Hydrogen and Fuel Cells as Strong Partners of Renewable Energy Systems

Commissioned by the European Hydrogen Association (EHA) and the Germany Hydrogen and Fuel Cell Association (DWV)

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Hydrogen, like electricity, is a universal energy carrier that can be produced as secondary energy from a wide variety of primary energy sources. Considering the whole energy chain from production to end-use, hydrogen, used in fuel cells to power transport and stationary applications, can provide significant benefits in terms of greenhouse gas emissions and local pollutants through increased efficiency and/or lower rate of emission per end-use energy unit.

Thus, it can facilitate the transition from today’s energy world into an energy world with growing fluctuating renewable electricity supply.

As the EU Strategic Energy Technology Plan is pointing out in its Technology Map, "The possible competition for primary energy sources for hydrogen production and other sectors of activities indicates a need for synergies and coordination between policies and industrial sector strategies". From today’s observations, there will also be a mix of different solutions suited to individual mobility needs. This will include shifts in the modal split.

The European Hydrogen Association, EHA, in collaboration with the German Hydrogen and Fuel Cell Association, DWV, present this brochure as a contribution to this discussion describing how hydrogen could accelerate the use of sustainable primary energy sources in our future energy system in Europe by integrating hydrogen as a storage medium and as a fuel in Europe’s transport systems. Therefore, renewable energies and hydrogen form a perfect alliance from an energy system's point of view.

Through an in-depth verification of existing studies and data the brochure addresses the future energy situation, the expected reduced contribution of fossil and nuclear primary energy supplies as well as the increased contribution of renewable energies within the next decade. As a result, it is shown that the arising energy supply gap despite an increasing supply of renewable energies in the medium term only can be bridged by a more efficient use of energy in general. The expected cost reductions of wind power and photovoltaic energy are highlighted.

In addition, global and regional biofuels potentials are limited and fall short by far against today’s energy demand. Current discussions about biofuels center mostly on cars. With a view to phase in renewable energies in all transportation sectors, heavy-duty vehicles, aircrafts and ships are far more dependent on biofuels due to the lack of alternative options. Thus, electricity from renewable energy sources needs to become the important fuel source for the transport sector.

There is a broad consensus that the future powertrain is electric. Battery vehicles would be the most energy efficient solution. However, by evaluating different secondary energies (e.g. electricity, hydrogen) with respect to energy density, efficiency, environmental aspects and subject to customer performance expectations and infrastructure development (both electricity grid and hydrogen infrastructure), hydrogen in combination with fuel cell vehicles have excellent perspectives already in the medium term but definitely in the long term.

Furthermore the brochure refers to recent EU project results that indicate that the development of a sustainable European hydrogen supply, distribution and end use system can be implemented in an an efficient and economic way.

EHA and DWV would like to invite to a discussion on the best solutions hydrogen can provide in combination with renewable energy sources towards a more efficient and sustainable transport and energy system in the future.

2 HyWays – an integrated project to develop the European Hydrogen Energy Roadmap (http://www.hyways.de)
3 CONCAWE/EUCAR/JRC2006 (http://ies.jrc.cec.eu.int/wtw.html)
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driving the future
Drivers for change
The aggregate supply of fossil and nuclear energy is expected to peak by around 2015.

After the peaking of the oil supply (today), the global supply of natural gas, coal and nuclear fuel is expected to reach a combined maximum by around 2020 – at the latest. This will have significant impacts on the total energy supply. With peak oil we are entering into a transition phase towards a post-fossil energy area.

The limitation in availability of fossil energy resources as well as the threat of climate change to mankind and biosphere have led to the formulation of political goals with regard to security of energy supply and especially reduction of greenhouse gas emissions. All the underlying issues can be addressed in an efficient and sustainable way by energy conservation, by the increased use of renewable energy sources and by the use of hydrogen and fuel cells.
In the long term, renewable energies will be able to provide more energy than all fossil and nuclear fuels will have been able to supply at their aggregate peak. On a global level, solar energy and wind power can become the major pillars of our energy system.

The transition from fossil fuels to renewable energies is a transition from primary energy fuels (i.e. crude oil, natural gas, coal) to electricity (e.g. from photovoltaics, solarthermal power plants, wind or hydropower). This will offer new options and opportunities but also new challenges for the future energy system.

To a large extent, the transport sector will be electrified. Soon, road vehicles will start to switch to renewable electricity as a “primary energy source”. Hydrogen will become a very essential partner for the future transport sector. As electricity from wind and solar energy is difficult to store, hydrogen will serve as electricity storage and as a transport fuel for future vehicles.
Europe has set ambitious targets for a sustainable, competitive and secure energy market. The reduction of greenhouse gases (GHG) and the introduction of renewable energies are important goals within the European energy policy.

**European energy policies**

Today, the European Union is a major driver of environmental policy influencing national legislations in Europe. There is a long track-record of initiatives, framework programmes and directives in the field. Milestones have been the establishment through the European Emissions Trading Scheme (ETS), renewable energy targets, urban air quality targets, and noise emission reductions, which have been laid out among others in the 2001 Renewables Electricity Directive\(^8\), the 2003 Emission Trading Scheme Directive\(^9\), the 2005 Clean Air Strategy\(^10\), the 2005 Urban Environment Strategy\(^11\), the 2006 Energy Efficiency Action Plan\(^12\), the 2007 Fuel Quality Directive\(^13\), the 2008 CCS Directive\(^14\), or the 2008 Renewable Energy Directive\(^15\).

The European ETS and the German feed in tariff for renewable energies have become blueprints for policy makers worldwide.

**Transport sector**

The scope of the first phase of the European Emission Trading Scheme (2005-2007) was confined to large energy producers and users. However, the transport sector is of vital importance to the European economy, accounting for almost 20% of total primary energy consumption. It continues to be the fastest growing consumer of energy, indicating its strategic importance.

