The Potential Role of Hydrogen and Fuel Cells

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The Potential Role of Hydrogen and Fuel Cells

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Abstract

This paper outlines the role fuel cells and hydrogen can play in the future energy economy. The drivers to implement hydrogen are discussed with an emphasis on CO_2 emissions reduction. The different sectors in which hydrogen can contribute to clean solutions are mentioned. As for the transition to renewable energy, the stationary energy sector and transportation will grow together, even more through electro-mobility.

1 Introduction

There are three **drivers** for novel energy solutions which are internationally acknowledged: energy security, environmental protection and competitiveness. Their ranking differs by countries and shifts over time, but the general goals stay the same. Environmental protection splits into the global issue of climate change and local pollution. Local pollution is particularly important in modern urban sprawls and hence fuel cell development for automotive applications was triggered in California owing to the high level of local pollution in the Los Angeles basin in the late 1980s. As the issue of global climate change became increasingly recognized, fuel cell technology was geared toward less CO_2 emissions in the energy pathway contributing to the general **goals** for energy technology. Energy diversity which goes along with the introduction of renewable primary energy sources helps achieving energy security. In other words, if the issue of environmental protection is pursued effectively energy security is a natural outcome. **Tools** procuring these goals are high conversion efficiencies in the energy pathway, enhanced use of renewable primary energy, the introduction of storage capability to the energy pathway for enhanced use of intermitting renewable primary energy, a further focus on a low level of limited emissions and reduction of overall CO_2 emissions. This translates into four **grand challenges** of energy technology: renewable energy, electro-mobility, efficient central power plants and cogeneration.

2 Anthropogenic climate change is real

Even though minor irregularities have recently been discovered in the 4th Assessment Report of the Intergovernmental Panel on Climate Change [1], there is no reason to doubt the vectors outlined in the report. Additionally, the limelight of the media has recently shifted away from climate change to the more palpable issues arising from the financial and economic crisis.

In the longer term though, climate change can be expected to alter the living conditions to the worse. The following picture underlines that the trend of rising temperatures coincides for the measured data (black lines) and the modeling data when anthropogenic impact on climate change is considered. The rising temperature trend fits the measured data only when anthropogenic CO_2 emissions are included, cf. Figure 1.

