HyWays

SECOND PHASE OF THE PROJECT

ASSESSING MEMBER-STATE OPPORTUNITIES AND CHALLENGES FOR HYDROGEN AND FUEL CELLS

(DELIVERABLE D3.23)

Arman Avadikyan
BETA

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Disclaimer

The results in this report are a reflection of a non-final stage of the HyWays project, with substantial stakeholder consultation still under way. Significant modifications are still due, and consequently none of the results given in this report should in any way be considered as final HyWays results.

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INTRODUCTION

The aim of this contribution is to give a qualitative evaluation of hydrogen related opportunities and challenges for the 10 Member States (MS) participating in HyWays.

The progressive transition toward a hydrogen economy could result in the use of a range of new technologies, products, services, as well as increased use of renewable energy sources, creating for each MS a set of new economic opportunities. These opportunities could come from the creation of new manufacturing or service activities, export potential, new jobs and improved knowledge and skills. Opportunities may in this context be related on the one hand to hydrogen infrastructure and production and on the other hand to transportation and stationary applications.

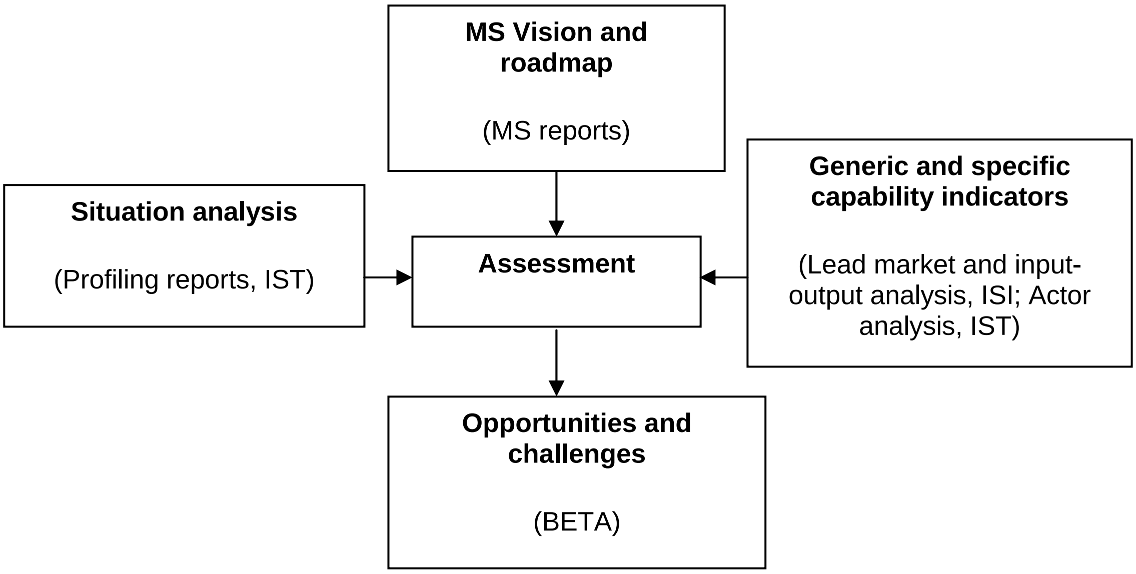
It should be recognised, however, that a hydrogen future is not guaranteed and that competing technologies could win in the future and represent thus a threat to the widespread deployment of hydrogen, all the more so since hydrogen technologies are seen as a long term solution and that in the mean-time more mature and alternative technologies may dominate the market.

The roadmap towards a hydrogen economy and the transition strategy adopted by each MS will certainly depend on several attributes such as the current energy system and infrastructure, resource availability, actors' strategies, government policy, comparative sectoral advantages and technological strengths, but also on the implementation of appropriate policies at the European level and coordination/cooperation between MS.

Considering the above mentioned factors and the work already accomplished within WP3 of HyWays (see Figure 1) this contribution will focus on identifying potential opportunities, barriers and challenges specific to each MS during the transition towards a hydrogen based energy economy. Opportunities and challenges will be considered in relation with:

- hydrogen infrastructure development
- hydrogen production
- hydrogen end-use applications

Figure 1: Assessment of Opportunities and Challenges



FINLAND

The existing energy system in Finland is characterised by a wide diversity of primary energy sources. The share of renewable energy sources (essentially wood biomass) contributing to total primary energy supply is 23%, which is the second highest in the EU after Sweden (Ministry of Trade and Industry, 2004). This diversity of energy sources and the importance of renewables along with a highly competitive innovation system in environmental technologies give Finland the opportunity and the potential to position itself as a key actor in certain development areas related to fuel cell and hydrogen technologies.

Because of its considerable and not fully exploited biomass resources in the form of forests and the critical role of the forest industry in the Finnish economy, the use of biomass for hydrogen production and the development of related technologies are among the prime objectives in Finland. Finland has a long history of economical exploitation of forest resources and the forest industry is a key actor on the bio energy market. Over time, structures have developed that facilitate an increased use of biomass for energy and which progressively made biomass an integral part of the energy system. Improvements of the forest industry infrastructure, strong domestic manufacturers of forestry equipment, continuous technical development and harvesting logistics, increasing production volumes have resulted in reduction in production and transport costs and have been important factors in shaping and accelerating the development of bio energy. Since the 1980s, government policy has also continuously supported bio energy through RD&D and economic instruments such as investment grants and energy and environmental taxes. Being an energy intensive sector the forest industry is the largest bio-fuel user. As such it had a great influence on the development of bio energy. The pulp and paper industry is an important player in the energy market and has largely benefited from energy policies supporting biomass through carbon and energy taxes. The ties between the forest industry and the power industry are also traditionally strong. Forest companies are major electricity buyers and they also own electricity generation facilities and companies (Pohjolan Voima). The integration of bio-fuels production within the forest industry has allowed the use of existing skills and transportation infrastructure in the forest industry. It has also led the Finnish forest industry to be very active in energy RD&D

programmes (Ericsson *et al.*, 2004). Furthermore, Finland has been since the 1980s at the forefront of biomass gasification RD&D which could be critical for hydrogen production processes. Gasification technologies have been a long term priority for such actors as VTT, Tampella and Ahlstrom (now Foster Wheeler). This may create for Finland the potential to become a lead adopter of biomass in fuel cell and hydrogen related applications. The central role of local authorities in the planning and choice of energy systems in Finland may be in this regard an important driver. Finally, even if biomass resources have traditionally been used mainly in regions where they have been produced, the development of an international bio-fuel market and efficient logistics could also provide important opportunities for Finland to export excess biomass resources or bio-hydrogen to other regions and contribute to the use of bio-hydrogen for fuel cell applications.

While the limited coverage of the gas network in Finland (Southern parts) has been an important driver for the diffusion of biomass as a local energy feedstock, planned new gas pipelines (such as the North Transgas project) could create the opportunity to diversify import sources and contribute to hydrogen production from natural gas, particularly in Southern regions. Among actors already producing hydrogen for industrial uses one can mention among others Woikoski (hydrogen gases for industrial use) and Finnish Chemicals (hydrogen as a by-product in paper chemical manufacturing).

The increased use of natural gas will however require the implementation of appropriate CCS strategies which, due to the lack of suitable CO_2 storage sites in Finland and long transport distances to the closest storage areas abroad, will have to overcome important economic and technological barriers (Koljonen *et al.*, 2002). Nuclear power is also expected to play an important role in Finland and is considered as a key motivation and a window of opportunity to introduce hydrogen energy. A specific feature of the Finnish energy policy is to maintain fair competition and versatile conditions for the use of all economically feasible energy sources available. There is thus an effort to allow for simultaneous expansion of natural gas and nuclear energy in parallel with renewables in order to satisfy the increasing electricity demand. However, this could in the short mid-term decrease the renewable sources available for hydrogen production and hydrogen power.

With regard to end-use applications Finnish R&D activities focus more particularly on fuel cell technologies and system integration with respect mainly to distributed and stationary energy systems (small residential, remote and off-grid, telecom,…), portable and consumer electronics and industrial transport vehicles (mining vehicles, military vehicles, ship APU,…). According to Tekes (2006) the Finnish industry has a potential to cover a large sector of fuel cell products. Specific strengths of the Finnish industry supporting the development of fuel cells are related to world class knowledge on CHP, district heating and distributed energy production and management systems, consumer electronics, system integration expertise, leading technology areas (engineering, materials, electronics, ICT) supporting the fuel cell system and application development. Of particular importance for Finnish companies is to strive for export markets since domestic markets for fuel cell products and applications will be limited. Furthermore although the per capita investment in fuel cell RD&D activities in Finland is comparable to that of Germany and the USA, it is considered that to support the growth of a significant fuel cell industry the funding and the number of Finnish companies in fuel cell development need to be increased in order to establish a critical mass for domestic operations (Tekes, 2006). Particularly, the development of distributed energy-related energy systems could generate new business opportunities and contribute to the export income of Finland. Even if the share of CHP based electricity generation (industrial and large scale district heating) in Finland is among the highest in the world, fuel cells could be particularly well suited for small scale CHP (residential buildings and leisure homes in less densely populated and rural areas) by improving their power-to-heat ratio.

Finnish programmes investigate both high temperature (SOFC and MCFC) and low temperature (PEM, AFC and DMFC) fuel cells. The DENSY (Distributed Energy Systems) programme financed by Tekes allocates part of its budget to fuel cell and hydrogen R&D. An alternative of special interest to Finland is the use of gasification of biomass and different wastes in high temperature fuel cells. Industrial actors focusing on the development of fuel cell and hydrogen technologies include among others Hydrocell (AFC and metal hydride storage systems), Wärtsilä (SOFC for distributed power generation and marine applications), Labgas (PEM for portable applications), Nokia (portable fuel cells), Enfucell (DMBFC for low power portable electrical devices). VTT, the technical research centre of Finland is also involved in PEM and SO fuel cell component and system RD&D activities (FINSOFC project initiated in 2002 with several companies). A demonstration project for small CHP in residential houses has already taken place in Äetsä using surplus hydrogen from the chemical industry.

With respect to transport applications, the situation in Finland is in several aspects similar to that of Norway: Specific climate conditions may render the adoption of fuel cell vehicles more challenging and the limited size of the domestic / Nordic market may not create the critical mass necessary to allow the built-up of a hydrogen infrastructure, unless other European countries follow similar strategies. Nevertheless the coordinated approach developed by the Nordic countries to strengthen their hydrogen and fuel cell activities should be critical in creating a favourable climate to accelerate such infrastructural investments.

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FRANCE

The transition strategy adopted by France will certainly depend on several attributes of the current energy system and infrastructure developed since the beginning of the 70s and which is predominantly based on nuclear electricity. One should however take also into consideration that a sustainable and viable hydrogen economy will be a driver for renewable energies where France has important potentials. Given that in France the energy conversion sector is the lowest contributor to CO_2 emissions, the main sector explaining the attractiveness of hydrogen as an energy carrier is the transport sector. Furthermore, the importance of the automotive industry for the French economy and the strong export orientation of car manufacturers contribute to the strategic importance of fuel cells and hydrogen technologies in France. Besides, hydrogen infrastructure built-up would create critical and long term opportunities for exporting large scale project management and engineering competences. A detailed survey of fuel cell and hydrogen related RD&D activities since the beginning of the 1900s can be found in the IPHE (2004) and IEA reports (2004).

