice is projected to shrink in both the Arctic and Antarctic and in some predictions Arctic late-summer sea ice will disappear almost entirely by the later part of the 21st century. It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent and, based on a range of models, it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and heavier rainfalls. Moreover, extra-tropical storm tracks are projected to move towards the poles, with consequent changes in wind, precipitation, and temperature patterns to continue the broad pattern of trends observed over the recent half of the last century.

Changes in the climate will turn to changes in the ecosystem, in particular **agriculture**. The situation in Europe is evident. Recent data [15] show clearly that the amount of rain has decreased slightly, but the number of rainy days in Europe has decreased strongly. This fact which is particularly evident in south Europe caused a high number of dramatic changes in the territory, sometimes enhanced by a questionable policy of constructions in highly populated areas. Another destructive effect of global warming is on agriculture. South Europe climate is increasingly changing towards a ‘tropical climate’ and the first sign of this change can be seen in the fact that hundreds of animal and vegetal species from lower latitudes have colonised south Europe, sometimes replacing indigenous species. The Mediterranean Sea is the most invaded sea of the planet with its 750 alien species, mostly tropical and subtropical species coming with ship traffic to the Mediterranean and settling due to favourable conditions. Similar phenomena are observed also for animals and plants on dry lands in Italy, Spain, and Greece: a tropical squirt from Thailand is a typical example as far as animal species are concerned. In 2005, Italian production of corn, soy, and milk was reduced by 30%, 25%, and 20%, respectively, due to climate changes. To balance such losses, Italian farmers are switching the production to less heat-sensitive species, such as peanuts [15].

2.3 Strategies to reduce the CO_2 emissions

With the scenario depicted in the previous paragraphs, it becomes mandatory to agree on common strategies for reducing the emission of carbon dioxide and other greenhouse gases: **decarbonisation** of the fuels is the main issue in this effort. Renewable energy sources only constitute a very small part of today's energy production and, compared to fossil fuel, renewable pathways to hydrogen are currently scarce and costly. Decarbonised fossil fuel may therefore play a key role in the transition to an all-renewable energy economy. Figure 2 summarises the concept of decarbonisation and indicates the future trend. In this scenario, it is expected that the fuel cells tomorrow will play the same role that the internal combustion engines played in the past transition from the coal to the oil age, thus facilitating the first step towards decarbonisation. Today, feeding fuel cells with natural gas could be considered an unsatisfactory compromise and perhaps, it is not the best solution in terms of global warming and carbon dioxide emission. Nevertheless, while the shares of fuel cell engines and fuel cell-based stationary energy production are far from substantial, the transition to the full hydrogen age will be rather difficult, if possible at all.

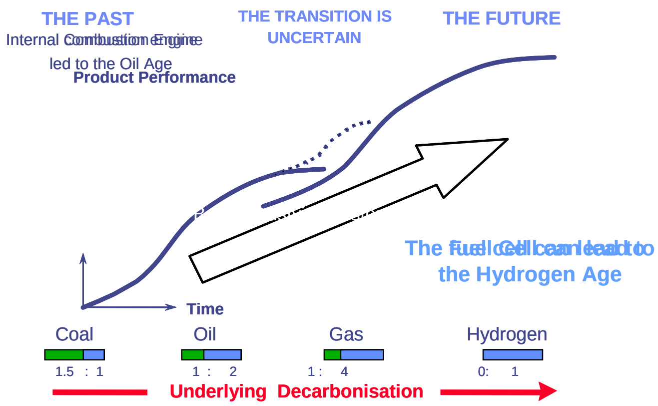

***Figure 2**: Decarbonisation and product performances.*

The transition is further complicated by the fact that, since producing renewable energy sources, such as solar panels and windmills is energy-intensive, replacing polluting energy production by renewable alternatives will require an increased use of energy during the transition period. A key challenge is to accelerate this transition as quickly as possible and without a parallel increase in emissions.

Harmonised worldwide implementation of CO_2 reduction strategies is, however, far from being realised. Many countries have made substantial progress in applying these strategies. Nevertheless, the contribution of industrialised countries to worldwide CO_2 emissions still is over-proportionally large. The costs of developing and applying CO_2 reduction technologies are tremendous, if not prohibitive for most of the emerging economies. There are serious obstacles, though, to reducing CO_2 emissions while satisfying the energy needs of our world, e.g. lacking international harmonisation, national needs and egotisms, rapid growth of world population, and a strongly increasing energy demand of emerging economies. Summing up, though an anthropogenic contribution to global warming cannot be proved for the time being, it cannot be ruled out forever. Therefore, internationally harmonised measures for CO_2 reduction have to be taken in the sense of a no-regret policy to avert potential damage from mankind and, thus, contribute to a sustainable development with fossil energy [16].