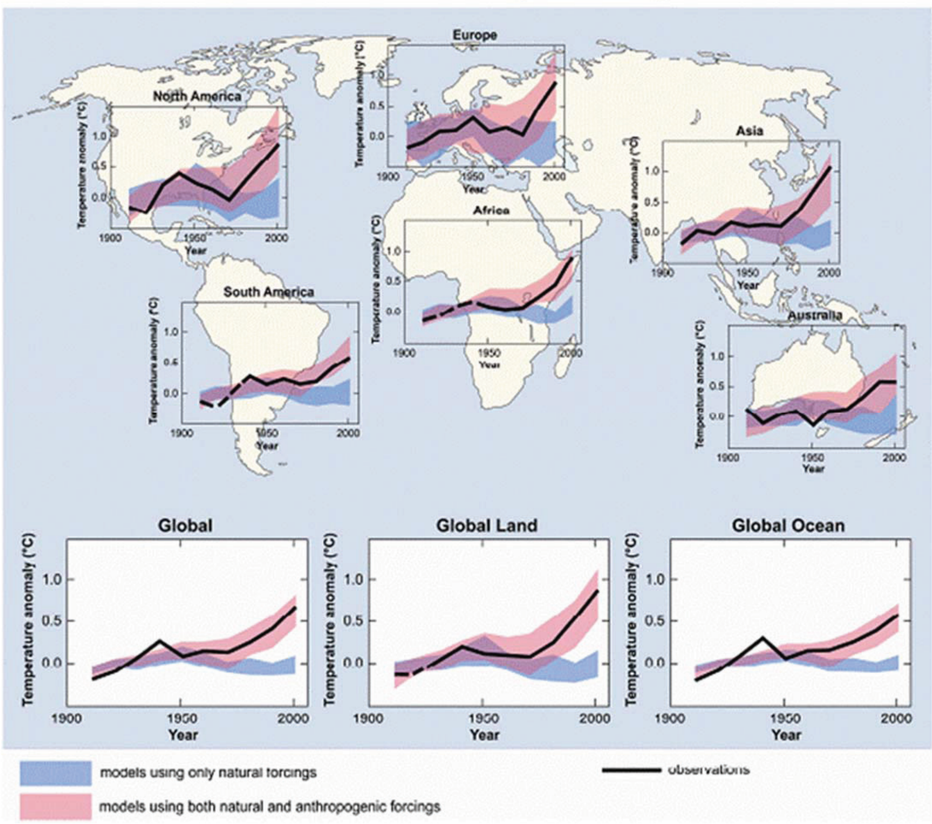

Figure 1: Modeled temperature data with (purple) and without (blue) anthropogenic impact in comparison to the measured Data (black lines). The modeling data bands are composed of the results of different models and hence exhibit a certain bandwidth. The modeled data fit to the measuring results only when anthropogenic effects are considered [1, Fig 2.5 p 40].

Over the past 20,000 years climate gases increased notably when the ice age ended about 12,000 years ago. The increase then leveled off until the industrial revolution happened. From that time on the climate gas concentrations shot up to all-time highs far beyond the levels over the past 650,000 years owing to anthropogenic emissions. Consequently, the radiative forcing of the atmosphere (the property of the atmosphere to absorb incoming solar radiation) leaped up. Figure 2d exhibits the change of the radiative forcing over time. Now, the challenge for mankind lies in adapting to the inevitable climate change which is going on rapidly and to mitigate potential further effects by cutting the climate gases down to levels which allow for a limited increase in the average global temperature. In mitigation novel energy technologies come in and hydrogen and fuel cells will play a role.

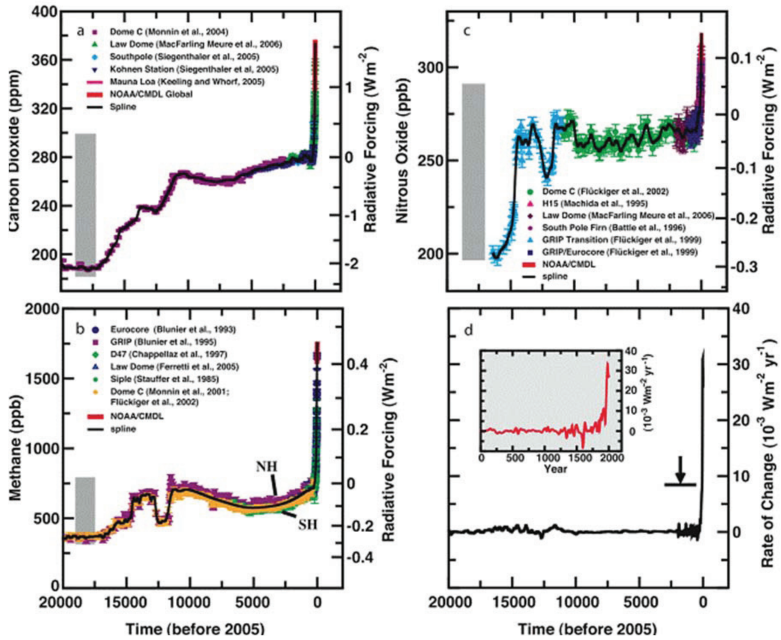

Figure 2: **Concentration and radiative forcing of climate gases over the past 20,000 years. The grey bars show the band in which the climate gases naturally varied over the last 650,000 years. Whereas the natural variation over the past 20,000 years occurred within these bands, today's levels exceed the peaks concentration of the natural variation significantly [2].**

Since these changes have implications on the food chain and food supply as well as water supply and land distribution, the IPCC concludes in its Summary of the 4th Assessment Report that 'the existing population can only be supported by extensive use of technology, in OECD countries as well as in developing countries' and that 'further expansion can only be managed by further advancement and deployment of technology'.

3 Options to Reduce the CO_2-Emissions and the Role of Hydrogen

Socolow introduced the idea of stabilization wedges, with which he associates the different contributions available technologies can make to the total need of reduction in CO_2 output [3]. With this approach he suits the need for imminent action on climate change.