The availability of hydrogen and dedicated infrastructure for industrial uses (merchant and as a by-product) might create in France favourable business conditions in the early phases of hydrogen related applications (HyFrance, 2007). Although the geographical coverage of hydrogen pipelines is limited to some industrial areas, the expertise of industrial gas suppliers such as Air Liquide in designing, building and operating these pipelines may become an important driver in the emerging deployment phase of hydrogen. Particularly the cross-border hydrogen pipeline network which extends over France, the Netherlands and Belgium, provides the opportunity to develop common hydrogen pilot projects. The fact that these hydrogen pipeline networks are localised in different regions might create the opportunity to set up a diversified and complementary set of demonstration projects in partnership with experienced users (on-site industrial CHP applications or fleet vehicles). Furthermore, in the case where by-product hydrogen is produced near hydrogen or natural gas pipelines, it can directly be fed into the existing infrastructure and be valued for energy related industry uses.

The extensive natural gas network also provides France with favourable conditions in order to use the existing infrastructure to transport a mix of hydrogen and natural gas (HyFrance, 2007). Such a strategy in the initial phases would allow the transport of hydrogen to regions where hydrogen demand potential is high (urban centres) without requiring risky high capital investments for large-scale hydrogen pipelines. The natural gas grid might also be an important facilitator for the development of SMR hydrogen production plants. From the perspective of the industry, the adoption of SMR would create business opportunities for natural gas suppliers (Gaz de France), industrial gas suppliers (Air Liquid) and hydrogen plant manufacturers (Technip). With the Institut Français du Pétrole (IFP), France possesses also a key actor conducting research related to the production of hydrogen from natural gas via SMR. Research projects in this field have also been initiated within the national PACo network.

Until recently infrastructure related demonstration projects (on site production plants, hydrogen refuelling stations) were almost non-existent in France. This situation is however changing, namely with the recent launch of national demonstration projects such as Alt-Hy-Tude (with the aim to test the operation of hythane fuelled buses and refuelling stations in the cities of Dunkerque and Toulouse) and the participation of French regions/cities to European demonstration initiatives such as HyChain (coordinated by Air Liquide and whose aim is to develop a small scale local distribution platform in the city of Grenoble as well as in the Ruhr valley and in Milan). Despite the low number of demonstration activities at the national level, French industrial actors such as Total and Air Liquide take nevertheless actively part in many infrastructure demonstration projects abroad.

Closely related to the use and sustainability of large scale SMR plants is the availability of CCS technologies. CCS is a domain where France is relatively well positioned in terms of geological characteristics (Paris basin, Lacq gas field) as well as in terms of industrial and research competences (DGEMP-DIREM, 2006). Particularly for French oil service companies the opportunities are expected to be very important. Although it is necessary to differentiate issues related to CO_2 storage from those related to nuclear waste, the experience gathered since several decades by the nuclear industry in dealing with radioactive waste could be a very valuable asset in order to deal with CCS issues. Among the main actors engaged in this area are IFP, Gaz de France, Alstom and Total. Other private actors (EDF, Arcelor, Lafarge and oil service companies…) or public actors (BRGM, IPGP, ENSMP, universities…) are active in related fields. CCS has also been considered by the New Energy Technologies programme of the National Research Agency as one of the main strategic research projects. Due to the international dimension of CCS, French actors are also actively involved in European and international R&D projects.

Beside SMR, electrolysis is considered as one of the most suitable hydrogen production options in the French energy system context. Particularly, Air Liquide has experience in operating small-scale on-site hydrogen generators via water electrolysis. The company operates several small on-site hydrogen generators throughout the world for industrial applications. An important French equipment company in this domain is also CETH (created in 2000 as a spin-off from the CEA) involved in the construction of small on-site plants.

The electrolysis option is mainly justified because of nuclear energy as a carbon free electricity source. Increasing natural gas prices along with the taxation of CO_2 emissions or the costs incurred through CCS could be important drivers for the development of the electrolysis option. In France, the abundant supply of nuclear energy has created a situation where electricity prices were in the past relatively lower than in most of the other European countries and where an important part of the excess electricity produced was exported. Although currently and in the short term this situation creates a favourable context for adopting the electricity mix electrolysis option for hydrogen production, several questions remain open. In fact widespread use of electrolysis for hydrogen production would place in the future additional burdens on the electricity production system, especially given the trend of increasing electricity demand in France. Therefore an important challenge relates to the significant increase of nuclear plant capacity to meet hydrogen demand if fuel cell/hydrogen vehicles are mass produced. Around 2020 a number of nuclear reactors will be due for decommissioning. They will be replaced by a new generation of nuclear generators (e.g. EPR) and by gas fired power stations. In the former case electricity prices may increase not only because of increasing demand but also due to higher nuclear investment costs. Critical factors which may affect the economics of electricity for hydrogen production will also be related to the structuring of the integrated European electricity market (convergence of electricity prices). In the short term (until 2020) an important issue will be the allocation of excess electricity between export and domestic hydrogen production.

In the long term, the development of new generation nuclear reactors may confer to France a significant competitive advantage in hydrogen production and export. Particularly high temperature processes (based on next generation and innovative reactors including EPR and Generation IV reactors), supported by substantial government R&D and efforts to market and export of nuclear plants, are considered as a strategic domain where France could develop and maintain a competitive advantage with regard to hydrogen production by electrolysis. Nevertheless the feasibility of these concepts remains highly uncertain from not only a technological point of view but also with regards to the evolution of the future energy system and the issue of public acceptance.

France has also an important RES potential (biomass and wind). Although until now the market share of wind based electricity generation has been very low compared to leading countries (Germany, Spain) (Buquet and B. Chabot, 2006), wind resources are considered to play a non negligible role to support hydrogen production in the future . Hydrogen used for energy storage would in fact constitute a key step to solve the problem of wind energy intermittency. Additionally, storing wind electricity through hydrogen would allow a more flexible system without creating tensions in overloading the electricity grid. One can also mention the possibility that, once wind energy technologies have achieved their maturity, market based instruments such as bidding procedures and green certificates replace progressively the feed-in tariff system. Such a policy shift, based on efficiency arguments, could represent for France an opportunity to increase its installed wind electricity capacity because of its comparative advantages in terms of wind energy potential. But the dominant position of nuclear energy may still represent a barrier to the rapid deployment of business opportunities related to wind energy.

Because of its favourable climate and soil conditions, France has also a considerable biomass potential. Hydrogen production from biomass represents an important business opportunity for the French agricultural sector which could have pervasive effects in several sectors and contribute to the economic and industrial competitiveness of several regions. One of the important challenges will be here to develop the critical interfaces between industrial sectors, which traditionally used to operate separately. The use of biomass resources for energy purposes will certainly imply a change in the structuring of different industries, for instance through a closer integration between oil companies and the agriculture sector in order to allow bio-energies and bio-hydrogen to massively diffuse in the transport sector. In France, particular emphasis is put on lignocellulosic cultures (straw, wood and residual wood). Biomass gasification technologies for cogeneration applications has been investigated by the AGRICE (Agriculture for Chemicals and Energy) public-private R&D consortium focusing more broadly on the use of biomass resources for chemistry, materials and energy applications. Among public research institutes, the IFP, the CEA, the CIRAD and the CNRS are particularly involved in the development of biomass gasification processes. Since the creation of the National Research Agency, the New Energy Technologies Programme includes also important efforts on gasification technologies. Moreover, some private companies are involved in biomass gasification development activities but until now they have had limited success. Of these companies, the most commercially successful has been Touillet/Martezo, which has operated two gasification plants in the past for electricity production (Kwant and Knoef, 2004).

The electricity network structure and the centralised electricity production based predominantly on nuclear plants has created until now in France a situation where the development of decentralised energy solutions and CHP plants (mainly industry and district heating where the potential is still considerable) has been slower and less important than in other European countries. Several obstacles have contributed to the relative underdevelopment of CHP and decentralised solutions in France. Among these, low electricity prices and electricity generation overcapacity have played a structuring role. Both factors might however become less decisive in the future if, as expected, overcapacity drops by 2020 and nuclear electricity prices converge within a more competitive and integrated European energy market. But the market share of decentralised energy may still be more limited in France if nuclear electricity production continues to dominate in the mid and long term (WADE, 2005).

Although the involvement of industrial actors in the development of stationary fuel cell applications (PEM and SOFC) remains less important than for instance in Germany, one can notice since the beginning of the century the emergence of an increasing number of companies investigating this domain (IPHE, 2004). Among the main private actors one can mention EdF and GdF; energy service companies such as Dalkia, Elyo and COFATECH (GdF subsidiary), fuel cell system developers: Axane (Air Liquid), Hélion

(Areva/Technicatome Group), SNECMA (SOFC technology); components and stack suppliers: Saint Gobain (for SOFC technology), PaxiTech (CEA spin-off), reformer, heat exchanger developers: CETH (CEA spin-off), N'GHY (EMAC spin-off) and Irmatech. Several demonstration projects have also already been launched in France since the year 2000 (involving GdF and EdF) and other demonstration projects are in the planning phase (Lucchese, 2005).

The regulatory framework supporting the adoption of CHP solutions (e.g. gas tax exemption, feed-in tariffs for renewable cogeneration) along with the liberalisation of markets will certainly create more favourable conditions for decentralised energy systems. In fact the potential for cogeneration in district heating as well as in the industrial and tertiary/residential sectors remains still important in France. In industry, the use of cogeneration can still contribute significantly to a reduction of CO_2 emissions. Industrial CHP might in the near future be based on high temperature (HT) fuel cells because of their excellent efficiency and high power to heat ratio. In the tertiary/residential sectors small or micro CHP might also be a promising solution to satisfy electricity/heating demand. CHP as a decentralised solution could also play a specific role in rural/regional development and planning through, for instance, the possible use of local energy sources (e.g. agricultural waste) and the creation of local employment. The increasing tendency towards regional decentralisation might be an important driver for local initiatives in this area.

France being a large automotive sector country, the positioning strategy of car manufacturers with respect to fuel cell vehicles may have important impacts in terms of its global competitiveness and employment prospects. Although indicators do not currently position the French automotive sector as a leading actor in fuel cell development (compared to Germany), the will to support the emergence of a national fuel cell industry through national R&D initiatives has become in recent years very strong. The two main French car manufacturers, Renault and PSA Peugeot adopted in the past a less enthusiastic position towards fuel cells. Even if they have developed fuel cell car prototypes they have until now not been involved in demonstration projects. Nevertheless they actively participate in European and national programmes (PACO and PAN-H) and have developed over the years strategic alliances with several international and national fuel cell system developers. Among public actors playing a key role in fuel cell transport applications one can particularly mention the CEA (particularly with PSA Peugeot), IFP, CNRS and several universities and engineering schools. Furthermore several French companies are beginning to develop fuel cells for niche transport applications (e.g. Axane-Air Liquide, Hélion, Paxitech) even if their main domains are the micro-stationary or portable applications.

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GERMANY

Potential markets for fuel cells and hydrogen lie in areas where Germany has a strong position, namely automotive and energy systems. The German innovation system has a competitive advantage particularly in advanced technologies such as automobile, engineering, or chemicals, fields which are of specific importance to fuel cells and hydrogen. These sectors form a core element of Germany's economy and competitiveness. Germany's leading position in these domains can thus foster its global market position and extend its export potential.