A hydrogen economy based on fossil fuels (including natural gas) without CO_2 handling will at best have limited benefits due to continued emissions of GHGs. This calls for identifying practical and environmentally sound CO_2 handling strategies. It is important to develop safe long-term solutions for CO_2 in parallel with work for a more efficient use of energy and increased use of renewable sources. Europe is in a position to implement a clean hydrogen economy by taking advantage of the availability of fossil resources, combined with the large storage potential of CO_2 in the North Sea basin.

Today, natural gas and water are being injected into oil reservoirs for oil recovery. In old oil fields the use of CO_2 for enhanced oil recovery (EOR) may increase the total amount of oil recovered. Moreover, by creating a demand for CO_2, petroleum companies would be willing to pay for it, which could pave the way for a large-scale CO_2 infrastructure. More importantly, in particular from an environmental perspective, petroleum companies could invest in emptying existing reservoirs rather than embarking on new oil exploration in sensitive areas like the Arctic. Paradoxically, the problem is to provide enough CO_2 in order to meet the demand for EOR in existing and future oil fields in the North Sea. CO_2 can be collected by capture from existing power plants and non-energy industries. With a common infrastructure for transportation and injection of CO_2 in the North Sea region, economies of scale and profitability can be achieved.

CO_2 storage beyond EOR and deposition in salt water-filled formations (saline aquifers) has a considerable potential. Studies suggest there is a capacity to store 100-150 years of EU's present CO_2 emissions. This capacity could help to further reduce GHG emissions beyond the first Kyoto protocol. In fact, combining CO_2 handling technology with the bio-based generation of energy will enable a negative net emission of CO_2, thus opening up the possibility of mitigating or even reversing climate change tendencies in the longer run.

An important issue when discussing global warming and carbon dioxide emission is **energy efficiency**. Any discussion of energy policy deals with three issues: energy supply (and, hence, security), climate change, and costs or prices. Energy efficiency is an obvious win-win-win approach. Every barrel of oil or ton of coal that we do not burn means less carbon dioxide in the atmosphere and a higher efficiency. Fortunately, many leading businesses are taking practical steps towards reducing their contribution to climate changes. US energy intensity is already improving by 1.5% per year. If we could accelerate this rate to 2% per year, energy use in 2050 would be nearly 50% lower than it would be otherwise, but still 60% higher than current levels: clearly not, where we should be, if our energy sources are not carbon-friendly. So what these figures tell us is that energy efficiency is an essential component, but not the only one, of any long-range effort to protect the climate.

With the use of natural gas, for example, emissions of greenhouse gases can be limited, but there are real challenges to be overcome in terms of supply and costs. With coal, by contrast, it is climate and not costs or supply that we need to worry about (unless we put real effort into carbon capture and sequestration and can make it work at an affordable price). Costs, of course, are an important challenge for nuclear power, as are considerations of waste and weapons proliferation. Costs also are a challenge with renewables: a challenge that clearly influences the supply and use of these technologies. When looking at oil, challenges are faced in all three areas. The world may have ample supplies overall, but the security of these supplies is an obvious concern, as are prices and climate.

Energy efficiency will reduce the demand of fossil fuels and, thus, constitutes an effective way to reduce emissions of GHGs. However, it must be very clear that electricity savings alone cannot contribute to the clean production of hydrogen, as long as the electricity is generated from fossil and nuclear sources. If this is the case, the performance of hydrogen vehicles would be very poor in terms of both energy efficiency and GHG emissions, as compared to other alternatives. Figure 3 [6] reports the energy consumption from well to wheel, expressed in MJ/km, and the GHGs reduction in 100 g/km: note the 'H2 from EU el. mix' performances as compared to other alternatives in Figure 3. The fossil fuels (typically natural gas) resulting from energy efficiency measures should rather be converted into hydrogen directly, combined with CO_2 handling. This will ensure efficient production and near-zero emissions of GHGs as shown in the column 'H2 from NG+CO2 handling' in Figure 3.