Figure 3 shows the Stabilization Triangle, the absolute emission of CO_2 that is to be compensated by applying CO_2 friendly technologies within the next 50 years; based on 2004 as a starting date. He argues that existing technologies and technologies that can be implemented in the foreseeable future should be used to confront climate change for two reasons: on the one hand side this is possible and on the second hand side later action would require much stricter action since more CO_2 already accumulated. This triangle can be broken down to contributions of different sectors, as visualized in Figure 3.

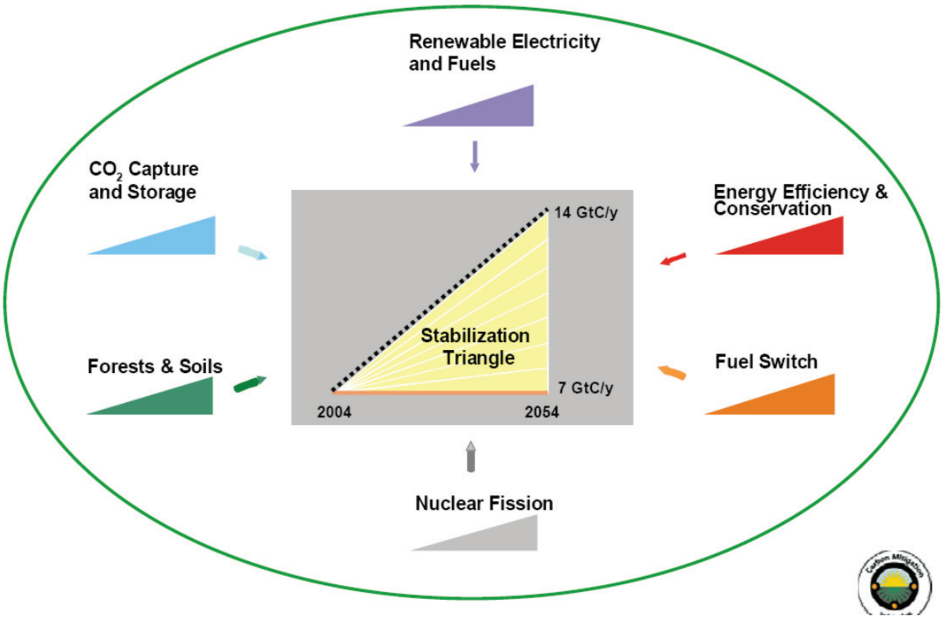

Figure 3: Listing of the different sectors that can contribute to the Stabilization Triangle.

Hydrogen technology comes in in four out of six of the sectors depicted in Figure 3. Via **electrolysis** of **renewable energy** and hydrogen storage, hydrogen technology bears a great potential to compensate for the fluctuation of renewable energy. If mass storage is required it can be stored in geologic saline formations. Compressed air storage delivers a physical storage density of 10 MJ/m^3 at 100 bars. Hydrogen on the contrary delivers a chemical storage density of 1014 MJ/m^3 at the same pressure, real gas properties considered. The physical compression energy is just about 1% and needs not be considered. **Fuel cells** contribute to **energy efficiency and conservation**. For **passenger cars and urban buses** hydrogen is a clean fuel for fuel cells with a reasonable storage density that can substitute gasoline and diesel in mass markets, providing a **fuel switch.** Finally in **CO_2 capture and storage**, hydrogen also plays a role when **pre-combustion capture** in IGCC power plants is applied. In summary, hydrogen plays a crucial role in four out of the six important contributing sectors to cut down CO_2 emissions.

4 Reflection on the Importance of Energy Density of Renewables

As of 2010 the catch words of the energy and climate program in Germany [4] are: cogeneration, renewable resources, CCS technology, biogas, biofuels and electro-mobility.

Renewable energy provides a great potential as it is abundant. As for solar energy, the solar influx on 1% of the usable land mass is sufficient to meet the complete world energy demand with electric power; conversion efficiency included. The challenge with renewable energies lies in harnessing them though, because of their low energy density and their strong fluctuation. The following picture shows the fluctuation of the wind power influx into the TenneT Grid in Germany as of May 2010 [5].