Issued patents and publications show that today Germany is among the major players in fuel cell and hydrogen technologies (European Commission, 2005). It plays a head role in Europe, and the total output of patents and publications in recent years has been slightly smaller than in Japan and even the USA. This goes along with a broad coverage of fuel cell and hydrogen technologies and applications. Major German companies, namely DaimlerChrysler and Siemens, are engaged in fuel cell development and commercialisation. Many research institutes carry out also fuel cell and hydrogen related research with private and public funding.

Several German car manufacturers have developed strong positions in fuel cell and hydrogen based vehicles. The German automotive industry is furthermore very actively engaged in several national and European wide demonstration projects. DaimlerChrysler´s determined engagement from the early 90s on fuel cells has played a key role in Germany and has created positive prospects for the rapid development of a national R&D base (Wengel, 2006). In addition, many suppliers to the automotive industry are engaged in fuel cell research. Nevertheless German carmakers seem to follow different strategies. Whereas DC is very actively engaged in fuel cells with Ballard Power Systems, BMW is particularly focused on hydrogen combustion engines and prepares also the use of SOFCs in auxiliary power units (APUs) for bigger cars. Volkswagen in turn seems to consider fuel cells in a long term perspective.

With respect to stationary applications, opening up of competition in the energy sector as well as support for the use of renewable and more efficient energy technologies are driving forces for FC development. Germany has several power plant producers, big utilities and residential heat and generation equipment providers strongly involved in fuel cell development and commercialisation activities (Fuel Cell Today, 2003). Some started ambitious demonstration projects not least in order to prepare for possible competition. Support for the use of renewable and more efficient heat and power technologies, the regulatory framework urging the replacement of residential heating systems within the next 5-10 years, the renewal perspectives of an important share of power plants which should be replaced within the next 25 years, the availability of an extensive natural gas distribution grid create strong opportunities for the early introduction of the fuel cell option in the energy mix. In addition, the companies see very good export opportunities in Europe and overseas (Wengel, 2006).

Although in the future a reduced demand for heating in general could limit the potential for combined heat and power (CHP), and thus also for fuel cells, the modular nature of the latter might lead to a technical advantage over conventional CHP systems. In addition, the fuel cells' potentially high power-to-heat ratio corresponds well with the shift of demand patterns towards an increase in electricity demand. The use of distributed small-scale fuel cell systems such as virtual power plants might thus open up new fields of application.

Furthermore the growing contribution of renewable energy sources (RESs) to heat and electricity supply might also limit the market potential for stationary fuel cells. Therefore, in the long run the market introduction of stationary fuel cells might help to open up new fields of application for renewables by facilitating the use of gaseous fuels from renewable energy carriers in fuel cells (Krewitt *et al.*, 2006).

Germany has also a strong position in hydrogen production related technologies such as in steam reforming, electrolysis and coal/biomass gasification. In the mid and long term particularly gasification technologies could be an important economic and business option for Germany because of its important coal and biomass resources. But, although endowed with a large potential in wind power and a strong wind turbine industry, high electricity prices and end-use competition for renewables may be in the short term a barrier to the electrolysis option. On the other hand, due to the high presence of fluctuating energy carriers for electricity production such as wind power, hydrogen could be in the mid-long term a storage option for Germany.

At least three regions in Germany have important capacities to play a leading role in the early deployment of hydrogen related applications because of their traditional position in the automotive industry (Bavaria and Baden Wurttemberg) and energy systems (North Rhine-Westphalia). The concentration of major actors in these regions has been a key factor in the emergence of fuel cell and hydrogen technology related clusters since the beginning of the 1990s.

All in all, several indicators such as the availability of by-product hydrogen and pipeline (Ruhr Gebiet), important demonstration activities, population density, and age of passenger cars among others create favourable conditions for Germany to benefit from the market introduction of fuel cell and hydrogen related technologies.

However, whether Germany has the critical mass to become a lead user country is at least questionable. German lead markets might be possible in some fields (such as residential heating and power systems) but in most application areas (like automotive) the European level might certainly be a prerequisite (Wengel, 2006).

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GREECE

Because of the increasing necessity to limit CO_2 emissions (mainly from electricity generation) and the historical problem of local air pollution in major cities, due to the road transport sector, hydrogen and fuel cell based energy systems are considered by the Greek government progressively as a key element to be included into the energy planning of the future. Although, compared with large automobile countries, Greece does not have the potential to become a lead market in hydrogen and fuel cell related areas, all in all the economic risks of a hydrogen economy may be considered as much smaller for Greece. Nevertheless, even if until recently a limited number of Greek companies have been involved in hydrogen and fuel cell systems development (e.g. HELBIO and Tropical S.A.), there is an increasing interest emerging for a diversified set of applications including niche markets. Furthermore, a significant number of universities and research centres are participating on several European projects while the national funding on hydrogen projects is steadily increasing (IEA, 2004).

The deployment of hydrogen as an energy carrier in Greece will certainly impact the policy around the use and expansion of natural gas. The relatively recent introduction of natural gas in the Greek energy system for electricity production, especially with the goal to diversify fuel supplies and to attenuate the dominance of lignite-based generation creates the possibility to adopt a synergetic approach in planning the development of natural gas and hydrogen distribution networks in a coordinated way. This is viewed by the Greek Gas Company (DEPA) as an opportunity. In fact the development of competition in energy markets could have a significant effect on natural gas and hydrogen networks. Hydrogen as a potential energy carrier may allow gas companies to increase their share in the energy market through innovative and environmental friendly technologies. Natural gas based hydrogen production could play a particularly important role in Thessalia and Attiki which already possess an extended gas grid and which are the main energy consuming regions in Greece and where big industries and main economic activities are concentrated. The share of natural gas based schemes will also depend upon the availability of cost competitive natural gas (compared to indigenous lignite), as well as the infrastructure to deliver it (Hugh, 2005). Diversification of import sources and environmental policies (regulations and taxes) could contribute to the competitiveness of natural gas. Beyond the positive effects of the expansion of natural gas grids on hydrogen deployment, there is however the risk that sites with an important RES resource potential be cannibalised by such a development.

Since the current energy system of Greece is heavily based on cheap and plentiful domestic supplies of lignite, it is expected that this will play a structuring role as important as natural gas for hydrogen supply in the mid-long term. In this case an important challenge will be the high capital intensive infrastructural investments necessary to connect the lignite fields (north and central Greece) where hydrogen will be produced to the main user centres around Athens and Thessaloniki (Hugh, 2005). Furthermore the built-up of such a hydrogen infrastructure would be faced with complex topographical constraints due to the mountainous terrain of Greece. But the energy demand of these regions could be an opportunity to better exploit the potential domestic sources available locally and in other regions and to better connect them to the main economic centres of the country. For the Public Power Corporation (PPC), which is the main actor for lignite mining operations and electricity generation, hydrogen would represent the opportunity to diversify its activities in related and innovative areas. PPC is already participating in several European programmes related to CCS and coal gasification with the production of hydrogen for energy uses (IEA, 2004).

Greece has significant RES potentials, and already has a high proportion of RES-electricity generation compared to many other Member States. A distinctive feature of Greece is its large number of populated islands which are not yet connected to the electricity grid on the mainland. Many Greek islands have already significant experience on RES systems through installers and users (ROKAS SA). Therefore RES-hydrogen systems which are particularly applicable to the niche market of Greek islands because of their renewable (wind and solar) potential in the emerging phases, might also have a significant role in the national hydrogen development in the long term, since the wider adoption of these systems and electrolysers could drive down their costs. Through the implementation of such RES-hydrogen installations, islands could become self-sufficient in all the energy sectors and even export energy. Tourism is a vital source of income, and the promotion of RES based systems could increase the attractiveness of islands. Whilst the implications of such a transition in cost would be considerable, one should also consider that energy is today very expensive on the islands, which could give the first installations that would operate for storing RES excess energy a chance to compete (Hugh, 2005). The experience gained would also be valuable and applicable to other remote communities in Europe.

Besides the islands, there is also an RES potential on the mainland through biomass and wind. For the latter a precondition of higher penetration of hydrogen through RES/electrolysis systems would suppose the enforcement of the electricity transmission grid capacity. Investments in the electricity grid would be an essential determinant for the development of RES based hydrogen on the mainland. The biomass potential and the export opportunities for biomass based hydrogen production systems are also a priority of the Greek company Helbio focusing on bio-fuel processor systems for remote, off-grid locations and areas of inexpensive bio-fuel production (e.g. Brazil) (Lymberopoulos, 2005).

Environmental concerns and particularly urban air pollution are in Greece the main drivers for the interest in fuel cell and hydrogen end-use applications. Localised pollution is due substantially to transport but also to local heating and industry (Hugh, 2005). Taking into account the fact that almost half of the Greek population is concentrated in the Athens and Salonika regions, these will play a critical role in the deployment of transport / stationary applications and the development of the hydrogen infrastructure. Although islands may be the main drivers in the initial phases for RES based hydrogen applications, these two central regions will play a critical role in the structuring of the hydrogen deployment phase. In the CHP sector, the government (through the Operational Programme for Energy) has already initiated support schemes (investment subsidies, tax exemption, favourable tariffs) for cogeneration projects based on natural gas and biomass. The projected increase of these sources in parallel with the liberalization of the energy market would open up new market opportunities for decentralized CHP applications in the industrial and tertiary/residential sectors (local heating). Fuel cell and hydrogen based systems would however have to compete with alternative and more cost effective solutions at least in the short term and would need to be subsidised. Concerning the transport sector, some specificities of the Greek context are the historical problems with local air quality due to urban road transport, the age of the car fleet which is amongst the oldest in Europe, the level of traffic in urban areas. This particular situation stresses the importance of policy support at the regional and national levels for fuel cell vehicles to be progressively adopted first in public transport and then in private vehicles.

The need for low cost energy, the socio-economic conditions specific to different regions, the necessary investments in natural gas, hydrogen and electricity infrastructures, and the replacement of the existing car fleet may pose several challenges to the wider adoption of fuel cell and hydrogen technologies in Greece and should require strong policy commitment. But focusing its long term strategy on RES based hydrogen production and more generally on regional sources will not only have environmental benefits but may create new business and job opportunities in these regions. In this context the participation of Greece in large scale European demonstration projects should be of critical importance in terms of industrial experience.

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ITALY

Italy is one of the most active European countries in the hydrogen and fuel cell field and is in this field one of the largest spenders in Europe after Germany. Both at the national and regional levels, opportunities for hydrogen and fuel cells are explicitly recognized. At the national level, hydrogen is envisaged as being a key element in contributing to greenhouse gas reductions, improvement of supply security through a diversification of energy sources and an increase of domestic production (Italy's energy supplies being more dependent on imports than the European average), as well as fostering renewable sources. At the local and regional levels, important drivers are the protection of urban environment (a challenge due essentially to the pollution from road traffic) and the promotion of industrial competitiveness through innovation. Italian legislation (new energy law Legge Marzano published in 2004) already provides incentives to use hydrogen for electricity production, independently of the production feedstock, considering hydrogen as equivalent to renewable sources and eligible for tradable green certificates.