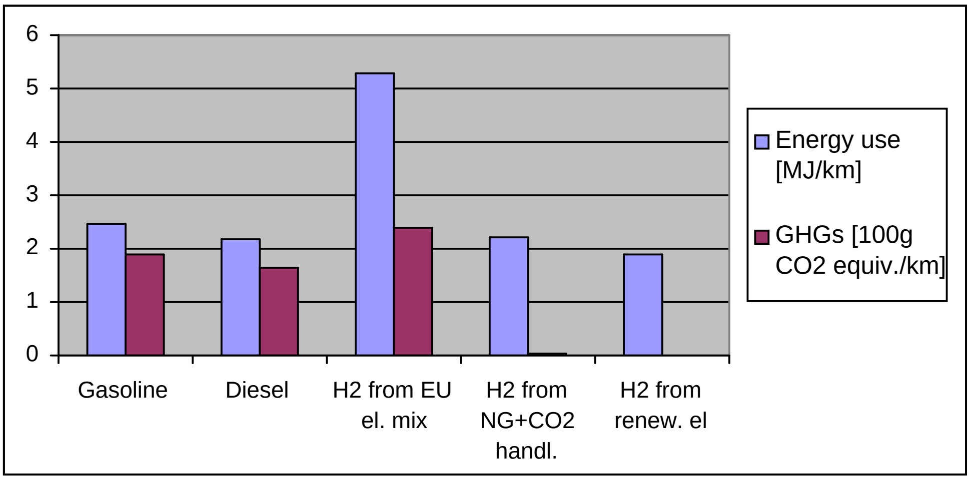

***Figure 3**: Performance of different vehicles (fuel cycle included), based on [6].*

When discussing the efficiency of the different devices for the production of electrical energy (independently of the source of energy), it is clear from Figure 4 that fuel cells are among the best devices reaching efficiencies of about 70%.

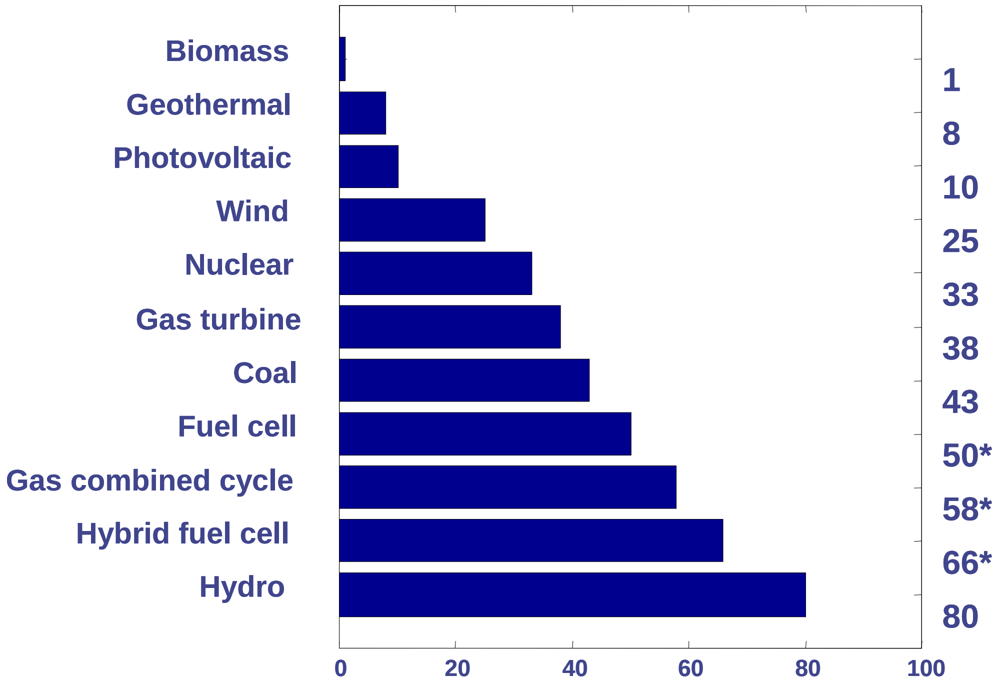

***Figure 4**: Efficiency of energy production systems; (*) efficiencies improve with heat recovery.*

This is another reason why fuel cells should be used now to generate electricity, with fossil fuels serving as feed material. This once more confirms the conception of the fuel cell being the winner technology to be used in the transition to hydrogen age. In the hydrogen era, however, great care should be devoted to the storage and transportation of hydrogen. Since hydrogen reacts with tropospheric hydroxyl radicals, emissions of hydrogen into the atmosphere disturb the distributions of methane and ozone, the second and third most important greenhouse gases after carbon dioxide. Hydrogen therefore is an indirect greenhouse gas with a global warming potential GWP of 5.8 over a 100-year time horizon. A future hydrogen economy will therefore have greenhouse consequences and not be free from climate perturbations. If a global hydrogen economy replaced the current fossil fuel-based energy system and exhibited a leakage rate of 1%, then it would produce a climate impact of 0.6% of the current fossil fuel-based system. If the leakage rate was 10%, then the climate impact would be 6% of the current system. Attention must be devoted to reducing to a minimum the leakage of hydrogen from its synthesis, storage, and utilisation processes in a future global hydrogen economy, if the full climate benefits are to be achieved in comparison to fossil fuel-based energy systems.