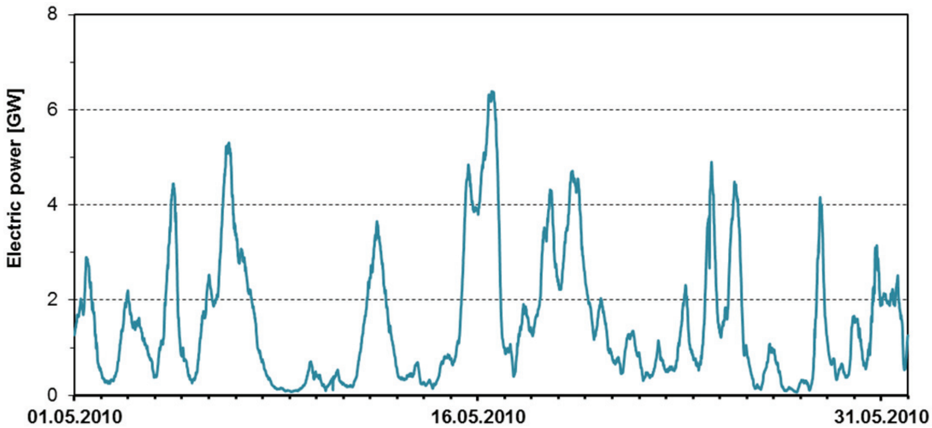

Figure 4: Fluctuation of the power influx in the TenneT balancing group based on quarterly hourly values in May 2010 [5].

Figure 4 shows that with wind energy there is basically no base load that can be provided; the influx changes between zero and hundred percent. Hence, the first and foremost requirement for a transition to renewable energy is energy efficient and cost-effective storage and reconversion to electric power. Table 1 shows the energy density of different renewable energies and puts them into a perspective by comparing them to oil extraction.

The comparison shows, that hydropower is **most efficient to harness**, all renewable energies considered. The second most effective renewable energy is wind power, which is already one order of magnitude lower than hydropower, but one order of magnitude higher than photovoltaic power. The weakest case is represented by biomass, which is three orders of magnitude worse than hydropower. The advantage of biomass is that no major installation is needed if it is grown on farmland. Yet, the energy input into fertilizers and tilling as well as collecting the biomass is to be considered. These factors make the efficiency of biomass very depending on the specific situation under which it is grown, resulting in a broad band from high efficiencies down to questionable efficiencies.

The comparison shows that oil – and the same holds true for coal – is the most convenient energy to harness because of its high energy density that was created over millions of years in geologic processes out of biomass. As for renewable energies there is a clear ranking from hydropower over wind power to photovoltaic power and biomass. Beyond the high energy density of hydropower, a major advantage is the base load capacity of run-off-river power plants. Once the river run-off is quantitatively used – as it is the case in many countries with high population densities – artificial lakes are needed for further development of water resources. The second best solution in terms of energy density, which also does not consume the land which it is put on, is wind power. Only the third best to harness is solar energy. From a primary energy point of view – except for geothermal energy – all other renewable energy is based on the solar influx to the earth, be it directly through radiation on PV and crops or indirectly through cloud formation fueling hydropower. Therefore, their potential is inherently than that of solar energy. Often the potential was considered the primary argument for choosing the primary energy. This paper argues that the energy density is more important since it determines the effort and cost to harnessing the renewable energy.

Table 1: Listing of power densities of renewable energy in comparison to fossil oil based on averaged annual values to account for the fluctuations. As active area for hydropower the area of the water dam was used, for wind power the footprint that moving rotor blades cover was used, for photovoltaics the cell area was used and for biomass the tilled land was used. These values are compared with the power density of an oilfield, which can provide this power density just for limited time until it is exhausted. This comparison is fair, since the installation for harnessing the renewable energy has a lifetime in the same range of 10 to 20 years.