With SAPIO and SOL, Italy possesses two important industrial gas suppliers having long term experience in producing, storing and distributing industrial hydrogen. Hydrogen production technologies could open up new business and export opportunities for the machinery and equipment sectors which traditionally play an important role in Italy. An important role in hydrogen deployment is also played by electric and gas utilities, i.e. Enel, Edison and ENI and municipal energy companies.

Due to the extensive domestic natural gas network, import infrastructure and strong industrial players (ENI), natural gas and steam methane reforming are expected to play a critical role in Italy throughout the transition period to 2050. Hydrogen mixing with natural gas in the natural gas distribution network, if viable, represents in the short term the most appropriate hydrogen deployment strategy for industrial and policy actors. However, since Italy's natural gas dependency is projected to increase, with risks of saturation and thus pressures for existing import connections, despite new domestic production possibilities, a challenge might be the increasing demand competition through time between natural gas based hydrogen and direct use of natural gas. The existing and planned expansion of natural gas use in electricity generation and corresponding infrastructure development could be both a threat and an opportunity for extending hydrogen pipeline networks, depending on the evolution of technologies, actor attitudes and the management of policies. Furthermore, the use of other fossil fuel based hydrogen production technologies such as coal gasification is considered as an opportunity for diversification in the mid and long term, since Italy's current reliance on coal is low compared to the rest of Europe. The use of coal to produce hydrogen through the coal gasification process can be an effective way to solve the problem of old plants producing electricity, as they are mainly based on highly polluting fuels; they can be substituted at the end of their life by hydrogen plants with lower problems in terms of acceptability from local populations. To be acceptable from an environmental point of view, both options (natural gas and coal) would however necessitate CO_2 capture and sequestration. The study of CO_2 sequestration in geological sites (deep aquifers, depleted oil and gas fields) and development of related technologies are one of the priority areas in Italy. ENEL and ENI are key actors in this field. The use of coal in combination with CCS would create important business and industrial opportunities in the coastal areas and harbours where coal should be imported through maritime transport.

With respect to the electrolysis option using the electricity mix, a possible disadvantage for Italy is the electricity prices which are among the highest in Europe. This could in the short term represent a barrier for the adoption of this option. In the long term, nuclear power could however accelerate the use of this option if the government comes to reconsider its position towards nuclear energy.

Italy has furthermore significant RES potentials (biomass, wind and more particularly direct thermo-chemical conversion with solar energy in the long term). RES based hydrogen systems could in the long term be a key element in accelerating the deployment of this potential and create important economic opportunities in several Italian regions (particularly in the South). Although until now the development of renewable markets for electricity production in Italy has been moderate due to grid and administrative barriers, new policy measures (transition from fixed feed-in tariffs to a more market-oriented minimum quota obligation scheme with tradable green certificates) could benefit hydrogen production through renewables. Advances in solar thermal generation and changes in the promotion of renewables for electricity production may in parallel promote hydrogen production as a solution to intermittency problems.

It is also important to notice that in Italy, Regional governments have a central role in energy planning and decision making. Several regions have expressed a firm support for hydrogen. The particular active position of Italy in hydrogen related demonstration projects shows the importance of regional actors and the key role they play at the European (the Lombardy region as a member of the Hydrogen Technology Platform and the Zero Regio demonstration programme) and national and regional levels (the Bicocca demonstration Project focusing on the development of hydrogen in urban areas set up by the Milan Municipality, the Lombardy Region and financed partially by the Ministry of the Environment). It is thus possible that much political drive for hydrogen in Italy will come from this level of governance. The experience gained through demonstration programmes provided by the Regions could be fundamental both during the development and pre-commercialization stages. Particularly in the initial phases when decentralized production will dominate, regional policies might play a decisive role in the built up of a hydrogen infrastructure through the creation of regional hubs and clusters. Such regional initiatives would furthermore be based on specific potentialities of the territories (renewable and non renewable resources, industrial competences, energy demand) and might hence favour a diversified hydrogen deployment approach at the national level.

In the end-user applications area Italy has a strong research background and has initiated already several demonstration projects. For small-medium size power generation plants and CHP applications several fuel cell technologies have been investigated since the mid-1980s (particularly MCFC, PAFC and PEM). Particularly Ansaldo Fuel Cells, ENEA, CNR-ITAE, CESI and universities have been very active with respect to MCFC and PAFC technologies for which important experience has been gained through co-generation demonstration projects in cooperation with Municipal Authorities and energy utilities (e.g. Milan and Bologna). Efforts have also been intensified currently in PEMFC for CHP applications developed by Arcotronics Fuel Cells. The increasing energy demand in the residential/commercial sectors makes fuel cell/hydrogen applications an attractive option for distributed generation and CHP in Italy. Whilst in the short mid-term there might be a lack of interest to switch to hydrogen in the residential sector, as an increasing share of existing housings are using natural gas, the commercial and industrial sectors might position themselves as lead users of distributed generation systems where the investment can have a quicker payback.

Italy has one of the highest per capita levels of car ownership in the world. Moreover, there is a relatively high proportion of old low-efficiency vehicles circulating in the country. Although local pollution has seen considerable improvements with policy, urban areas still face emission and noise pollution problems (e.g. Milan). The main growth area in Italy's CO_2 emissions is expected to come from the transport sector. A unique feature of Italy is also the high number of mopeds/scooters in the transport system. High population density in metropolitan areas combined with local/regional policy commitment to reduce air pollution in large cities could thus represent a critical driver for hydrogen infrastructure built up and hydrogen use in the Italian transport sector. Other indicators (e.g. high passenger car age) may in the short term be a barrier for the rapid adoption unless appropriate tax exemptions for CO_2 free vehicles are provided.

For the Italian automotive production sector, fuel cell vehicles represent a critical opportunity in terms of industrial and technological competitiveness. Italy is an important player in car and truck production plants. Moreover, it's the largest producer by far of motorcycles and mopeds/scooters. In this domain Italy has built a strong expertise and research background with active participation in several demonstration projects. Several public and private actors are engaged in fuel cell development for automotive applications. Nuvera Fuel Cells is one of the European leading developers of PEMFC components/systems and fuel processors. The company has a long cooperation track with Fiat. The Italian automotive company has developed several vehicle prototypes and fuel cell buses for demonstration purposes through its subsidiaries IRISBUS-IVECO. Other important industrial actors such as Aprilia, Piaggio are focusing on fuel cell scooters which could emerge as the first mass market for transport applications. Compared with leading competitors such as Germany, Italy might thus position itself as a fast follower in hydrogen vehicle and fuel cell stack production. But losing market shares due to late market entry could mean drastic job losses and GDP losses in this sector of strategic importance for the Italian economy.

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NETHERLANDS

The Netherlands are one of the most active countries in Europe for fuel cell and hydrogen related technologies (SenterNovem, 2005). Yearly investments in this sector are estimated to be around €35 million. The energy industry is a key component of the Dutch economy. As a natural gas country the use of natural gas is strongly intertwined with all kinds of economic activities in the Netherlands and companies' interest in gas production and distribution is large (Shell, Gasunie). Natural gas is the major carrier for both central electricity production and distributed heat and power generation. Almost all Dutch houses are connected to the gas grid. The natural gas grid and available knowledge on natural gas distribution thus offer strong business opportunities, but also challenges for hydrogen production and applications. In the past the discovery of the Groningen field and the introduction of natural gas in the Dutch energy system engendered major spin-offs to other Western European countries. A possible but still uncertain route (due to technical constraints which may act as show stoppers) would consist in introducing hydrogen into the energy infrastructure by mixing hydrogen with natural gas. In the early introduction phases this would allow the more flexible use of the existing natural gas infrastructure to catalyse new markets for hydrogen while, at the same time limiting investment in costly pipelines. In order for the dense natural gas network in the Netherlands to become an advantage for the transition towards a sustainable hydrogen economy, a critical issue is to consider these existing assets in synergy with other renewable energy sources and how these might improve the competitiveness of both these sources and gas networks.

A crucial role in the early deployment phase of hydrogen as an energy carrier may be endorsed by the Rotterdam-Rijnmond area (Bosch *et al.*, 2005). The critical position of Rotterdam as an energy hub and the already existing hydrogen production facilities and energy industry infrastructure (hydrogen pipeline, refineries, LNG terminal, biomass import, biofuels production, and concentration of hydrogen expertise through the presence of companies such as Shell, BP, Air Products and Linde/HoekLoos) can make the region one of the principle centres for hydrogen production in Europe if backed up by an energy port strategy. In fact, Rotterdam is a major port where energy sources for hydrogen production can easily be imported and thereby create new business and economic opportunities. The high population density in the region combined with the existing hydrogen infrastructure creates also an early consumer market potential for end-use applications. The Rotterdam-Rijnmond region is thus favourably and practically suited to realise bridging demonstration projects with a significant up-scaling and market growth potential in the wider Randstad area. Opportunities might also emerge through the possibility of infrastructure and trade connections with neighbouring regions having similar practical experience in the area of hydrogen transport and distribution and where chemical and oil refineries are concentrated, namely Belgium (Antwerp region), Germany (Ruhr region) and North of France (Smit *et al.*, 2006).

Concerning hydrogen related production technologies The Netherlands have extensive experience in gas technologies, handling, logistics and transport. Notable activities and distinctive competences exist with respect to hydrogen production from natural gas with a focus on partial oxidation, purification and liquefaction equipments.

In the long run coal gasification with CCS for hydrogen production may also create significant market opportunities. An integrated coal gasification combined cycle power plant (IGCC) using a Shell gasifier is already in place in the Netherlands (Buggenum). This experience is an important asset. Recently, there has been interest in altering the fuel mix at Buggenum to include biomass as well as coal and to possibly produce hydrogen in addition to electricity.

Whilst investment in CCS technologies has been comparatively low in the Netherlands, there is an important potential for CO_2 storage in onshore and offshore aquifers, onshore and offshore gas fields, and onshore coal fields. Provided CCS becomes a viable and accepted option, this could represent an important economic and business opportunity for the oil and gas industries in the long term with the diffusion of central SMR / coal gasification technologies and increased CO_2 taxation and trade. In this context, CCS technology transfer may be considered as a possible option in the future.

Although renewable energy resources are strongly supported by policy measures, the prospect of the Netherlands becoming a lead market in hydrogen related uses of these resources compared to some other countries (Norway, Finland) seems rather weak. Nevertheless the

Netherlands have significant experience with industrial-based electrolysis which could be valued with wind based electrolysis. Biomass gasification has also been high on the agenda since the beginning of the 1990's. Several small scale biomass gasification projects have been planned and set up since then for electricity generation. The most promising market opportunities for hydrogen production from biomass seem to exist in the long term because of a centralised production framework. At least two questions remain however open concerning hydrogen production. The first is the competition for biomass between end-use applications (hydrogen, bio-fuels and electricity). The second is availability of domestic biomass resources, measures aiming to develop in a sustainable way both domestic resources import strategies and policies.