As almost all of the energy consumed in this sector is fossil fuel, transport is also the fastest growing source of greenhouse gases. Consequently, the inclusion of the transport sector into the ETS has been discussed from the very beginning\(^16\). In its second phase (2008-2012), air transport will be required to join the ETS from 2012 at the latest.

The inclusion of road transport is currently considered less efficient compared to other policy instruments. Thus, other measures have been taken by the European Commission to ensure that the automotive industry’s self commitment to reduce greenhouse gas emissions from cars on sale in Europe to 140 gCO\(_2\)/km by 2008, will be met at the medium term by 2012 with 130 gCO\(_2\)/km through improvements in motor technology. An additional 10 gCO\(_2\)/km reduction is expected to come from complementary measures, such as efficiency improvements for car components and introduction of biofuels. Several EU member states have already implemented a CO\(_2\)-based vehicle taxation\(^17\).

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\(^9\) Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading within the Community
\(^10\) COM(2005)446 final
\(^11\) COM(2005)718 final
\(^12\) COM(2006)545 final
\(^13\) IP/07/120
\(^14\) Proposal for a Directive 2008/0015 (COD) on the geological storage of carbon dioxide
\(^15\) Proposal for a Directive 2008/0016 (COD) on the promotion of the use of energy from renewable sources
\(^16\) “The Commission should, in particular, consider policies and measures at Community level in order that the transport sector makes a substantial contribution to the Community and its Member States meeting their climate change obligations under the Kyoto Protocol.” (Directive 2003/87/EC)
\(^17\) ACEA Overview of CO2 Based Motor Vehicles Taxes in the EU, 6 March 2007
Challenges of urban transport

80% of Europeans live in an urban environment. Urban transport accounts for 40% of CO₂ emissions from road transport and up to 70% of other pollutants from transport. Electric drivetrains provide solutions to all these challenges. Subject to customer’s expectations on vehicle performance, hydrogen powered fuel cell hybrid vehicles are seen as the most promising technology to satisfy customer expectations at competitive costs compared to any other technology option.

Introduction of alternative fuels

The European Commission has proposed a mandatory 10% share to be covered by biofuels in 2020 in each member state. To which extent this target can be increased while maintaining sustainability in terms of environmental and socio-economic impacts (i.e. competition of different uses of agricultural land, e.g. food production) is still under discussion. Hydrogen is capable to make use of the huge renewable electricity production potentials to supply the transport sector, thereby ensuring sustainability, energy security and energy storage.

2020 – 20% share of renewable energies

The European Union’s binding target is to incorporate 20% renewable energies in 2020. Already today, limitations in energy transmission and distribution can be regionally observed when strong winds coincide with low power demands, e.g. in the northern parts of Germany, and likely soon in Scotland and Ireland as well. Electrolysers could play a key role in the context of demand side energy management. Producing hydrogen as automotive fuel and storing energy for back conversion to electricity are both highly efficient means to provide either a climate neutral vehicle fuel or to provide grid quality at a large scale whenever there are high shares of renewable energies in regional, national and European electricity grids.

To meet the challenges posed by integrating growing shares of renewable energies, hydrogen could be an integral and important part of the solution.

European Joint Technology Initiative

A European vision for hydrogen and fuel cells was presented in 2003 by the European Commission’s High Level Group on Hydrogen and Fuel Cells. Since then, the soon thereafter established European Hydrogen & Fuel Cell Technology Platform has brought together relevant European and international stakeholders to develop major documents, such as the Strategic Research Agenda, the Deployment Strategy and – the latest of all – the “Implementation Plan – Status 2006”\(^\text{18}\). This momentum has been translated into the Fuel Cells and Hydrogen Joint Technology Initiative (FCH JTI)\(^\text{19}\), a public-private partnership to prepare market introduction and commercialise fuel cell and hydrogen technologies due to publish the first call in 2008.

The initiative aims at joining industry, local, regional, national and European forces towards facilitating and accelerating the development and deployment of cost-competitive, world class European hydrogen and fuel cell based energy systems and component technologies for applications in transport, stationary and portable power.

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\(^{18}\) see HFP key documents through https://www.hfpeurope.org/hfp/keydocs

\(^{19}\) see Interim Structure (https://www.hfpeurope.org/fch/jti) and Industry Grouping (www.fchindustry-jti.eu)
Major challenges for the introduction of hydrogen

For hydrogen, the main barriers are in the area of deployment support as well as cost reduction of the end-use application, particularly the drive train of the hydrogen vehicle. Another major issue is the cash flow during the first phase of infrastructure build-up where upfront investments have to be made in order to meet future demand.

Type of policy support for hydrogen

The introduction of hydrogen into the energy system can be supported through financial incentives, such as taxes (including exemptions) or subsidies. Another type of instrument is regulations, such as minimum performance standards or limited city centre access. Finally, other instruments such as information (e.g. labelling systems) and education can be applied.

Changing legal and political conditions as enabler for transition to market

Given the fact that hydrogen is yet to enter the phase of large-scale demonstration projects, regulations such as minimum shares of zero emission vehicles in total sales should be applied with utmost care (HyLights, 2006). Obligations can provide a strong incentive with respect to market pull, but if the demand cannot be met, undesired market disruptions may occur, leading to a strong erosion of the willingness to support hydrogen.

Regulations with respect to city centre access can also provide strong incentives for the deployment of hydrogen vehicles. As a result of these types of regulations, early markets that tolerate initial additional costs can be created. However, a good balance needs to be sought between commercial availability of the technology and the timing of the implementation of these types of minimum performance regulations.

The proposed strategy to support the implementation of hydrogen technologies through R&D and deployment support schemes in the early phase is in line with the general innovation strategy for the support of innovative technologies in Europe.