Governments should facilitate the creation of a CO_2 market by establishing infrastructure and fiscal incentives that will make CO_2 for EOR purposes commercially viable. The introduction and future strengthening of the CO_2 emissions trading directive will clearly affect the energy markets and could result in favouring the use of nuclear energy. The European Commission's high-level group report also recommends the use of nuclear energy for hydrogen in the middle and long terms. Nuclear power for hydrogen may achieve a market advantage over fossil energy in this situation. It is not in the interest of the environment to increase nuclear capacity as long as the challenges related to nuclear waste handling remain unsolved. It is thus urgent to promote the use of decarbonised fuels with a view to counteracting this situation.

Solutions of the global warming problem - renewable energy, energy efficiency, and new environmentally sound technologies - already exist. The latest report from the IPCC [13] confirms that hundreds of technologies are now available at very low costs to reduce climate-damaging emissions and that government policies need to remove the barriers to these technologies.

The good news is that we can slow down and eventually stop global warming, but we must act today. The most important step we can take to curb global warming is to improve energy efficiency. Our cars and light trucks, home appliances, and power plants could be made much more efficient by simply installing the best current technology. Energy efficiency is the cleanest, safest, and most economical way to begin to reduce global warming.

No global warming solution will succeed, unless we can control emissions from cars. While there is no technology to remove carbon dioxide from a car's exhaust, we can make cars less polluting by making them more fuel-efficient. By using today's best technology, car producers could dramatically increase the fuel economy of their cars and trucks.

We also need to clean up our electrical power plants. Most utilities still use coal to produce electricity; part of the problem could be solved by converting these plants to burning cleaner natural gas. We could do much more to save energy in our homes and office buildings. More energy-efficient lighting, heating, and air conditioning could keep millions of tons of carbon dioxide out of our air each year. Harnessing the clean, abundant energy of the sun and wind is critical to solving the global warming problem. Today, the costs of wind and solar power are becoming competitive with dirty coal-fired plants.

3. Hydrogen and the energy market

3.1 Status of hydrogen economy

What is the status of hydrogen economy? There are only a few industrial sectors, where hydrogen is undisputedly used for energy production. The space business is one, which would even be inexistent without the highly energetic combination of hydrogen and oxygen in the space launchers' power plants. Hydrogen is also used in submarines, where high-efficiency hydrogen/oxygen fuel cells guarantee extended underwater travel and low to zero detection, because the condensed water steam exhaust has no contours. Hydrogen is used in refineries for the production of reformulated hydrogenated gasoline and the desulphurisation of diesel and in the cooling of large electrical generators.

There are areas in which hydrogen use still is in the phase of research and development or, at most, in the demonstration phase. Examples are (i) fuel cells to replace short-life batteries in portable electronics, such as laptops, camcorders, cellular phones, and the like, energised with the help of hydrogen or methanol cartridges; (ii) natural gas or hydrogen-supplied fuel cells in distributed electricity and heat supply or to replace boilers in central heating systems in buildings; (iii) fuel cells for auxiliary power units (APUs) in vehicles or airplanes; (iv) hydrogen and internal combustion engines or fuel cells on board of buses or automobiles; (v) liquefied cryogenic hydrogen instead of kerosene in aviation [17]. The technologically driven hydrogen energy economy is at its very beginning and will have to face many years or even decades before commercialisation.

In automotive industry, the Toyota engine is powered by a 90-kW fuel cell in combination with a nickel–metal hydride battery and regenerative braking, with the energy of braking being used to recharge the battery. Running on high-pressure hydrogen, the vehicle achieves a top speed of nearly 153 km per hour, has a range of more than 250 km, and reaches twice the tank-to-wheel fuel efficiency of a regular gasoline-powered car. Ford believes that the vehicle can help to establish a hydrogen infrastructure, while fuel cells continue to be developed. Hydrogen-fuelled vehicles became a step more feasible, as many car producers have opened hydrogen fuelling stations in the US (California) and Germany for their fuel cell-powered vehicles. Honda’s station uses solar power to extract hydrogen from water: solar panels on the station generate enough hydrogen to power one fuel cell vehicle, but additional electrical power from the power grid is used to increase the hydrogen production capacity [18].

3.2 Innovative technologies to facilitate hydrogen penetration in the market

Sustainable development requires innovation to reduce the so-called “ecological footprint” [19]. Such innovation may transform the way energy and energy carriers are produced, gradually shifting the emphasis away from the traditional hydrocarbon–based energy and ultimately yielding a sustainable mix of energy carriers and energy markets.