With regard to stationary applications the Netherlands are one of the leading countries in conventional CHP applications in Europe. The decentralised structure of the Dutch energy system, along with the advanced liberalised market and the strong support from the government for CHP and renewable energy sources have been the driving forces for the rapid diffusion of large scale CHP plants for industrial processes and district heating. Although the already high share of gas-fed CHP units may be a barrier to the wide diffusion of fuel cells in large scale stationary applications, fuel cells and hydrogen technologies can have the potential to open up new market segments for micro-CHP on a domestic scale. In the Netherlands, the potential market for micro-CHP could be high, as it is favoured by the dense gas infrastructure, the relatively cool climate and the tradition of decentralized cogeneration. Nevertheless, the adoption of fuel cell and hydrogen based micro-CHP systems as a long term option still faces numerous uncertainties and challenges. These uncertainties relate to the technology itself (cost/performance attributes) but also to alternative technological options (Stirling engine, gas engine) and consumer adoption (Meijer *et al.*, 2006).

In terms of application potential the greatest opportunities can be envisaged in transport applications. Although the Netherlands do not have an automotive industry *per se*, fuel cell related materials, components, systems, fuel processors and hydrogen storage technologies are actively supported by several actors (e.g. Nedstack, Hexion, ECN) through private-public cooperation (although principally focusing on stationary applications and including SOFC with natural gas) and could in the future lead to a competitive position in this sector and thereby contribute to significant business and export opportunities. Furthermore indicators such as high income per capita, high population density in sub(urban) areas and strong policy support create favourable economic conditions for the early and rapid diffusion of fuel cell vehicles. Except for some niche transportation applications where the Netherlands can play a pro-active role (bus fleets, ferry boats, scooters) in the adoption of fuel cells and hydrogen, the large scale deployment of a hydrogen economy should depend on the EU policy framework.

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NORWAY

Abundant energy resources and production (oil, gas and hydropower) represent in Norway key economic and business activities. Most of these resources are exported. Norway has a potential for increasing its energy production and export even more by developing innovations. In this, fuel cells and related hydrogen technologies would create new opportunities and potentials for large oil and gas and energy companies such as Statoil, Norsk Hydro and Statkraft. These actors and others (e.g. Institute for Energy Technology, SINTEF, Norwegian Defence Research Establishment FFI, Raufoss, Prototech, Kværner) are actively involved in fuel cell and hydrogen technologies. A characteristic of the RD&D activities in fuel cells and related hydrogen technologies undertaken by the industry sector is that the field is dominated by large industrial companies and institutes, but there are only few SMEs involved in these activities. As a consequence relatively large projects are favoured which account for a major portion of the resources spent on RD&D activities (Godoe *et al.,* 2003).

Norway is one of the world’s largest hydrogen producers for industrial uses, with powerful industrial players (Statoil and Norsk Hydro) having strong competences and expertise in producing, transporting and using hydrogen for industrial fertilisers where it is extensively used for ammonia production. The availability of hydrogen as a by-product creates favourable conditions for early experimentation and the creation of bridging niche markets. Norwegian companies have leading and strong technological or manufacturing positions in several technological fields such as electrolysers and reforming technology systems. Currently efforts are focusing on hydrogen storage technologies and on fuel cell enabling components such as membranes and catalysts (Godoe and Nygaard, 2006). A distinctive strength of Norway relates to electrolysers where Norsk Hydro is one of the leading equipment manufacturers. Its subsidiary Norsk Hydro Electrolysers supplies water electrolysis equipment as well as complete compression, purification, storage and gas handling systems. So far it has supplied over 300 electrolyser units for internal Norsk Hydro applications, as well as over 170 hydrogen generating units throughout the world for industrial purposes. The company plans to be a leading supplier of hydrogen filling station technology, and has already been largely responsible for the filling stations operating in Hamburg and Iceland for fuel cell bus demonstration projects (Cropper, 2004).

The investigation of hydrogen production from abundant, domestic natural gas resources has become a national priority in Norway (IEA, 2004; Godoe *et al*., 2003). Most of the large natural gas resources are in fact currently exported to Europe since most of Norway's electricity is produced in hydroelectric plants. The strategic use of these resources in Norway for more value-adding applications and to support hydrogen as an energy carrier in combination with CCS is seen as having large potentials for the energy industry and the Norwegian economy in general. Actors such as IFE, Raufoss, Prototech and Kværner are involved in activities focusing on the development of sustainable conversion technologies of natural gas into hydrogen and energy systems based on fuel cells. In the long term if centralised production becomes a viable option hydrogen export to other European countries could open up new business opportunities (e.g. infrastructure build-up, shipping, liquefaction). Norway could thus benefit from its strong capabilities in infrastructural (production and transport) technologies. Norway could in fact become - through the Nordic Pool and its trans-national positioning - a central hub for the building of a hydrogen corridor and the development of a cross border hydrogen infrastructure between Norway and central Europe. Currently, the explored natural gas is mainly exported via offshore pipelines and the onshore natural gas grid practically does not exist. The decision to use natural gas for domestic hydrogen production will have to be balanced with the economic importance of exporting natural gas.

Norway is furthermore one of the lead developers and users of CCS technologies. Given its particular interest in hydrogen production from abundant domestic natural gas resources and the possibilities to improve oil production there are significant efforts focusing on CO_2 sequestration and storage technologies. In addition to natural gas resources, Norway has access to huge areas suitable for CO_2 sequestration in the North Sea geological structures. These are estimated to have the capacity of storing all CO_2 from power production in the whole of Western Europe for some 600 years (IEA, 2004). These favorable conditions in combination with the diffusion of central SMR with CCS and increased CO_2 taxation and trade could represent an important economic and business opportunity in the long term. Several Norwegian actors are participating to major projects with other companies and research institutes at the European and international levels, one of them being the Sleipner project around the Statoil operated natural gas platform in the North Sea. The CO_2 tax scheme on energy use implemented by the Norwegian government since 1991 has been effective in encouraging companies such as Statoil and Norsk Hydro to investigate the effectiveness of capturing CO_2 and injecting it into oil wells or other geological formations.

Norway is a country already well-suited for the introduction of a renewable hydrogen economy. Almost all of Norway's electricity is produced by renewable water power and the electricity is relatively cheap compared to other countries. Although electricity production in Norway is almost entirely based on hydropower, the country has also important potentials in other renewable sources (wind in coastal areas and biomass from wood). Nevertheless, because of the hegemony of hydropower, technological and market developments in other renewable sources have been until now slower in Norway than in other Nordic countries (Finland and Sweden for biomass and wind for Denmark). Hydrogen as an energy carrier may contribute to the diversification of these sources and could create opportunities for cheap electricity for electrolysis and export to countries where this potential is constrained. Furthermore since petroleum and natural gas production remains a significant activity, it might be possible that RES/H2 systems be applied to this activity. Norwegian energy companies such as Norsk Hydro and Statkraft have launched important demonstration projects on renewable hydrogen systems. Since 2003, Norsk Hydro has established a new business unit "Renewables and Hydrogen", in order to focus its efforts on this business area.

Since electricity production for stationary applications is already based almost exclusively on renewables (hydroelectricity) which has been traditionally inexpensive and convenient, it could represent a critical brake on the wide diffusion of hydrogen and fuel cell stationary applications in Norway. Nevertheless, the difficult access to power grids in remote areas (e.g. islands) could create an opportunity for the adoption of decentralized fuel cell stationary applications in such markets. Since 2004, the public-private Utsira hydrogen-wind project, under the leadership of Norsk Hydro has demonstrated an autonomous energy system in the small island of Utsira. The project consists of an energy system that utilizes excess power from a wind turbine to produce hydrogen by electrolysing water, which is then stored and fed into fuel cells for generation of electricity when there is no wind.

The wider focus on renewables (wind, biomass, wave) because of increasing domestic consumption of electricity, the growing concern for electric power shortages, the difficulty to construct new hydroelectric power plants, combined with the liberalization of the energy market could contribute to a growing interest in adopting fuel cell and hydrogen based technologies and decentralized CHP. In fact Norway's particular topography and the widely spread population create the opportunity for the development of a decentralized (local and regional) hydrogen production system based on renewables (electrolysis and biomass gasification). Increasing electricity prices could accelerate this trend. Furthermore, this orientation could have important consequences (in terms of scale and scope economies) on the equipment and service sectors traditionally focused on the manufacturing of large plants and centralized management of infrastructures.

There is a huge potential for hydrogen and fuel cell vehicles to mitigate CO_2 emissions in the Norwegian transport sector. Expensive and already highly taxed gasoline with also high taxes on automobiles, except for the electric cars (additional incentives being no pay tolls or parking fees) could represent an important driver for the adoption of hydrogen fuelled vehicles. It is also possible that funding for a hydrogen infrastructure could be provided by the CO_2 taxes that exist in Norway since 1991. But, challenging climate conditions may render the adoption of such vehicles more difficult unless technological breakthroughs are realised. Furthermore, Norway does not have an automobile manufacturing industry and although several companies and research institutes have strong competences in PEM fuel cell materials and components, the focus has been mainly on SOFC technology for stationary applications. But Norway remains particularly active in transport related demonstration projects. Whilst participating in the European hydrogen bus demonstration project, the Norwegian HyNor project plans to build several hydrogen filling stations in southern Norway along the 540km route between Oslo and Stavanger and to operate a number of buses and cars using hydrogen as a fuel.

With respect to automotive applications, the limited size of the domestic / Nordic market may not create the high incentives required for investing in capital intensive hydrogen infrastructures unless other European countries follow similar strategies. In this context Norway might adopt a fast follower rather than a leader policy in the transport sector.

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POLAND

As a transition country and through its recent accession to the European Union, Poland's current specific energy system based mainly on coal and the adjustments necessary to modernise its aged power generating sector and comply with environmental regulations, create a whole set of opportunities but also considerable challenges. The drivers for hydrogen and fuel cell technologies in the Polish context should be envisaged in the light of the country's huge coal and lignite resources and also the fact that the deployment of these technologies will require massive investments. The current promotion schemes implemented within the EU framework for accession countries could in the short term create a unique situation for Poland to launch early actions to form the bases for future hydrogen and fuel cell mass markets.

Poland is the largest coal producer in the EU. Given the increasing demand for energy and the limited potential of renewables to respond to Europe's energy needs, Poland's huge coal reserves represent a key strategic asset for the supply security in Europe. A critical determinant for coal to become a competitive energy source is the development of clean coal technologies and cleaner coal fuels acceptable from technical, economic as well as environmental aspects. Coal based hydrogen production through gasification and CO_2 sequestration represents such a "green coal" pathway. Given the importance of the coal industry in Poland such a coal based hydrogen future would be of paramount importance for the modernisation of the coal based energy system and for economic growth through the creation of new markets and new job opportunities.

In the short term the focus on clean coal technologies gives Poland several opportunities which are related to the existing historical competences in this sector, the rational utilisation of existing infrastructure and also to the strengthening of its R&D base and partnerships both at the national, European and international levels with strong actors. The creation in 2005 of the Innovative Silesian Cluster of Clean Coal Technologies (ISCCT) is an initiative the objectives of which are on the one hand to accelerate the transformation process and sustainable development of the regional economy (based mainly on heavy industries) and where coal, coke and power industries play a highly structuring role (in terms of employment) and on the other hand to integrate the important R&D potential of industry, universities and research centres in Silesia. In the future, such a cluster could form the base for an extended trans-border partnership (including Germany, the Czech and Slovak Republics) for large scale demonstration of coal based hydrogen production and end-user applications (Czaplicka, 2006).