Hydropower	2 – 4	$kW\ m^{-2}$	
Wind power	120 – 140	$W\ m^{-2}$	
Geothermal	0.6 – 35	$W\ m^{-2}$	
Photovoltaic	15	$W\ m^{-2}$	
Biomass, 1st Generation	0.1	$W\ m^{-2}$	
Biomass, 2nd Generation	< 8	$W\ m^{-2}$	
Biomass, theoretical	1 – 2	$W\ m^{-2}$	Crop, EU
	5	$W\ m^{-2}$	Crop, equatorial
	40	$W\ m^{-2}$	Bacteria, EU
	75	$W\ m^{-2}$	Bacteria, equatorial
Oilfield	200 – 300	$kW\ m^{-2}$	Best case, 20 years
	100	$kW\ m^{-2}$	Average, 10 years

Since in Germany hydropower is at its capacity limit, wind power plus electrolysis for hydrogen storage represents an outstanding opportunity, which can be complemented by solar power. If the ponderous fluctuations shall be compensated without causing further CO_2 emissions, water electrolysis with hydrogen storage becomes indispensable.

5 How Hydrogen Fits into the Existing Energy Structures

The primary use of hydrogen ought to be in **fuel cell vehicles** for sake of efficiency and higher revenues for transportation fuels than for heating fuels. First of all, hydrogen vehicles are already at a highly developed level, delivering driving properties like existing vehicles with internal combustion engines, except for price and longevity which are subject to further development until the envisaged market introduction in 2015. Hydrogen fits well into the **semi-centralized** distribution of existing liquid fuels at gas stations. It poses new challenges to the distribution from its source to the gas stations. For the time being, the following options exist: hydrogen supply via pipelines, on-site natural gas reforming, on-site water electrolysis and – for the market introduction phase – supply of liquid hydrogen.

6 Cost of Hydrogen Gas Stations vs. Electric Charging for Battery Vehicles

The advantage of this semi-centralized approach becomes palpable when it is compared to the necessary amount and cost of electrical charging stations for batteries, representing the completely decentralized approach. Assuming an average gas station supplies in between of 1,500 and 2,000 kg hydrogen per day and 4 to 5 kg per car are fueled, 300 to 500 cars per day would be served. With an average cruising range of 12,000 km per annum and 500 km cruising range per tank load, the average car needs to be fueled every 15 days. Hence, one gas station would serve about 4,600 to 7,700 cars according to these assumptions. With 41.7 million vehicles on the road tin Germany in 2010 [6] according to the assumptions above 5,500 to 9,000 gas stations selling hydrogen would be needed. 9,000 gas stations might also be enough for a full spatial coverage of supply, as the comparison to the existing number of 14,700 gas stations in 2010 shows [7]. Since this number shrinks continually by about 160 gas stations per annum [7], an oversupply with the existing structure can be assumed.

For electric vehicles it can be assumed that at least 1.5 charging stations per car will be needed, since the charging process is time-consuming and the cars need to be fully charged when start cruising because of the short cruising range. Hence, one gas station compares to about 7,000 to 11,500 electric charging stations. At average investment cost of €2,000 per electric charging station [8] the total amounts to €14 - 23 million compared to about €2 million per hydrogen gas station [9]. It can be concluded, that charging station infrastructure for battery vehicles is an order of magnitude more expensive than the semi-centralized gas station infrastructure for fuel cells; full coverage of the market for each technology presumed. Admittedly, further infrastructure cost like hydrogen pipelines or electric grid reinforcement or extension is not considered since it is subject to further investigation. This estimation supports the idea that the semi-centralized supply of fuel is much more efficient than the fully decentralized approach of electrical battery charging; inconvenience of charging times and small cruising range not considered.

7 Transportation of Energy via Hydrogen and Electricity

The transportation of energy via gases is generally very effective. The energy loss in hydrogen pipelines is about 3% per 1,000 km. A conventional 400 kV AC power line entails about 9% of loss per 1,000 km [10]. High voltage DC-DC power lines lose only 2 to 3% energy per 1,000 km, but have an offset of 2 to 3% transformation losses at either end of the line, that sum up to 4 to 6% in total. Hence, it is more effective to transport gases like hydrogen over long distances. For short distance transportation and imminent use electricity is most efficient and cost effective. Other than electricity hydrogen can effectively be stored, like in great quantities in salt caverns comparable to natural gas. This makes hydrogen an effective management tool not just for short-termed fluctuations, but particularly for seasonal shifts of renewable energy input.