Beyond any doubt, hydrogen and fuel cells are the bridging technology to a renewable energy system: they must be introduced as rapidly as possible with full market penetration in an early stage already. Hydrogen produced exclusively from renewables is, and remains, the overall goal. However, there is a substantial gap in supply and demand of renewable energy for the production of hydrogen. Moreover, state-of-the-art renewable production of hydrogen is accomplished by electrolysis, one of the most costly sources of hydrogen at present. This certainly is a barrier for the deployment of hydrogen and fuel cell technology and will cause serious delays in the transition to the large-scale all-renewable hydrogen society. As shown in Figure 5, the International Energy Agency (IEA) has established two future scenarios for the supply of electricity based on renewable energy [20]. The first scenario encompasses all current policy measures for producing renewables and referred to as scenario A. In scenario B future policy measures for renewables are added. Finally, scenario C indicates the energy demand of an entirely hydrogen-driven transport sector in the EU. The gap in Figure 5 is equivalent to about 1.3 million 1-MW windmills. Today, 24000 MW of wind power are installed in the EU –it would meet only 1.8% of the total hydrogen demand.

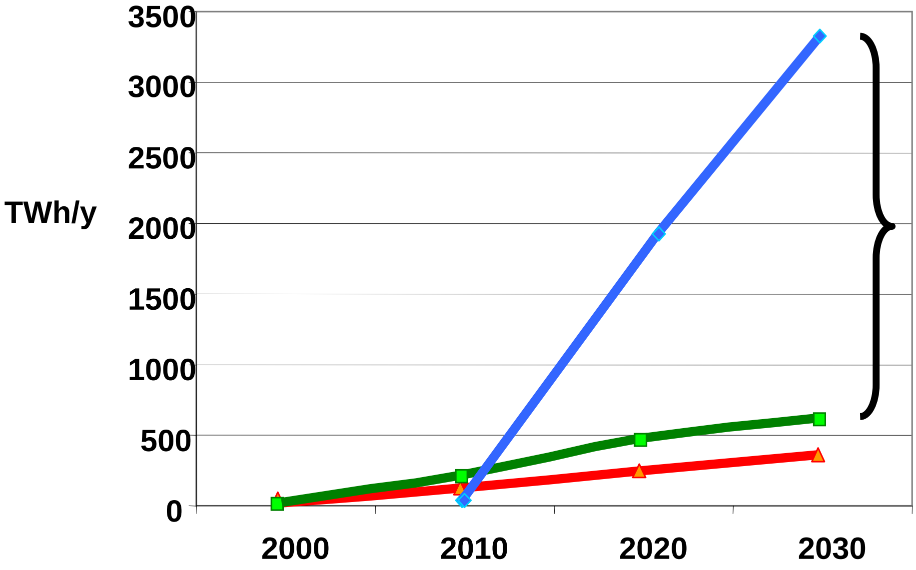

***Figure 5**: Calculated annual electricity demand for hydrogen as a function of the expected renewable generation (wind, solar, biomass, tide, wave, geothermal), based on [6, 21]: scenario A lower curve in red, scenario B middle curve in green, and scenario C in blue.*

Even in the most optimistic hypothesis of increasing energy efficiency and introducing further renewable sources of energy compared to IEA's scenarios, a huge imbalance between supply and demand of renewable energy will remain.

There are other ways to produce renewable hydrogen apart from electricity-based pathways, such as directly from biomass. However, the potential of these resources may constitute between 15% and 50% of total hydrogen demand, still leaving a significant gap.

Fortunately, producing hydrogen today is not terribly expensive. Figure 6 reports the relative costs of energy from different sources, including hydrogen reformed from natural gas [21]. The costs of hydrogen from renewables (solar, wind ,…) are much higher at present. To enter the transition period as soon as possible, however, it seems that the best way is to produce hydrogen from natural gas: the process is well known and has been technologically available since many decades in the petrochemical industry. This, in turn, will enable car manufacturers to introduce hydrogen and fuel cell vehicles. Fuel cell vehicle stocks and hydrogen infrastructure will then develop. Such hydrogen infrastructure will lay the foundation for the distribution and widespread use of hydrogen fuel from renewables in the long term.