Tax exemption – example Denmark

The Danish Government has released a National Energy Plan onwards 2025 to support the introduction of hydrogen as transport fuel. Hydrogen cars in Denmark are freed of all taxes and public support for energy R&D is doubled from $83 million to $166 million annually.

The new Danish energy plan is intended to help both Hydrogen Link and the Scandinavian Hydrogen Highway Partnership in reaching the goal of having an early hydrogen infrastructure in Scandinavia by 2012.

Link: Hydrogen Link (www.hydrogenlink.net)
Link: Scandinavian Hydrogen Highway Partnership (www.scandinavianhydrogen.org)

Zero Emission Vehicle (ZEV) Requirement – example California, USA

Fuels that can be used in a ZEV are electricity or hydrogen.

The ZEV program has been modified four times since its inception – in 1996, 1998, 2001, and most recently in 2003. The ZEV requires a certain percentage of annual vehicle sales to be ZEVs.

Given the uncertainty in the pace of technology development, the California Air Resources Board directed that an independent panel of experts be convened in 2007 to report on the status of ZEV technologies and their readiness for commercialisation.

The final outcome of this hearing process is expected for spring of 2008.

Proposed changes are:

Phase II (2009 – 2011) requirements remain largely unchanged. The most significant proposed amendments pertain to Phase III (2012-2014) and Phase IV (2015-2017). The most important changes are that ZEVs can be offset at larger percentages 90%-50% by so-called “Enhanced” Advanced Technology Partial ZEVs (Enhanced AT PZEV), i.e. plug-in hybrid electric vehicles (PHEVs) and hydrogen internal combustion engine vehicles. Also the cap on battery-electric vehicles (up to 50% in the earlier regulation) has been lifted.

The proposed changes act to simplify the regulation while maintaining the overall outcome of the Alternative Path.

Where the existing program would call for 75,000 ZEVs between 2012 and 2017, the California Air Resources Board Action of spring 2008 could result in as few as 7,500 ZEVs if manufacturers comply using the highest credit earning ZEVs.

A mix of ZEV types used for compliance in this time period, including fuel cell vehicles and a range of battery EVs, would result in a higher number of ZEVs (up to max. 75,000 ZEVs).

Link: ZEV California http://www.arb.ca.gov/msprog/zevprog/zevprog.htm
From where we come...
First markets – the role of by-product hydrogen

Today, large quantities of excess hydrogen are already available in some regions in Europe. In most cases hydrogen is produced as by-product in chemical processes. Hydrogen from these sources offers an interesting option for first applications in transport and stationary uses.

In case hydrogen can be used near the production site, it can constitute an early but also economic source for first large-scale vehicle demonstrations and commercialisations. Also the use in efficient stationary fuel cell CHP units is feasible and economic.

As these sources are not available everywhere, they will have to be complemented by other hydrogen supply sources as time progresses. Nevertheless, these by-product sources can assist in providing low cost hydrogen efficiently, as they save the energetic losses and associated CO₂ emissions of at least 20% incurred by natural gas reforming or other conversion processes.

In order to give an estimate, if it is assumed that 800 million Nm³ of by-product hydrogen can be made available as vehicular fuel in Germany, some 600,000 efficient fuel cell passenger cars could be operated [assuming an energy consumption of 0.3 kWh/vehicle-km and an annual operating range of 12,500 km/yr].

Europe

Potential for chemical hydrogen in 10 European countries

In Europe, largest quantities of by-product hydrogen are identified in Germany (~ 850 million Nm³ per year), Norway (~650 million Nm³ per year), France (~300 million Nm³ per year) and the Netherlands (~100 million Nm³ per year).
In Europe, similar by-product sources as in Germany exist also in France, Belgium, Italy, the Netherlands, and Norway. In Germany, France, Belgium and the Netherlands, hydrogen is even available in extensive industrial pipeline systems.

Potential for chemical by-product hydrogen in Germany

In Germany, at various locations there is a surplus of hydrogen which today can only be burnt for thermal uses.

This hydrogen, if substituted 1:1 by natural gas for its thermal uses, could be made available for other energetic uses with higher value, like e.g. vehicle fuel or direct use in stationary fuel cell systems. In most cases purification and additional compression is required.

Typical locations of such hydrogen sources are near Cologne, Frankfurt, Hamburg, Leverkusen and in North-Rhine Westphalia.

In Germany the potential amounts to between 800 million and 1 billion Nm$^3$/year or 2.5-3 TWh (9-10.8 PJ).

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2 Ludwig-Bülkow-Systemtechnik GmbH, 1998
Renewable electricity

Renewable energies, especially solar energy, have several times the potential to provide the total global energy required for stationary and transport applications. Energy storage and vectorisation to the user will be required.

Technical potential of renewable electricity – worldwide

Renewable electricity could become the most important energy of the world.

The figure summarises the technical potential for the production of renewable electricity from photovoltaics (PV), solar thermal power plants, wind and hydropower by world regions.

Technical potential for renewable electricity production Europe

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydropower</td>
<td>570</td>
<td>620</td>
</tr>
<tr>
<td>Wind onshore</td>
<td>650</td>
<td>730</td>
</tr>
<tr>
<td>Wind offshore</td>
<td>2890</td>
<td>3220</td>
</tr>
<tr>
<td>Photovoltaics</td>
<td>1060</td>
<td>1680</td>
</tr>
<tr>
<td>SOT power stations</td>
<td>1440</td>
<td>2240</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>3250</td>
<td>-</td>
</tr>
</tbody>
</table>

In the EU 27 the largest wind potentials (onshore and offshore) exist in the UK (>1,100 TWh/yr), Denmark (>550 TWh/yr) and France (>550 TWh/yr). The largest potential for electricity from solar energy (SOT and PV) are identified in Spain (900 - 1,750 TWh/yr). These countries might become major producers of renewable electricity. The potentials for electricity from offshore wind power alone are more than 3,000 TWh in the EU.