8 Energy Storage Density of Fuels and Batteries

Table 2 shows the comparison of hydrogen with gasoline, ethanol and batteries in terms of the energy storage density. The energy density of the chemical bond between two carbon atoms is very high, delivering a high energy density of fossil fuels and ethanol. This convenient situation will not be reached again with any environmentally friendly – i.e. CO_2 free – energy carrier. Hydrogen offers a realistic compromise which allows for a cruising range in vehicles of 400 to 700 km, depending on the storage design. The high efficiency of the fuel cell on board the vehicle, which is about twice as high as that of a gasoline engine, in respective driving cycles compensates for the lower energy density. The efficiency of the fuel cell is particularly high because vehicles are mostly operated in part load. Whereas internal combustion engines decrease in efficiency in part load, the fuel cell systems stay stable or even slightly increases in efficiency, due to their electrochemical nature.

Via **water electrolysis** hydrogen can be generated in the most efficient and cleanest way, reaching 80% of efficiency based on the lower heating value. The longevity and performance under dynamic load from renewable energy is subject to future investigation.

Table 2: Energy density of gasoline and ethanol in comparison to hydrogen and to batteries

	Physical capacity		Technical capacity	
	$[MJ\ l^{-1}]$	$[MJ\ kg^{-1}]$	$[MJ\ l^{-1}]$	$[MJ\ kg^{-1}]$
Gasoline	31	43	–	35
Ethanol	21	27	–	
Hydrogen	5 @ 700 bar	120	4 @ 700 bar	15
Batteries	1.5	0.5	Cooling cells	ditto

Hydrogen fuel cells can be applied for long-distance driving and city operation in vehicles and light duty trucks. They are to compete in the future with battery cars for short distance commuting, cheaper gasoline or diesel hybrid cars that cannot provide the effectiveness in CO_2 reduction as electro-mobility options do. Heavy duty trucks though are very likely to be operated with liquid fuels even in the long-term. Owing to the high energy consumption of the engines there is no concept of using hydrogen as a fuel for its remarkably lower energy density. In heavy-duty trucks, aviation and rail applications as well as marine applications biofuels are likely to provide the best clean alternative. Beyond saving on CO_2, electro-mobility for vehicles and urban buses in general – i.e. batteries and hydrogen operated fuel cells – saves on nitrogen oxide emissions that are produced in the combustion process as well as on particulate emissions as soot from the combustion process and as abrasive wear from breaking which is partially done through regenerative braking. Table 3 lists the characteristics of a cutting edge fuel cell vehicle.

Table 3: Characteristics of the Mercedes-Benz B-Class F-CELL [11]

Drive train		Electric motor with fuel cells
Net power	$[kW]/[PS]$	100/136
Nominal torque	$[Nm]$	290
Top speed	$[km\ h^{-1}]$	170
Fuel consumption NEDC	$[l_{Diesel\ equivalent}\ (100\ km)^{-1}]$	3.3
CO_2 total min.–max.	$[g\ km^{-1}]$	0.0
Cruising range NEDC	$[km]$	385
Capacity/ power lithium ion battery	$[kWh]/[kW]$	1.4/35
Freeze start-up capability		Down to -25°C

These characteristics show that fuel cell vehicles fueled with hydrogen are full substitutes for existing gasoline or diesel vehicles. Their cruising range is less than that of existing cars, but they can be refueled swiftly.

9 A Glance on Stationary Applications

For stationary applications natural gas is considered as being CO_2-lean and cheap. Natural gas burns with little emissions and can be used in fuel cells via reforming. Hence, there are no activities to introduce hydrogen as a staple energy for stationary applications. Fuel cell types for stationary applications are the phosphoric acid fuel cell, molten carbonate fuel cell, the solid oxide fuel cell and the high temperature polymer fuel cell, mentioned in the ranking of their development stage. Hydrogen as well as biogas may be well used in the future.

10 Summary

Anthropogenic climate change can be identified as the foremost driver for changes in the energy sector in Germany and many other countries. Renewable primary energy such as wind or solar energy introduces strong fluctuations to the electrical grid. Hydrogen is well suited to compensate these. In a worldwide consensus fuel cell vehicles are designed today for hydrogen as a fuel. These cars are full substitutes of today's vehicles, other than battery cars that impose strong limitations on their users. Since they run on hydrogen, the electric power sector and the fuel supply for vehicles will be closely connected in the future through electrolysis, when fuel cell cars will be introduced.

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