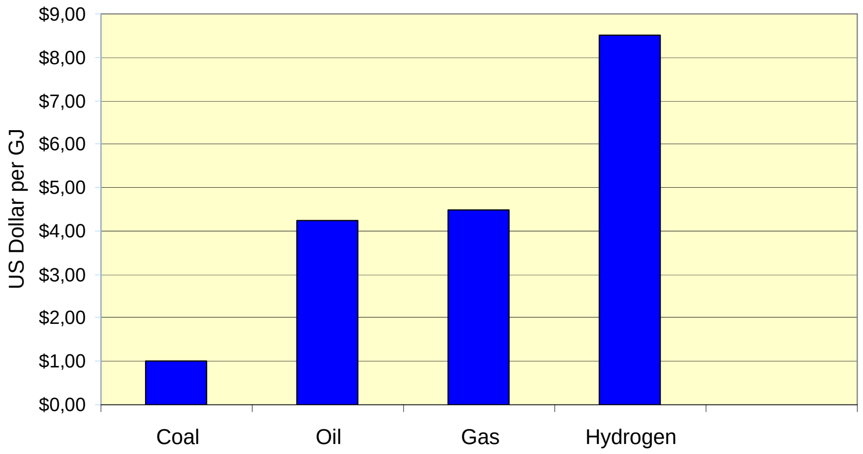

***Figure 6**: Comparison of costs of energy from coal, oil, gas, and hydrogen (hydrogen from natural gas).*

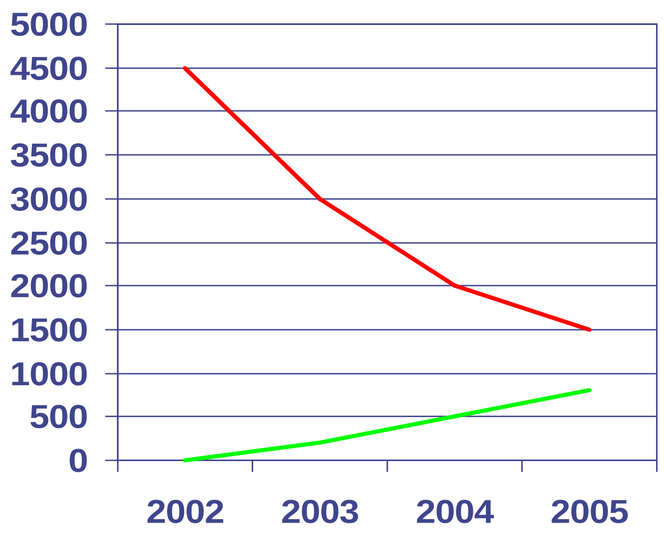

***Figure 7**: Costs of energy [$/kW] (in red) and energy production (in green) versus time (fuel cell with hydrogen from natural gas).*

Figure 7 shows the trend of the costs of energy obtained with fuel cells fed with natural gas per kW produced versus time [22]. In 2005, the costs are approximately $1500 per kW. By contrast, a diesel generator costs about $800 per kilowatt and a natural gas turbine even less. The costs will decrease with increasing the total energy produced due to economy of scale.

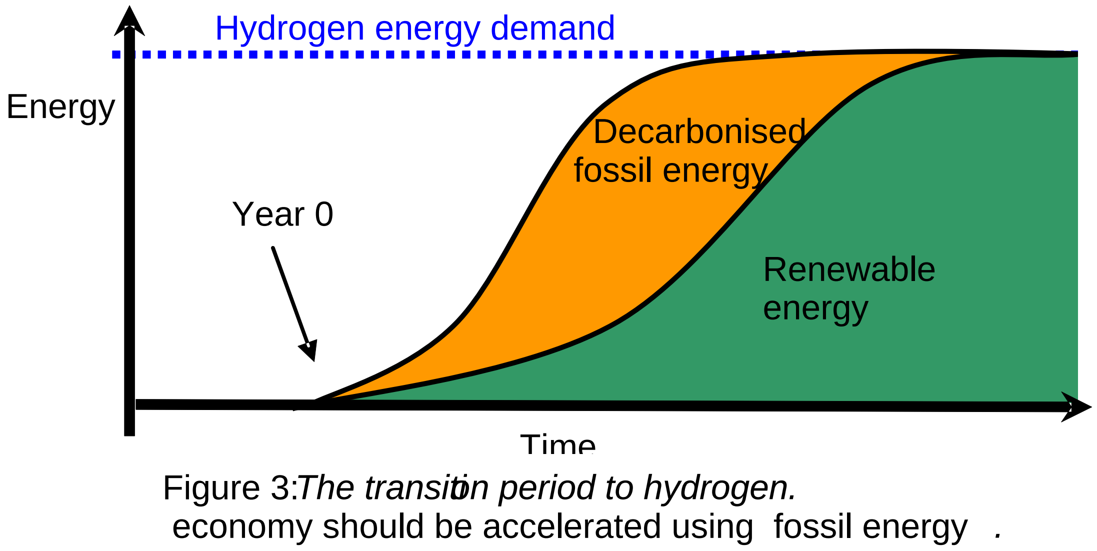

Figure 8*: The transition period to hydrogen.*

Figure 8 illustrates how this transition to a full hydrogen economy based on renewable resources will evolve in time. Production of hydrogen from fossil and renewable resources starts in year zero in Figure 8 [23]. Fossil energy boosts hydrogen in transportations, giving benefits to the environment and society in an early stage. At the same time, it is extremely important to work as fast as possible for the development and implementation of renewable solutions. Over time, renewables can replace fossil resources in order to ensure a sustainable long-term hydrogen economy. Increasing hydrogen production from decarbonised fossil energy in the short term will accelerate the transition towards commercial and common use of hydrogen and, at the same time, safeguard the commitment to struggling against climate change.