23 Matthies et al., Germanischer Lloyd, Hamburg; Garrad et al., Garrad Hassan and Partners, Bristol; Scherweit et al.; Windtest RKW, Kaiser-Wilhelm-Koog: Study of Off-shore Wind Energy in the EC - Joule I; co-funded by the Commission of the European Communities (CEC) in the framework of the JOULE I programme under contract no. JOUR-0072 and by the Bundesminister für Forschung und Technologie (BMFT) under ref. No. 0329118 A, and was partly carried out under contract to the Energy Technology Support Unit (ETSU) as part of the Department of Trade and Industry’s (DTI) Renewable Energy programme; Verlag Natürliche Energie 1995
For the EU the largest technical potentials for renewable electricity generation are identified for wind and solar energy. The technical potential in Europe is estimated at 500 to 4,000 TWh per year for wind energy and at 1,500 to 2,000 TWh per year for electricity from solar thermal power stations (SOT) and more than 1,000 TWh per year for electricity from photovoltaic plants.

In Germany the largest potentials are identified for wind and offshore and photovoltaics. There are large potentials for renewable electricity in Norway (mainly wind power), UK (mainly wind and marine power) as well as North Africa (mainly solar electricity) beyond the future needs for local consumption. Surplus electricity from wind farms (e.g. in the North Sea) and solar power plants (especially from countries in North Africa such as Morocco) could be used for import to the EU and/or the production of hydrogen fuel. The potential for electricity from solar thermal power stations in North Africa amounts to 40,000 to 400,000 TWh per year. With 20 HVDC transmission lines each of 5,000 MW some 700 TWh of electricity per year supplied from solar thermal power stations in North Africa could be imported to the EU until 2050 at electricity cost of about 0.05 €/kWh.

To illustrate the immense potential of solar energy, only a cumulated net area, equivalent to a square of 700 x 700 km² would be needed to cover the total final energy demand of the world. In reality, the total final energy would not be covered by only one energy source. Power plants will be installed distributed on all continents and not only at one place. This figure should illustrate the immense energy density and potential of solar energy.
The potential of biomass for transport fuel production is limited and in direct competition with food production and other usages. In principal the energetic use of biomass should primarily focus on the stationary use and not on the production of transport fuel (e.g. BTL).

**Worldwide potentials**

The worldwide potential of solid biomass is estimated at about 95 EJ per year. Higher potentials indicated in some literature sources (e.g. in Hoogwijk) are based on extremely high intensification of agriculture with high input of fertilizers and pesticides and therefore can not be considered as sustainable.

Taking into account all these considerations and findings, it is obvious, that it is not possible to substitute today’s EU transport fuel consumption or even a reduced demand of transportation fuel in the future completely by biomass from within the EU. A further increase of biofuel use requires the import of biofuels or biomass for the production of biofuels. But also on a worldwide level the potentials are limited and there are serious conflicts with the stationary sector for the energetic use of biomass and the food production chain worldwide.

As a result it can be concluded that biomass can only meet a relatively small fraction of the overall energy demand as negative environmental and social impacts should be avoided. The highest fraction of the future energy demand will be met by wind power and the direct use of solar energy.

**European potential**

The potential of solid biomass within the EU amounts to about 7 to 8 EJ. Additionally the potential for bio gas from residues amounts to about 0.6 to 1.0 EJ per year which is sufficient for the generation of about 50 to 90 TWh electricity per year.

The efficiency for the conversion of solid biomass to BTL is about 42% leading to a potential for BTL of about 3 EJ per year without taking into account the competing use of biomass in the stationary sector (heat and electricity generation). For comparison, the transport fuel demand in Europe in 2004 was 15.3 EJ (road: 12.7 EJ; aviation: 2.1 EJ; rail: 0.3 EJ; domestic navigation: 0.2 EJ).

Short and medium term use of long term set aside land like pasture or permanent grass land are not an option for climate neutral biomass or biofuel production because carbon bound in the soil is emitted as CO₂ if permanent grass land is converted to arable land until a new equilibrium (the typical carbon content of arable land) is reached.

**Where would biofuels be used in transport with preference?**

Taking into account the very limited role biofuels will be able to play in transportation at all, passenger cars and light duty vehicles should be the least recommended area of application. Why ? Hydrogen and electricity can be introduced into passenger cars and light duty vehicles comparatively easy (lowest restrictions concerning weight and operating ranges), whereas in heavy duty long distance trucking, maritime shipping and aviation the restrictions are much more severe. If at all, biofuels should preferably supply these modes of transport – although their supply potentials would also be insufficient to cover only a significant share of the demands of these sectors.

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31 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4, Agriculture, Forestry and Other Land Use, The Intergovernmental Panel on Climate Change, 2006
The increasing demand of palm oil for CHP plants in the EU leads to an additional incentive for the expansion of palm oil plantations.

In 2007 already about 1.3 TWh electricity have been generated in Germany from the import of 0.3 million t of palm oil.

The total import of palm oil to Germany in 2007 was about 0.8 million t. More than 80% of the palm oil produced in the world comes from Malaysia and Indonesia.

In Indonesia the conversion of natural forests or peatlands to oil palm plantations leads to extremely high CO$_2$ emissions from soil decomposition and from peatland fires. Drainage of peatlands leads to CO$_2$ emissions of 70 to 100 t per ha and year only due to the decomposition of dried peat.

As a result, the production of palm oil would lead to CO$_2$ emissions which are 5 to 8 times higher than the emissions arising from the production and use of crude oil based diesel, only due to the decomposition of dried peat. Including peat fires the CO$_2$ emissions can be up to 25 times those attributable to crude oil based diesel.
The share of renewable electricity is expected to increase significantly since the largest potentials for renewable energies in Europe and Germany are identified as wind, hydropower, solar and geothermal electricity.