Furthermore the focus on clean coal based hydrogen production gives Poland the opportunity to position itself as a central actor in several European projects (e.g. European Social Fund such as in the case of ISCCT, Hypogen, HyCom, JTI), which allows Poland to gain valuable experience and knowledge for supporting the emergence of early hydrogen communities (e.g. Cieszyn, Borne Sulinowo, Krakow).

In the early deployment phases, the availability of coke oven gas gives Poland the opportunity to produce a considerable amount of hydrogen at the regional level without significantly resorting to coal or natural gas. In fact Poland's coke industry produces a significant amount of coke oven gas (which is mainly considered as no-market value, waste stream gas) containing over 50% of hydrogen. After separation and cleaning up, it could be considered as a low-cost hydrogen source to supply early markets (Rogut, 2003).

Among RES, Poland has also an important potential of biomass resources. The national RES strategy of Poland envisages increasing the share of RES in its primary consumption to 10% in 2050 for hydrogen production (HyWays, 2006). The use of biomass for hydrogen production would have not only environmental advantages but also economic and social benefits. In fact with other RES sectors, biomass would critically contribute to new sustainable jobs along the full biomass supply and utilisation chain and open up new market opportunities for the Polish agriculture sector. Projects on advanced biomass/coal co-firing plants and increasing research efforts on coal/biomass gasification at the national level and through participation on European projects (Gierulski, 2002) could also favour the use of biomass for hydrogen production.

Poland is also becoming an attractive wind energy market in Europe. While the current installed capacity is rather low, it is estimated that the installed capacity for wind power could be above 1,500 MW in 2010. The majority of newly implemented RES projects in Poland are, excepting biomass, in the wind energy and sector and most current wind farms projects are concentrated in Northern Poland, along the Baltic Sea coastline (Embassy of Canada in Poland, 2006). The region could thus in the future be an important driver for wind based H2 production demonstration projects.

Poland has a long history with respect to CHP plants. These are mainly implemented in both district heating and industrial sectors; the dominating fuel being hard coal. RES based or natural gas based CHP systems are however in their emerging phase. Except in the pulp and paper industry there are for instance up to now no referenced biomass CHP plants in Poland. The fact that currently many local district heating plants in rural municipalities and smaller towns need to be replaced represents an important opportunity to introduce innovative solutions among which hydrogen and fuel cell based CHP systems and decentralised solutions could be a promising option to replace coal-fired plants. Particularly the development of SOFC technologies, on which R&D in Poland is essentially focused would create favourable conditions for the adoption of stationary applications based on biomass and natural gas. Nevertheless the adoption of biomass as an energy source faces several challenges. The centralised energy transfer system and excess electric power may slow down the introduction of innovative systems. Further barriers to be broken are lack of experience with handling biomass at larger sites and lack of knowledge of biomass CHP practices among managers of DHP companies and decision makers from local authorities. Furthermore the possible introduction of nuclear energy after 2010 and the dominance of hard and brown coal may still represent a threat for the future deployment of CHP systems in Poland (Gierulski, 2002; Okonek, 2004).

In the automotive industry, Poland is increasingly becoming one of the most attractive countries for companies producing car components (apart from low labour costs, high qualifications of the labour force and the extended network of subcontractors explain this situation). Furthermore Poland's location in the heart of Europe creates possibilities of cooperation with other automotive plants in the neighbouring countries. Although Poland could hardly position itself as a leading country in fuel cell vehicle technologies, early markets can be developed in several agglomerations such as Krakow, Warsaw and Katowice through sustainable urban transport and urban planification policies focusing on hydrogen and fuel cells buses and taxis. The extension and development of new highway infrastructures could also create the opportunity to install and demonstrate hydrogen filling stations.

Whilst coal gasification with CCS is considered as the principal driver for a hydrogen based energy system in Poland, the risk of too narrow a focus on this option, given the uncertainties related to CCS technology (critical for the large scale adoption of coal based hydrogen production) and the long term feasibility of gasification technologies, might lead to missing shorter term market opportunities for fuel cell and hydrogen applications. The restructuring, extension and renewal of infrastructures (grid, highway, replacement of depreciated power generating assets, vehicle fleet stock) and the RES potential might be used in Poland as an opportunity to support early market creation for fuel cell and hydrogen applications (e.g. fleet vehicles, CHP with decentralised hydrogen production) adopting a more diversified approach. Such a policy would however require strong national commitment, regional development initiatives and a considerable support from the EU.

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SPAIN

The rapid economic growth of the Spanish economy which has accelerated since the country joined the EU in 1985 has contributed to a significant increase in energy use. Contrary to most of the OECD countries energy consumption in Spain rose also above GDP growth rates, meaning an increase in energy intensity. A pressing policy objective for Spain is thus to develop actions directed at decoupling GDP growth from energy use and CO_2 emissions by improving energy efficiency and focusing on less polluting resources. Furthermore, the future growth in energy demand raises issues on long term supply security since Spain's indigenous resources are limited and the country is highly dependent on imports (IEA, 2005). Fuel cells because of their high efficiency and hydrogen as an energy carrier because of the possibility to produce it through a diversified set of primary resources are thus investigated actively by Spain since the 1990's as promising options to respond to the nation's long term energy challenges.

The Spanish Plan for Scientific Research, Technological Development and Innovation supports fuel cell and hydrogen technologies as key domains to achieve energy efficiency and to increase the share of renewables in the energy mix. Spanish industries participate in numerous EU-sponsored hydrogen and fuel cell RD&D projects and there is significant participation by public research institutions and technology centres (e.g. CIEMAT, INTA, CSIC, CIDAUT, IKERLAN). Spain is also highly active in demonstration initiatives for hydrogen infrastructure and fuel cells. Investment from Spanish private companies, research and technological centres and universities for the period 2001-2005 has been approximately €50 million. Significant involvement of several industries in the development of hydrogen and fuel cell technologies along with the presence of powerful actors in the traditional energy and utility sectors (Elcogas, Endesa, Iberdrola, Repsol YPF) but also in innovative energy sectors (renewables) could confer to Spain early mover advantages through competitive positioning in some targeted technological and application domains. Nevertheless, the large scale deployment of a hydrogen based system will be highly dependent on its capability to deliver a secure and low priced energy supply to sustain the continued growth of the Spanish economy. This could be all the more challenging since the structural funds that Spain received in the past and that have facilitated Spain's economic growth and infrastructural development will progressively be reduced.

From the perspective of domestic energy resources, the most important driver for the adoption of hydrogen as an energy carrier is RES. The geography and climate of Spain explain the great potential of RES for clean production of hydrogen in the future. Currently Spain's installed wind-power capacity makes it the second-largest wind-energy producer in the world (around 9000 MW) after Germany (16,000 MW), and Spanish companies - both turbine manufacturers (Gamesa Eólica) and wind farm developers and operators (Iberdrola and Acciona Energia) - have acquired a world leading position in the global wind-power market (Graber, 2006). Spain continues to have very ambitious targets in wind energy. The development of hydrogen production and storage technologies is in this context considered as a key facilitator for wind to become a significant source of energy by solving some of the key issues related to the intermittent nature of wind energy and the complementary relationships between electricity and hydrogen networks. Within the European RESH2 project Spain currently focuses on the exploitation of wind energy for the production, storage and use of hydrogen on the Canary Islands.

Similar paths are also envisaged for solar energy and biomass. As for wind turbines, Spain has a world class photovoltaics industry. It has a strong manufacturing and exporting base that includes manufacturers of cells, modules, inverters and system components. The market for this energy, benefiting from government support and legislation is expected to grow significantly in the coming decade and could attract significant investments from the private industry including power utilities such as Endesa. With respect to hydrogen, INTA has gained experience demonstrating solar hydrogen production and is investigating the combination of hydrogen PEM fuel cells with photovoltaic powering systems used in telecom applications. Hynergreen, a subsidiary of Abengoa is also working in the feasibility of renewable hydrogen production by means of solar thermal power, using solar concentration and chemical thermocycles (ICEX, 2006).

Spain has also an important potential in biomass from the agricultural sector for electricity production and bio-fuels in the short-mid terms. Nevertheless electrical and thermal applications have been much slower to develop than initially targeted. Overcoming supply bottlenecks will be in the future key to accelerating the adoption of biomass based energies.

Several R&D projects are focusing on the production of hydrogen from waste biomass sources. Particularly Abengoa Bioenergy, the second largest bio-fuels producer in the world, is developing a bioethanol-to-hydrogen conversion facility using fermentation processes. Additionally several research centres are investigating biomass gasification and pyrolysis processes.

Though RES potential will represent a critical driver for the hydrogen economy, Spain also investigates the possibility to produce hydrogen from fossil fuels. Coal is Spain’s most abundant indigenous energy source and is therefore considered as a promising candidate for hydrogen production. Although currently the share of coal in energy production is decreasing (in favour of natural gas), the development of efficient and clean coal technologies is expected to increase its importance in the future. The coal industry plays in fact in several northern regions an important economic role and is a major employment provider. Spain has already significant experience with clean coal technologies. Elcogas was one of the first European companies to operate an Integrated Gasification Combined Cycle (IGCC) plant at Puertollano producing power and hydrogen for industrial uses. The company investigates advanced IGCC concepts with and without CO_2 sequestration for efficient hydrogen supply in combination with high temperature fuel cells (e.g. EU MIGREYD project). Along with advanced coal mining process (the difficult to mine Spanish coal deposits makes domestic production currently uncompetitive compared to coal imports), the development of innovative IGCC technologies could turn coal into an economic and domestic source of central hydrogen production in Spain.

Similar to coal, the share of nuclear reactors in Spain has progressively dropped in electricity production in favour of natural gas and renewable (IEA, 2005). Nevertheless nuclear power continues to play a vital role in Spain in terms of security of supply and CO_2 emissions reduction. The Spanish nuclear industry and major electricity generating companies (Endesa, Iberdrola and Union Fenosa) possess significant expertise in the operation of nuclear power plants. This provides a favourable background for future nuclear power based processes such as high temperature electrolysis and thermo-chemical cycles to be considered as promising hydrogen production options. Nevertheless the governments’ commitment to phase-out nuclear energy in the medium-term without precluding it as an option for future capacity needs, creates an uncertain and ambiguous environment which could be all the more detrimental in a competitive market because of the economic risks associated with nuclear power due to their long construction lead times and high capital costs.

Spain has experienced since 1993 the fastest growing natural gas market within Europe and this is expected to continue in the coming years to improve security of electricity supply and CO_2 emissions. The major driver for this increase has been combined-cycle gas turbine (CCGT) power stations built by incumbent companies (e.g. Gas Natural) but also often by several new market entrants within a liberalized gas market. Despite the rapid growth of its gas infrastructure and the introduction of LNG plants, the natural gas network is still less developed than that of other countries (e.g. Germany and France) and should require substantial investments in gas infrastructure (transmission networks, LNG terminals, storage facilities). Furthermore, the growing demand will have to be satisfied by increasing imports of natural gas (which is already exclusively imported) and could in the future weaken supply security unless cross border interconnections between Spain and Europe are expanded and supply sources are diversified (IEA, 2005). Though natural gas for hydrogen production is envisaged as a possible option (mainly through on site SMR), the potential for natural gas based hydrogen could remain limited because of the dominant use of natural gas in electricity production and due to the above mentioned factors.