When considering the energy situation realistically, renewable electricity generation, such as photovoltaics, wind and tide power, and so forth, still has a long way to go before it constitutes any significant share in terms of electricity supply. These sources must displace an enormous generation capacity in order to dominate the markets. In this situation, society can choose to use renewable electricity to replace either (i) conventional electricity generation or (ii) conventional fuels for vehicles in the short term. For both pathways, benefits will become manifest in terms of increased sustainability and reduced emissions. By choosing the second option, converting energy from electricity into hydrogen via electrolysis will considerably increase the relative energy costs compared to conventional road fuels. Renewable generation will suffer, as the increased competitiveness with conventional generation built up over several decades will be lost. In the short term, it is therefore necessary to use decarbonised fossil energy for hydrogen to accelerate the development towards a sustainable energy system.

At present, direct conversions of biomass and bio-waste into hydrogen are the only renewable sources of hydrogen that come close to competing with fossil sources. Improving the competitiveness of these renewable energy sources through the introduction of proper fiscal and other framework conditions will be necessary.

Although optimism for hydrogen economy is virtually universal, it is improbable that hydrogen will become a major fuel source in the short term. This is not because the various obstacles will not be overcome, but because hydrogen is an energy carrier and not an energy source. In fact, whatever energy sources may be exploited in the future, it could be put to more effective use directly, without a significant involvement of hydrogen or fuel cell technology in general. The real costs of fuel cell engines currently are still rather high and the total GHGs release from hydrogen vehicles per km is comparable to that of fossil-diesel hybrids. In the short term, bio-diesel from bio-methanol or other bio-options could compete with fossil diesel within 4 years, and the efficiency of the diesel hybrid will exceed that of the practical fuel cell.

4. Conclusions

Energy, economic and political crises as well as the health of man, animals, and plant life are all critical concerns. Environmental protection issues show that there is an urgent need for expediting the process of implementing the hydrogen economy, since a worldwide conversion from fossil fuels to hydrogen would eliminate many problems. The optimal end point for the turn to hydrogen economy will be the substitution of the present fossil fuels by clean hydrogen. The production of hydrogen from non-polluting sources (such as solar energy) is the ideal way [17].

Hydrogen has an outstanding potential for being the key factor in driving the energy market to a sustainable system. Hydrogen can deliver high-quality, highly efficient energy services, while contributing to reducing local, regional, and global environmental impacts.

In this scenario, versatile, clean, and flexible fuel cells play a central role, since they provide for transportation services and supply heat and electricity for a wide range of applications. Together with other distributed-generation alternatives, they contribute substantially to the shift to a more flexible, cleaner, and less vulnerable distributed electricity generation system. In addition, fuel cells are a strategic component of the transition to a less polluting and less oil-dependent transportation system.

Hydrogen production, initially fossil-based (steam reforming of natural gas), will develop towards renewable resources (solar and biomass) in the long run, contributing to driving the global energy system towards sustainability. In addition, hydrogen is produced close to the demand centres, mainly from indigenously available resources, and this dispersed hydrogen supply brings tangible benefits in terms of security of supply for a number of regions. This local production of hydrogen contributes to reducing the reliance on imported energy carriers and the dependence on long-distance transportation infrastructures, thus mitigating the vulnerability to geopolitical uncertainties.

Although the global hydrogen production system progressively shifts towards renewable sources, significant differences exist in the hydrogen production in different regions with time. Industrialised countries mainly rely on steam reforming of natural gas to satisfy their hydrogen needs, while developing and emerging countries, where a higher demand for hydrogen occurs, rely on a more diversified supply system with a higher share of renewable-based hydrogen production (biomass, solar, wind...).

The main result of hydrogen-based energy production is decarbonisation. This is combined with substantial improvements of energy intensity, resulting in considerable reductions of emissions and, consequently, in relatively low climate change impacts. This highlights the key role that hydrogen could play to “hedge” against the risks of uncertain climate change. Pursuing the penetration of hydrogen within the current hydrocarbon-based energy system, while being compatible with the dominant technologies could pave the way for the long-term transition to an energy system with a low release of carbon into the atmosphere [23].

Clearly, a number of technological, institutional, political, and social obstacles remain on the way of a transition towards a sustainable hydrogen-based global energy system. Achieving the large-scale transformations that would result in a clean and sustainable hydrogen-based energy future requires substantial efforts in a number of fields and the involvement of many different social actors. In particular, the combination of government measures and business actions is necessary to stimulate the growth of a sustainable hydrogen energy industry, the commercialisation of the technologies, and the development of a supporting infrastructure [24]. Among other actors, current energy supply companies could become prime players in the transition, if they recognise the challenges and are able to harness the opportunities that hydrogen-based technologies bring along.