In 2007, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety has published the Guiding Study 2007 “Development Strategy Renewable Energies”. This study predicts that the electricity production from renewable resources will increase from 74 TWh in 2006 to 156 TWh in 2020.

With regard to the current and presumably also the future electricity production this represents more than 25% of the overall production. This scenario also reflects the already enacted and binding goals of the European Union.

Scenario – renewable electricity in Germany until 2020

As can be seen in the figure the share of fluctuating and non-dispatchable renewable resources (onshore wind, offshore wind, solar) is increasing steadily reaching 59% of all renewable electricity in 2020.

Offshore wind energy will be the main contributor to this growth.

The proportion of fluctuating and non-dispatchable resources will amount to 90 TWh in 2020, about 3 times the value of 2006.

Challenges for the electricity grid

The increasing share of wind and solar energy will increase the risk of fluctuations within the electricity grid.

This situation can be improved by various measures such as grid extension, demand side management, the controlled charging of plug-in hybrids, smart grids, etc. but in the long term perspective the requirement for the storage of electricity is inevitable.

The dena Grid Study Phase I claims that in order to maintain the current level of grid stability it is necessary to apply generation management and/or to enable the grid for exporting electricity to neighbourhood countries and/or to implement new storage technologies.

As generation management impedes the full utilisation of the installed wind capacity and electricity export in countries facing comparable situations (Denmark, The Netherlands, etc.) may be impossible at least occasionally the storage option will turn out as the smartest solution by far.

Fluctuations within the electricity grid

A factor of 3 is considered and shown by the dark blue line giving an example of how production from fluctuating resources may look like in 2020 (wind energy production of 2006 has been up-scaled by this factor).

The graph shows that periods of very limited electricity production can last for several days (at special weather conditions even weeks) and that on the other hand in periods of strong winds the electricity grid is not capable of absorbing the large amounts of energy.

Both weather conditions may occur also stretched over large areas. Solar-based electricity may reduce this spread to a certain extent.

Vertical load curve and feed-in of wind power in the E.ON grid

[Graph showing load curve and feed-in of wind power]

[Graph showing load curve and feed-in of wind power]
...to where we go
With increasing share of renewable electricity our future energy system will require large scale storage systems for electricity.

Today, pumped hydro power stations are the only widely used means to store electricity at industrial scale. But due to topographic restrictions the potential for further extension and new installations is very limited.

Other storage technologies such as battery systems, compressed air energy storage (CAES) are either premature or are not economically attractive in past and current energy markets. But there is still the need for the large-scale energy storage.

The only technology at present knowledge which has the potential for single storage systems in the 100 GWh range is the storage of hydrogen in underground salt caverns.

**Hydrogen as storage for electricity**

Hydrogen can be produced from electric power by high pressure electrolyser (e.g. at a pressure of 30 MPa). Different technologies for hydrogen production are possible but are not considered here.

For efficient storage hydrogen has to be further compressed before stored in underground salt caverns at a pressure up to 30 MPa. For high power levels the most efficient conversion back to electricity can be achieved in combined cycle power plants.

In the lower power range fuel cells can be applied. Round-trip efficiencies are expected to be in the range of 35-40%.

The achievable storage capacity (energy density) of compressed hydrogen is more than one order of magnitude higher than the one of compressed air.

The storage of compressed hydrogen in salt caverns being relatively cheap, this technology qualifies especially for long-term storage of bulk energy to be reused during long-lasting unavailability of wind energy.
Hydrogen as transport fuel

A further pathway for the utilisation of sustainably produced hydrogen will be its use in the transportation sector.

The current discussions on CO₂ reduction and the availability of fossil fuels show, that car industry is speeding up with their efforts to develop hydrogen powered vehicles and that first vehicle sales can be expected for 2010 followed by a broad market entry from 2015 onward.

This development, besides the use of battery powered vehicles for short distances, constitutes a disruptive technology, opening up totally new possibilities and chances for the utility sector in becoming a fuel supplier.

The intelligent integration of this additional pathway improves the economic viability of the hydrogen storage concept and thereby lowers the overall demand for storage capacities.

Furthermore, it can be observed that hydrogen propulsion in passenger cars based on the NEDC is an almost twice as efficient (1.7 x) end-use technology than today’s direct injection diesel powertrains and thus displaces conventional fuels and powertrains more efficiently than using hydrogen in stationary conversion units (combined cycle power plants or fuel cell systems) where it competes for the time being with almost as efficient natural gas-based end-use technologies.

Finally it should be mentioned, that the topics raised in this chapter – large-scale storage of hydrogen, utilisation of hydrogen as a storage medium for electrical energy and the utilisation of surplus energy in the transportation sector – only played a sub-ordinate role in RD&D activities in the past.

Based on the above mentioned possibilities this technology can provide, it is urgently needed that both industry and politics attend to this topic and provide the required resources allowing to find suitable answers to the pending changes in the energy landscape.
Energy costs are expected to increase during the next decades due to the depletion of fossil and nuclear energy sources on one side and rising investments in new power plants and infrastructure on the other side.

**Electricity costs**

According to [RECCS 2007] the following generation costs for electricity from fossil energy sources with CCS result:

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2050</th>
<th>CO₂ certificate</th>
<th>Not included</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG CCGT</td>
<td>5.2 to 6.3</td>
<td>6.0 to 7.7</td>
<td>not included</td>
<td></td>
</tr>
<tr>
<td>Coal steam turbine</td>
<td>5.9 to 6.4</td>
<td>5.8 to 6.4</td>
<td>not included</td>
<td></td>
</tr>
<tr>
<td>Coal IGCC</td>
<td>6.3 and 6.7</td>
<td>6.1 to 6.6</td>
<td>not included</td>
<td></td>
</tr>
</tbody>
</table>

But the assumed prices for natural gas and hard coal are comparatively low (compared with Nitsch et al. 2007). In [RECCS 2007] the hard coal price is assumed to be 2.25 to 3.00 €/GJ (65 to 88 €/t) in 2050.