Improving energy efficiency and intensity in all sectors is considered as a central step to mitigate CO_2 emissions and to contribute to supply security in Spain. This objective is an important driver for the development of fuel cells.

Promising markets for fuel cell/hydrogen based CHP applications are the industrial and to - a lesser degree - the tertiary/household/institutional sectors where important energy efficiency potentials exist. Spain has already a significant number of CHP plants in operation which are mainly used in the industrial sectors. Although CHP installations benefit from subsidies for electricity generation, this support does not currently take into consideration minimum efficiency requirements. A restricted support to plants that improve energy efficiency would in the future create a more favourable environment for fuel cell CHP plants. Although the electricity consumption has significantly increased in Spain due to improved living standards, the mild Spanish climate reduces the requirements for district heating. Nevertheless the increasing demand for cooling services might be an opportunity for fuel cell technologies to penetrate the Spanish air conditioning and district cooling markets. Several stationary fuel cell demonstration projects have already been launched in Spain for industrial (MCFC plant sited near Madrid and constructed by the Spanish/Italian consortium including Iberdrola, Endesa, Babcock & Wilcox, Ansaldo Ricerche, ENEA and ITAE; MCFC plant operation by IZAR) and residential applications using PEM (INTA and CIDAUT; CARTIF technological Centre). Though strong uncertainties remain on the technologies and fuels that will dominate the stationary market in the future (natural gas, wind, photovoltaics, fuel cells, hydrogen) strong complementarities between these options may favour their joint development (IEA, 2004; Garcia-Conde, 2003).

Transport is another sector in which demand growth (car ownership, size of cars) and CO_2 emissions have been exceptionally high in Spain (+40% from 1990) compared to other OECD countries. This has also contributed to urban air pollution concerns. The transport sector is the central focus of both the *Energy Saving and Efficiency Strategy in Spain 2004-2012* (E4) and the vehicle renovation programme PREVER. These initiatives might be used to support initially the introduction of fuel cell and hydrogen fleet vehicles and buses in cities to improve local air quality. Currently, the relatively low taxation of vehicle fuels and the absence of fiscal incentives to purchase fuel efficient cars (vehicle registration tax being only linked to engine size and not to fuel efficiency) may slow down the renewal of the existing stock of old vehicles. A differentiated use of fiscal instruments would thus be critical to speed up the retirement of old vehicles and the adoption of fuel efficient and clean vehicles such as fuel cells.

Spain has been very actively involved in demonstration projects for transport applications. Important market introduction initiatives have been taken by Madrid and Barcelona urban transport authorities, which manage the demonstration of public buses running on hydrogen in Madrid and Barcelona. This initiative, implemented within the European Framework Programme CUTE is also supported by the Spanish government through its Technical Investigation Promotion Programme with the involvement of companies such as Natural Gas and Repsol YPF.

Fuel cells are also becoming a strategic innovation field for the strong export oriented car industry in Spain. Vehicle component manufacturers are working on fuel cell component manufacturing and integration as a possible new business development and an industry of manufacturing MEAs and PEM fuel cell stacks is progressively emerging (e.g. David Fuel Cell Components, Ajusa) (Castro, 2005).

Experience gained through European demonstration activities in highly populated areas (Barcelona and Madrid) and favourable weather and geographical conditions for decentralised energy production from renewables (e.g. Navarra, Zaragoza) may be valued by Spain and its committed regions as opportunities to play a critical role in the early adoption phases of mobile and stationary applications. In this context factors that have contributed to the success of the wind energy industry in Spain and internationally (e.g. strong governmental support at both the central and regional levels, investments by major utilities, social acceptance, and strong innovative entrepreneurship) may also contribute to Spain's competitive advantage in targeted fuel cell and hydrogen related technological and application domains.

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UNITED KINGDOM

In recent years several reports commissioned by the Department of Trade and Industry stressed the role hydrogen energy and fuel cells could play in contributing to competitive CO_2 reductions and supply security in the UK, along with supporting innovation and economic growth. These reports (E4Tech, 2004; Fuel Cells UK, 2003 and 2005) and other studies (Fuel Cell Today, 2003) provide useful information on the international competitiveness of the UK in the hydrogen economy and the capabilities of actors and market opportunities for hydrogen and fuel cell applications.

Among the areas concerning hydrogen energy production, the UK has one of the best potential (with France) in wind resources (particularly off-shore wind). This resource base is stronger than in Germany. The UK can benefit from this position and may become the leader in the integration of renewable hydrogen production systems (e.g. on islands), though this may also involve components and systems sourced outside the UK (e.g. electrolysers where Germany and particularly Norway have strong system supply competences) as development of early commercial electrolysers is mostly done outside the UK. But the UK is in a good position to lead in some areas as a result of specific capabilities in materials (e.g. membranes) and electrochemistry R&D (E4Tech, 2004). Transport applications would in the long term also open up major new markets for RES, including export opportunities both for system engineering capabilities and for hydrogen.

Particularly the presence of powerful oil and gas sectors and industrial gas handling capabilities, the existence of large scale SMR and liquefaction plants and the extensive natural gas pipeline infrastructure constitute critical assets in the early phases of hydrogen deployment. With respect to natural gas reformers the UK is also particularly well positioned in terms of patent activities. Opportunities could build on the UK strengths in industrial hydrogen facilities to explore the creation of integrated technologies/services for export. Although, the use of natural gas in the short term could help to adopt a low risk investment approach by using existing assets, in the long term the sustainability of this approach will be confronted with CCS feasibility and should also take into consideration impacts on import dependency, security and economic risk (higher natural gas prices) issues. The UK could also in the long run strongly benefit from business opportunities with respect to the CO_2 storage potential in the North Sea.

UK's position in biomass and coal gasification technologies is rather low. There is no explicit policy related to biomass use for hydrogen. There is also very little experience with operation of large scale biomass gasification plants, and none with biomass gasification to hydrogen. Although the UK has some research capabilities in this area (thermal processes) the main biomass gasification developers and research activities in Europe are outside UK (Germany, Finland, the Netherlands). In the case of coal gasification a UK project with CCS is under preparation with Progressive Energy, BOC and Centrica in the Teeside region where major international producers of hydrogen and other hydrogen related industries are traditionally installed. But the majority of technology development on coal gasification and CCS is currently outside the UK (e.g. Norway) (E4Tech, 2004).

Concerning fuel cells, the level of disclosed public spending in the UK compares relatively poorly with many other countries (UK Fuel Cells, 2004). Moreover, the UK has around 15 fuel cell systems installed; a very small fraction of the total number of complete systems built and operated worldwide (6,800). As far as international patent records are concerned, around 5,000 patents relating to fuel cells had been granted worldwide by 2003, of which less than 80 belonged to UK companies. By contrast almost 400 belonged to German organisations and 1,900 to Japanese ones. According to Fuel Cell Today (2003) fuel cell businesses already support over 850 jobs in the UK with around half of these employed by the ten most active organisations.

In spite of the UK's disappointing share of fuel cell patents and public support level, its fuel cell industry does have specific strengths and the UK has a high number of organisations that are active in fuel cells. It has also a number of world-class component and system developers in PEM fuel cells and fuel processors. These include Johnson Matthey, Rolls-Royce, Intelligent Energy Accentus, Eneco and Imperial College. The UK has the second largest fuel cell emerging industry in Europe. It also has a good chance of becoming a world player in fuel cells: the technology is still immature and given the right support, the UK could regain a significant position (Fuel Cells UK, 2003).

Stationary applications are considered to be a key early market for fuel cells in the UK (Fuel Cells UK, 2005). The UK is considered ahead of many of its counterparts in terms of de-regulation of stationary power, potentially providing greater flexibility for novel solutions. Furthermore, the UK has an extensive natural gas network, providing an established fuel infrastructure for fuel cells able to run on natural gas.

Distributed generation is of particular interest, with drivers such as increased demand for electricity, the need to replace existing generating capacity infrastructure and infrastructure investment risk. The UK Government's 2003 Energy White Paper reiterated a commitment to achieve a target of 10GWe of good quality CHP capacity by 2010. The evolution from a centralised to a distributed power generation infrastructure brings with it many challenges. To address these challenges, OFGEM and the DTI have established the Distributed Generation Coordinating Group (DGCG) (Fuel cells UK, 2005).

In Scotland, there is particular interest in the potential role of fuel cells as a buffer for intermittent renewables. This has yet to be demonstrated, and is likely to be of most benefit under specific conditions, such as remote island communities which currently need to import power.

Balanced against the positive features of the UK, there are though a number of uncertainties and barriers (Fuel Cells UK, 2005):

• At this stage there appears to be little enthusiasm among utilities to explore the potential of fuel cells (this contrasts with Germany);

• The low differential between electricity and gas prices makes the economic case less strong than it might otherwise have been;

• Current good electricity grid coverage means that, in comparison with some other countries, there is little demand for remote non-grid connected applications.

The picture on the transport side is less promising than that relating to stationary applications. The UK is generally considered to be lacking in specific strengths compared with other countries, which are likely to attract deployment of fuel cell vehicles. Furthermore, unlike other countries, public financial incentives to demonstrate fuel cell vehicles have been until now limited (Fuel Cells UK, 2005). However, the UK has been successful in participating in the European CUTE Project, which allowed the deployment of three fuel cell powered buses, together with refuelling facilities, in London.

Furthermore one may notice that UK's strengths in specialist applications, for example in offshore or military uses but also in high value markets, may create in the short term a platform for the UK development of hydrogen powered niche products (E4Tech, 2004).

Among demand side factors, regions could be key drivers in the early adoption of fuel cell and hydrogen applications (Hodson and Marvin, 2005). Almost all of the installations to date have been initiated in the UK by the regions, and there is enthusiasm to create fuel cell and hydrogen "clusters" where this is in line with regional objectives (local carbon reduction and economic regeneration objectives). Several regions are particularly active in fuel cells and hydrogen (London, South Wales, Shetland Isle, Aberdeenshire, Teeside, Midlands)

The city of London and other densely populated and urbanised regions could act as early demonstrators and early adopters. Factors which might have a positive demand side role include policy measures to favour very low or zero emission vehicles and public procurement commitments (bus fleets). The high fuel taxes in the UK (the highest in Europe) could also be an important driver in transport applications. *Transport for London*, for example has already exempted fuel cell vehicles from its congestion charge scheme.

Another region attracting much attention and efforts is Teeside (Roddy, 2004). The Tees Valley Hydrogen Project, which started in 2001, aims to make the Tees Valley a centre for hydrogen and fuel cell development and commercialisation. It has gained widespread support from industry and academia, and is initiating many projects. The Tees Valley has the unique advantage in the UK of combining an industrial hydrogen production and distribution infrastructure; an underground hydrogen storage facility; the skills, resources and facilities for hydrogen-related technology RD&D available from the chemicals, steel and heavy engineering industries; renewable energy expertise and proposals for on and off-shore generating capacity; and a regional and local regeneration agenda with the possibility of demonstrating CHP applications.

The UK’s membership of the European Union could also be a significant factor in the development of and commitment to projects (such as Lighthouse projects) emerging through the Hydrogen and Fuel Cell Technology Platform.

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CONCLUSION

The analysis of opportunities and challenges for hydrogen and fuel cells shows that the different Member-States participating to HyWays consider these technologies as a key element of their long term energy strategy and policy. Nevertheless a closer look into the activities and strategies pursued by each country reveals similarities but also noticeable differences with respect to the drivers that motivate the transition towards hydrogen as an energy vector.