Together with other activities, international partnerships on research, development, demonstration, and deployment [25] are necessary for a successful development of hydrogen technologies and their commercialisation. International public–private collaboration in research and development will contribute to sharing costs and risks, identifying and exploiting niche market opportunities, and implementing buy-down strategies to ensure that these technologies will move along their learning curves. They could also facilitate technology transfer and access to attractive markets, key issues for speeding up the global deployment of a cluster of cleaner and more efficient hydrogen-based technologies.

The time of action is now. We cannot leave the decision to the next generation and we have to move to an environmentally friendly energy system. We cannot wait for the oil reservoirs to empty to use hydrogen as an energy carrier. After all, the Stone Age did not end, because they ran out of stones…

References

[1] IEA (International Energy Agency), Towards a sustainable energy future, Paris, France, 2001.

[2] Riahi K, Roehrl RA, Schrattenholzer L, Miketa A, Technology clusters in sustainable development scenarios. Progress Report of Environmental Issue Groups, International Forum of the Collaboration Projects in Spring, 2001, Tokyo, Japan.

[3] IEA (International Energy Agency), Key World Energy Statistics 2006, CD-ROM, Paris, France, 2006.

[4] The Bellona Foundation, Hydrogen: Status and possibilities (Report 6: 2002), available at: www.bellona.org/en/energy .

[5] European Commission High Level Group on Hydrogen and Fuel Cell Technologies: a vision for our future, 2003, available at: europa.eu.int/comm/research/energy/pdf/hydrogen_summary_report.pdf .

[6] GM Well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems, A European study, GM 2002, available at: www.lbst.de/publications/studies__d/2002/TheReport_Euro-WTW_27092002.pdf .

[7] Zittel & Wurster, 2002, The prospects for a hydrogen economy based on renewable energy, L-B systemtechnik, available at: www.hyweb.de/Wissen/pdf/ireland2002.pdf.

[8] Kruger P, Electric power required in the world by 2050 with hydrogen fuel production – Revised, Int. Journal of Hydrogen Energy, 2005, 30:1515-1522.

[9] BP Statistical Review of World Energy June 2006, available at: *www.bp.com/statisticalreview*.

[10] Marland, G., T.A. Boden, and R. J. Andres. 2006, Global, Regional, and National CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

[11] Intergovernmental Panel on Climate Change (IPCC), available at: www.mnp.nl/mnc/i-nl-0170.html .

[12] Intergovernmental Panel on Climate Change (IPCC), 'The IPCC Third Assessment Report', 2001 Geneva, Switzerland, available at www.grida.no/climate/ipcc_tar/ .

[13] Intergovernmental Panel on Climate Change (IPCC), 'Climate Change 2007: The Physical Science Basis', Contribution of Working Group I to the Fourth Assessment Report of the IPCC, 2007, Geneva, Switzerland.

[14] Britt R. R., Health warning issued for global warming, Live Science, web, 2006 available at: LiveScience.com .

[15] Bergamaschi W., Greco D., Iadicicco R., Palombo F., Relazione sullo Stato Sanitario del Paese, 2006 Ministry of Health, Rome, Italy, available at: www.ministerosalute.it/normativa/sezNormativa.jsp?id=380 .

[16] Kessel D.G., Global worming: facts, assessment, countermeasures, J. of petroleum science and engineering, 2000, 26:157-168.

[17] Winter C.J, Electricity, hydrogen: competitors, partners? Int. Journal of Hydrogen Energy, 2005, 30:1371-1374.

[18] Momirlan M., Veziroglu T.N., The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet, Int. Journal of Hydrogen Energy, 2005, 30:795-802.

[19] Gosselink J.W., Pathways to a more sustainable production of energy: sustainable hydrogen a research objective for Shell, Int. Journal of Hydrogen Energy, 2002, 27:1125-1129.

[20] IEA (International Energy Agency), World Energy Outlook 2002, Paris, France, 2002.

[21] Hoffmann, Ogden, and Bossel/Eliasson, The British Petroleum Company, 3.2.2003, available at: www.bp.com .

[22] Azar C., Lindgren K., Andersson B.A., Global energy scenarios meeting stringent CO2 constraints: cost-effective fuel choices in the transportation sector, 2003, Energy Policy, 31:961-976.

[23] Barreto L., Makihire A., Riahi K., The hydrogen economy in the 21st century: a sustainable development scenario, Int. Journal of Hydrogen Energy, 2003, 28:267-284.

[24] NHA (National Hydrogen Association), Strategic plan for the hydrogen economy: the hydrogen commercialization plan, 2000, available at: http://www.hydrogenus.com/commpln.htm.

[25] PCAST (President's Committee of Advisors on Science and Technology), Powerful partnerships: the federal role in international co-operation on energy innovation, Panel on International Co-operation in Energy Research, Development, Demonstration and Deployment, Washington, USA, 1999.