However in the future the costs of electricity from fossil energy based power plants will not be lower than those of electricity from renewable energy sources. This would constitute a further advantage of renewable energies compared to fossil energy sources.

**Carbon Capture and Storage (CCS)**

In case CCS (Carbon Capture and Storage) will become obligatory the cost for electricity produced from coal and natural gas will substantially increase the electricity costs from fossil fuel based power plants. Estimates for additional costs of CCS are in the range of 1.7 to 2.5 cent/kWh in 2020 and 1.4 to 2.3 in 2050.

The graph shows rising costs for fossil energy sources and decreasing costs for renewable energies depending on the assumption, that the break-even point between fossil and renewable electricity production will occur sometime between 2020 and 2030.

Up to this date, the introduction of renewable energies will lead to higher average energy cost whereas after passing the break-even point, the growing contribution of renewable energy sources will reduce electricity costs compared to a purely fossil scenario.
**Costs of transport fuel**

The figure below shows the cost of hydrogen from renewable electricity (wind power, photovoltaics) and BTL (biomass-to-liquid) from short rotation forestry (farmed wood) expected for the time horizon 2010 to 2020 compared with gasoline and diesel from crude oil.

The fuel costs for BTL are about the same as for hydrogen from renewable electricity if the higher efficiency of fuel cell vehicles is taken into account.

Both BTL and hydrogen from renewable electricity lead to fuel costs which are slightly below those of taxed conventional gasoline and diesel at a crude oil price of 50 €/bbl.

In the future, increasing prices for crude oil will lead to an increase of the price for conventional crude oil based fuels. Cost parity for hydrogen with untaxed conventional gasoline and diesel will result.

Renewable transportation fuels such as BTL and hydrogen from renewable electricity can reduce GHG emissions significantly. On the other hand, potentials for biomass are limited and thus also the potential for BTL.

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**Well-to-wheel fuel cost versus GHG emissions**

for hydrogen from renewable electricity and for BTL from biomass compared with crude oil based diesel and gasoline

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**Major assumptions**

The fuel consumption of the hydrogen fuelled fuel cell hybrid vehicle is assumed to be 0.84 MJ/km

(≈ 2.6 l gasoline equivalent per 100 km).

The fuel consumption of the gasoline fuelled hybrid vehicle amounts to about 1.52 MJ/km

(≈ 5.0 l gasoline equivalent per 100 km) and the fuel consumption of the diesel fuelled hybrid vehicle amounts to about 1.46 MJ/km (≈ 4.5 l gasoline equivalent per 100 km or ≈ 4.0 l diesel per 100 km).

The fuel consumption for the vehicle is derived from Concawe/EUCAR/JRC.  

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Implications of hydrogen infrastructure

European Hydrogen Energy Roadmap

Between 2004 and 2007, HyWays, an integrated project, co-funded by research institutes, industry and by the European Commission has developed a roadmap for the introduction of hydrogen as transport fuel in Europe.38

In the first phase (2010-2015) limited number of small hydrogen refuelling stations (HRS) should be build within Europe. 400 local HRS should serve hydrogen fuel for 10,000 vehicles and another 500 HRS would be required for selected “hydrogen corridors”.

In the second phase (2015-2025) bigger and more HRS will be build. Between 13,000 to 20,000 HRS could provide hydrogen fuel for up to 10 million hydrogen vehicles.

After 2025, the hydrogen infrastructure will gradually increase in extent and density to approach coverage of conventional refuelling infrastructure.

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38 HyWays, 2007 (www.hyways.org)
Introduction phase

High initial costs (due to under-utilization of hydrogen production plants and H₂ refuelling stations [HRS]) have to be assumed for the introduction of the hydrogen supply and refuelling infrastructure. On the other hand a fast reduction to 1.1-1.6 € per liter diesel equivalent after three years can be expected. Relevant variations of cost between countries occur (depending on availability of feedstock, stakeholder selection of hydrogen pathways, car and population density).

First hydrogen sources

One of the cheapest hydrogen sources at an early stage and practically readily available can be hydrogen by-product from chemical industry at locations where available and easy to vectorise. This hydrogen can supply early vehicle markets locally without providing later full market coverage.

Infrastructure costs

For a fully functioning hydrogen road transport system for 2030, the HyWays project assumed a scenario covering ten European countries. By 2030, approximately 16 million hydrogen vehicles could be on roads and 85-100% of the population would have access to hydrogen filling stations.

The figure on the lefthand shows the cumulated investment costs estimated for the hydrogen infrastructure part aggregated for all ten countries for the base case scenario until 2030. Major investment cost for H₂ infrastructure are identified for H₂ production facilities, refuelling stations and pipelines & trailers.

Related to the total investment costs, the H₂ infrastructure part amounts to only 15-20% of the total investment (i.e. H₂ production, transport, distribution and dispensing). About 60% of the investment costs have to be brought up for the conventional part of the vehicle. The H₂-specific onboard part of the vehicle (e.g. FC and storage) amounts to about 20% of the total investment costs.

Industry estimates

Other infrastructure estimates like the ones preformed by General Motors for the USA and by GM and Shell together for California indicate that the monetary efforts for the build up of hydrogen refuelling infrastructure are well comparable with other infrastructure build-up activities in the USA.

The GM Analysis of 2003 shows that roughly 11,700 hydrogen refuelling stations (HRS) will be need in 100 US metropolitan areas, interconnected by 130,000 miles of highways, allowing the refueling of about 1 million fuel cell vehicles (FCVs).

70% of the US population would be in reach of a HRS within two miles distance.

On highways a HRS would be in average every 25 miles.

The investment costs are estimated to be in the order of 10-15 B$. Transforming this approach to one single large region like Los Angeles would result in 240 HRS at a cost of about 250 M$.

HyWays has identified that long-term hydrogen costs of 0.11 – 0.16 €/kWh (3.8 – 5.4 €/kg) or 1.1 – 1.6 €/litre diesel equivalent) can be achieved. 

Hydrogen and fuel cells a strong partner...
...of renewable energies
For stationary applications, the most efficient energy pathway is the direct use of renewable electricity e.g. from solar or wind energy.

Carbon-based energy sources (e.g. natural gas or biomass) used in stationary combined heat and power (CHP) plants offer the highest efficiency.

Hydrogen being a secondary energy and an energy carrier its use for stationary applications should be limited to remote or back-up power as well as to load levelling in the electricity grid and storage of large fluctuating renewable resources. In these cases, hydrogen is the ideal storage media for renewable electricity. The supply of back-up power for conventional power plants (e.g. for telecom or critical production process of industry) could be another promising use for hydrogen.

The production of hydrogen as transport fuel from renewable excess electricity is the most promising option as it substitutes today’s vehicle fuels efficiently and especially without any pollution.

**Greenhouse savings**

The stationary use of natural gas, biomass and wind electricity saves more greenhouse gas (GHG) emissions than the direct and indirect use as transportation fuel as long as there are coal fuelled power stations to replace.

It has to be noted that the onsite storage capacities of H2 filling stations with onsite electrolysis equipment can be used for the storage of excess electricity during periods where the supply of electricity from fluctuating energy sources like wind power and solar energy exceeds the demand. In this case the reference for substitution of electricity generated from coal does not exist. In this case the use of wind power to generate hydrogen provides storable energy at comparatively low marginal costs.

Savings of greenhouse gas (GHG) emissions for different options

The figure shows the savings of greenhouse gases (GHG) for different options.

* For natural gas a combined cycle gas turbine (CCGT) power plant is used to replace electricity from a coal fuelled power station.

** In case of biomass it is assumed that a biomass fuelled combined heat and power (CHP) plant replaces electricity from coal. The biomass is derived from short rotation forestry.
The best alternative transport fuel in terms of high conversion efficiency and low GHG emissions would be electricity used in battery electric vehicles. But until now there is no battery technology for pure battery electric vehicles which meets all requirements. Nevertheless, batteries will play an important role in hybrid and plug-in hybrid vehicles.

Therefore, hydrogen produced from renewable electricity probably will provide the best alternative transport fuel option in the future, in particular in combination with fuel cell electric vehicles for medium to long distances and for heavier road vehicles, like vans, buses and delivery trucks.

Biomass offers also GHG savings but competes with other land uses such as food production.

Natural gas as source for hydrogen production can provide a transition from fossil to renewable hydrogen. Natural gas derived hydrogen used in fuel cell vehicles provides approximately the same well-to-wheel energy efficiency as diesel fuelled vehicles while reducing GHG emissions up to 30%.
The following figure shows the amount of fuel which can be produced from one hectare of land for different fuel production pathways. It also shows the driving range for vehicles with corresponding powertrains.

Hydrogen produced from photovoltaics (PV) on one hectare of land offers the highest driving range (about 875,000 km/ha). *)

Use of one hectare of land for fuel production...

The illustrations show how many automobiles can be provided with fuel per hectare, based on fuel, generation path, and powertrain technology.

The most efficient alternative is hydrogen for fuel cell automobiles:

Biogenic hydrogen in fuel cell automobiles is as good as biogas in hybrid automobiles with an internal combustion engine.

Hydrogen from wind power in fuel cell vehicles generates at least 3 times as much yield per hectare.

Hydrogen from photovoltaics is 6-7 times more efficient per hectare than the biogenic paths.

In view of the previously illustrated potentials for biogenic fuels and fuels produced from electricity, the medium and long-term advantages and opportunities of hydrogen are obvious.

If electricity could be used directly for automobile propulsion in battery electric vehicles then the number of automobiles maintained per hectare would triple for the electric supply pathways shown.

All-purpose passenger cars complying with today’s customer needs do not seem feasible as pure battery-electric vehicles in the foreseeable future though. It is thus of utmost strategic importance to follow the sustainable and efficient route of hydrogen production for transportation purposes.

*) If electricity could be used directly for automobile propulsion in battery electric vehicles then the number of automobiles maintained per hectare would triple for the electric supply pathways shown. Though all-purpose passenger cars complying with today’s customer needs do not seem feasible as pure battery-electric vehicles in the foreseeable future.
Future challenges and the role of hydrogen

The limitation in availability of fossil energy resources as well as the threat of climate change to mankind and biosphere have led to the formulation of political goals with regard to security of energy supply and especially reduction of greenhouse gas emissions.

All the underlying issues can be addressed in an efficient and sustainable way by energy conservation and more efficient use of energy, by the increased use of renewable energy sources and by the use of hydrogen and fuel cells.

Hydrogen with the highest feedstock flexibility of any available energy carrier can provide a clean storage media and facilitate the transition from today’s energy world into an energy world with growing fluctuating renewable electricity supply.

Hydrogen therefore allows to significantly extend the use of renewable energy sources in the transport sector.

In particular, hydrogen used as an automotive fuel in hybridised fuel cell powertrains can provide superior well-to-wheel efficiencies compared to today’s fuels and thus reduces primary energy consumption and greenhouse gas emissions.

Additionally hydrogen offers the potential to provide operating performance (e.g. driving range, fast fill, etc.) which cannot be achieved with pure battery electric vehicles in the foreseeable future.

Over the next decades, renewable electricity will become the leading energy supply pathway.

Due to efficiency reasons it should be directly used in applications wherever possible, be it in stationary or in mobile applications.

As it stands, heavy duty road transport, long distance passenger car/ light duty road transport, aviation and maritime shipping will not be operable with electrons directly in the foreseeable future.

In all these applications the increasing non-availability of conventional and biomass-based liquid hydrocarbons has to be substituted by hydrogen as clean fuel.

Also large scale seasonal or longer term electricity/energy storage most likely can only be done economically through hydrogen.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BTL</td>
<td>Biomass-to-Liquid (fuel)</td>
</tr>
<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
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<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
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<td>CCS</td>
<td>Carbon Capture and Storage</td>
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<tr>
<td>CH₄</td>
<td>Methane</td>
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<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
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<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
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<tr>
<td>DWV</td>
<td>Deutscher Wasserstoff- und Brennstoffzellen-Verband (German Hydrogen and Fuel Cell Association)</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
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<tr>
<td>EHA</td>
<td>European Hydrogen Association</td>
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<tr>
<td>EJ</td>
<td>Exa-Joule (= 10¹⁸ Joule)</td>
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<tr>
<td>ETS</td>
<td>(European) Emission Trading System</td>
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<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>FC</td>
<td>Fuel Cell</td>
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<tr>
<td>FCV</td>
<td>Fuel Cell Vehicle</td>
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<tr>
<td>GHG</td>
<td>Greenhouse Gases</td>
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<tr>
<td>GJ</td>
<td>Giga-Joule (= 10⁹ Joule)</td>
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<tr>
<td>GWh</td>
<td>Gigawatt-hour (= 10¹⁸ Wh)</td>
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<tr>
<td>H₂</td>
<td>Hydrogen</td>
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<tr>
<td>HFCs</td>
<td>Hydrofluorocarbons</td>
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<tr>
<td>HRS</td>
<td>Hydrogen Refuelling Station</td>
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<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
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<tr>
<td>IGCC</td>
<td>Integrated Gasification Combined Cycle</td>
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<tr>
<td>kWh</td>
<td>Kilowatt-hour (= 10³ Wh)</td>
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<tr>
<td>LBST</td>
<td>Ludwig-Bölkow-Systemtechnik GmbH</td>
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<tr>
<td>MPa</td>
<td>Mega Pascal (= 10 bar)</td>
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<tr>
<td>Mtoe</td>
<td>Million Ton Oil Equivalent</td>
</tr>
<tr>
<td>Mtoe</td>
<td>Million Tons of Oil Equivalent</td>
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<tr>
<td>N₂O</td>
<td>Nitrous Oxide</td>
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<tr>
<td>NEDC</td>
<td>New European Driving Cycle</td>
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<tr>
<td>NG</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>Nm³</td>
<td>Norm (standard) Cubic Meter</td>
</tr>
<tr>
<td>PFCs</td>
<td>Perfluorocarbons</td>
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<tr>
<td>PJ</td>
<td>Peta-Joule (= 10¹⁵ Joule)</td>
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<tr>
<td>PV</td>
<td>Photovoltaics</td>
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<tr>
<td>RECCS</td>
<td>Renewable Energy Technologies with Carbon Capture and Storage</td>
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<tr>
<td>RES</td>
<td>Renewable Energies</td>
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<tr>
<td>SF₆</td>
<td>Sulfur Hexafluoride</td>
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<tr>
<td>SOT</td>
<td>Solar Thermal Power for electricity production Plants</td>
</tr>
<tr>
<td>TWh</td>
<td>Terawatt-hour (= 10¹² Wh)</td>
</tr>
<tr>
<td>yr</td>
<td>Year</td>
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<tr>
<td>ZEV</td>
<td>Zero Emission Vehicle</td>
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In the year 2000 five national hydrogen organisations established the European Hydrogen Association (EHA) and started a close collaboration to promote the use of hydrogen as an energy vector in Europe. In 2005 major European industries active in the development of hydrogen and fuel cell technologies joined the EHA and enforced this effort to create a commercial market for stationary and transport applications and a role as market leader for the European hydrogen and fuel cell sector.

In 2005 the EHA opened its office in Brussels and established itself in a relatively short time as an active and recognized point of reference for European institutions. The EHA currently represents 14 national hydrogen and fuel cell organisations and the main European companies active in the hydrogen infrastructure development.

This unique membership structure has enabled the EHA to have up-close insight in national and local development and to communicate important issues regarding industrial and regulatory needs to key decision makers at EU level. By participating actively in important meetings of the Commission, European Parliament and other European organisations the EHA has been able to create more visibility of the contribution of the use hydrogen and fuel cells to EU policy to key decison makers in Brussels. In addition the EHA, in collaboration with its national member associations supports and promotes important developments in European Regions and Municipalities.

Link: www.H2EURO.org

The German Hydrogen and Fuel Cell Association (DWV) promotes and prepares the general introduction of hydrogen as an energy carrier and of fuel cells as efficient energy conversion technology into the market.

DWV brings the interested parties (companies, institutes, private persons) together, keeps them informed, informs the general public and the deciders in economy and politics and advises the process of regulation and standardisation. In a nutshell: DWV is the German hydrogen and fuel cell lobby.

DWV works in close cooperation with the European Hydrogen Association and other national partner organisations all over the world.

Link: www.H2DE.org

Ludwig-Bölkow-Systemtechnik GmbH (LBST) is a leading European consulting company for business and society focussed on the sustainable use of natural resources and energy as well as sustainable mobility.

Since 1982, LBST has been supporting leading national and international companies and other stakeholders in society in establishing and developing sustainable structures, products and services.

Link: www.LBST.de