If diversification of energy sources, mitigation of CO_2 emissions and economic growth are the three common denominators to all European countries, the modalities and the visions that will support such a transition depends and should in the future determine the adoption paths of these technologies. Besides technological leadership, indicators such as high income per capita, high population density, infrastructural development modes and strong policy support could have an important impact on the speed of deployment of these technologies in each country in the earlier phases.

In the following we summarise for each country the main lessons learnt:

Finland: With vast biomass resources and the importance of its forest industry infrastructure Finland has a great potential to become a lead adopter and exporter of bio-fuels and biomass gasifier technologies in fuel cell and hydrogen related applications. Finland could also benefit from specific but global business opportunities related to fuel cell components / product systems and its technical competences in distributed generation of CHP. But, the limited size of the domestic / Nordic market may not support the high incentives required for investing in capital-intensive H_2 infrastructures unless other countries follow similar strategies. In this context Finland might adopt a fast follower rather than a lead market policy. For stationary applications, cheap and extensive district heating and CHP based on biomass along with the lack of an extensive gas pipeline network could make, in short-mid terms, hydrogen a less attractive fuel for CHP. Although in Finland an important potential for H_2&FC vehicles exists (high vehicle purchase prices, CO_2 taxes), challenging climate conditions (similar situation in

Norway) may hinder the adoption of such vehicles unless technological breakthroughs are realised.

France: The availability both of an extensive natural gas infrastructure and of hydrogen as a by-product create in France favourable business conditions in the early phases of hydrogen related applications. France possesses strong expertise in the design, building and operation of energy infrastructures and hydrogen use in industrial processes. Hydrogen infrastructure built-up would thus create critical and long term opportunities for exporting large scale project management and engineering competences. Large and competitive wind energy potential, relatively low electricity prices and existing operational competences could make electrolysis an important option for hydrogen production and storage. But the dominant position of nuclear energy and infrastructural constraints could represent a barrier to the rapid deployment of business opportunities related to wind energy. Hydrogen production from biomass is also an important business opportunity for the French agricultural sector which could have pervasive effects in several sectors and contribute to the economic development of several regions. In the long term, the development of new generation nuclear reactors could also confer to France a significant competitive advantage in hydrogen production and export. Market share of decentralised fuel cell and hydrogen CHP applications can be expected in the short mid-term to be low given the highly centralised structure of the French energy system and the reliance on CO_2 free nuclear electricity production. Being a large automotive sector country, the positioning strategy of the French car industry with respect to fuel cell vehicles should have important impacts in terms of its global competitiveness and employment prospects. Although indicators do not currently position the French automotive sector as a leading country in fuel cell development (compared to Germany), the will to support the emergence of a national fuel cell industry becomes increasingly strong.

Germany: Potential markets for fuel cells and hydrogen lie in areas where Germany has distinctive competences; namely automotive, chemical, mechanical and engineering industries. Germany's leading position in these domains can foster its global competitive advantage and increase its export opportunities in fuel cell and hydrogen related applications. Germany has in fact significant operational and technological experience in hydrogen production related technologies such as in steam reforming, electrolysis and coal/biomass gasification. In the mid and long term particularly gasification technologies could be an important economic and business option for Germany because of its important coal and biomass resources. Although endowed with a large potential in wind power and a strong wind turbine industry, high electricity prices and end-use competition for renewables may be in the short term a barrier for the electrolysis option. On the other hand, due to significant policy support for renewables, hydrogen could be in the mid-long term a critical driver for the further expansion of these resources in Germany. With respect to stationary applications Germany has several power plant producers and big utilities strongly involved in fuel cell development and commercialisation activities. Support for more efficient heat and power technologies, the renewal perspectives of an important share of power plants, the availability of an extensive natural gas distribution system could be driving forces for the early introduction of stationary fuel cells in the energy mix. In addition, German companies see very good export opportunities in Europe and overseas for these applications. Some regions because of their strong energy based or automotive industries as well as other relevant economic indicators (e.g. availability of by-product hydrogen, important demonstration activities, population density, fast renewal of passenger cars) could become leading regions in the adoption of fuel cells in automotive and stationary applications.

Greece: A distinctive feature of Greece is its large number of populated islands. The combination of renewables (wind, biomass, solar) and hydrogen production using electrolysis could be a promising option and may offer export opportunities in the long term. Taking into account the fact that almost half of the Greek population is concentrated in the Athens and Salonika regions, these will play a critical role in the early adoption of transport / stationary applications and the development of the hydrogen infrastructure. The energy demand of these central regions could be an opportunity to better exploit the potential domestic sources (lignite, renewebles) available in other regions and to better connect them to the main economic centres of the country. The need for low electricity cost, the specific socio-economic conditions to different regions, the necessary investments in natural gas and electricity grid infrastructures may however pose several challenges to the wider adoption of fuel cell and hydrogen technologies and should require strong policy commitment. Furthermore, focusing its long term strategy on RES based hydrogen production and more generally on regional sources will have not only environmental benefits but may create new business and job opportunities in these regions.

Italy: Significant RES potentials (biomass, wind and more particularly solar energy) could in the long term create important economic opportunities in different Italian regions (e.g. solar energy in the South). Italy has a lead market potential for hydrogen related production technologies due to the strengths and export orientation of its machinery and equipment sector. For the Italian automotive production sector, fuel cell vehicles represent a critical opportunity in terms of industrial and technological competitiveness. Italy has built in this domain a strong expertise and research background. Several demonstration programmes both in the stationary and mobile applications are supported in several regions. Compared with leading competitors Italy might thus position as a fast follower in hydrogen vehicle and fuel cell stack production. But, loosing market shares due to late market entry could mean drastic job losses and GDP losses in this sector. High population density in metropolitan areas combined with local/regional policy commitment to reduce air pollution in large cities could represent a critical driver for hydrogen infrastructure built up and hydrogen use in the Italian transport sector. Other indicators (e.g. high passenger car age) may in the short term be a barrier for the rapid adoption unless appropriate tax exemptions for CO_2 free vehicles are provided. Furthermore since an increasing share of stationary applications progressively use natural gas there might be a lack of interest, in the short and mid-term, to switch to hydrogen in this market segment.

The Netherlands: Use of natural gas is strongly intertwined with all kinds of economic activities in the Netherlands and companies' interest in gas production and distribution are large. The natural gas grid and available knowledge on natural gas distribution thus offer strong business opportunities for hydrogen production and applications. The critical position of Rotterdam as an energy hub and the already existing hydrogen production facilities can make the region a centre for hydrogen production in Europe. Furthermore, the Netherlands seems to be in a good competitive position, especially for hydrogen technologies with a focus on partial oxidation but also strong competences in coal and biomass gasification technologies. The Netherlands has additionally significant potential for CO_2 storage. Provided, CCS becomes a viable and accepted option this could represent an important economic and business opportunity in the long term with the diffusion of central SMR and increased CO_2 taxation and trade. With respect to end-use applications, the Netherlands is one of the leading countries in the use of CHP plants in Europe. Fuel cells and hydrogen technologies along with the liberalisation of energy markets could open up new market segments for CHP. A barrier to the wide diffusion of fuel cells in stationary applications might however be the already high share of gas-fed CHP units. Although the Netherlands is not an automotive country, fuel cell related technologies are actively supported by many companies and could in the future lead to a competitive position in this sector and thereby contribute to significant business and export opportunities. Furthermore indicators such as passenger car age, income per capita, high population density and strong policy support create favourable economic conditions for the early and rapid diffusion of fuel cell vehicles.

Norway: As a "non automotive" country Norway's efforts are focused on the development of hydrogen technologies. Norwegian firms and research institutes are concentrating a significant share of their research and patent activities on the field of hydrogen production. Norwegian companies have leading and strong technological / manufacturing positions in several technological fields such as electrolysers, reforming technology systems, hydrogen storage technologies and also in some enabling components such as membranes. Norway is currently one of the world's largest hydrogen producers, with powerful industrial players having strong competences and expertise in producing, transporting and using hydrogen. Norway is furthermore one of the lead developers and users of CCS technologies. The favorable conditions for CO_2 capture and storage in the North Sea geological structures in combination with the diffusion of central SMR with CCS and increased CO_2 taxation and trade could also represent an important economic and business opportunity in the long term. Additional economic wins could be created through the export of hydrogen with new business opportunities (e.g. infrastructure build-up, shipping, liquefaction plants, renewable hydrogen export based on cheap electricity). However due to economy of scale effects of hydrogen corridors these opportunities may be of interest when a significant hydrogen demand level is achieved. Norway's interests in fuel cells is oriented towards stationary applications to provide power to a widely scattered population where access to power grids can be difficult. But cheap and clean hydro electricity might still be a barrier to the wide adoption of these applications. But, there is a huge potential for hydrogen and fuel cell vehicles to mitigate CO_2 emissions in the Norwegian transport sector. High vehicle purchase and CO_2 taxes and tax exemption policies already in place could represent an important driver for the adoption of hydrogen fuelled vehicles. But, as for Finland, challenging climate conditions, "small country" characteristics may lead Norway to adopt a fast follower rather than a leader policy.

Poland: Poland has the largest coal reserves and is the largest coal producer in the EU. Investments in innovative clean coal technologies for hydrogen production would open up new markets and create new jobs opportunities in hydrogen related industries in the medium and long term and would enhance the competitiveness of the Polish economy. This advantages should however be balanced against the uncertainties related to CCS technology which could be the critical driver in the large scale adoption of coal based hydrogen production. Hydrogen production from biomass and other RES could also create important economic and commercial opportunities particularly in the Polish agriculture sector with respect to employment. The restructuring, extension and renewal of infrastructures (grid, highway, replacement of depreciated power generating assets, vehicle stock) might be used in Poland as drivers to support early market creation for fuel cell and hydrogen applications (e.g. fleet vehicles, CHP with decentralised hydrogen production). Such a policy would however require strong national commitment, significant support for regional development initiatives and a considerable backing from the EU.

Spain: Spain has a strong wind energy industry for which hydrogen as an energy storage medium would lead to better utilising wind resources and to new business opportunities. A similar path could in the longer term be envisaged for solar energy. Likewise, fuel cell component manufacturing and integration capabilities may contribute to new business developments in the strong export oriented Spanish vehicle component manufacturing sector. Experience gained through European demonstration activities in highly populated regions and favourable weather and geographical conditions for decentralised energy production from renewables may be valued by Spain as opportunities to play a critical role in the early adoption phases of mobile and stationary applications. Significant involvement of several industries in the development of hydrogen and fuel cell technologies along with the presence of powerful actors in the energy and utility sectors could confer to Spain early mover advantages through competitive positioning in some targeted technological and application domains.

United-Kingdom: UK's oil and gas industry has significant expertise in fuel infrastructure planning, bulk hydrogen handling and operating large scale energy related production, storage and transport equipments. Additionally, the country could in the long term benefit from business opportunities with respect to the CO_2 storage potential in the North Sea. But compared to some of the leading Member States, the UK has a limited position in hydrogen production technologies and equipments such as electrolysers and gasifiers. Nevertheless**,** the UK has a strong competitive potential in some key areas such as materials and fuel cell components. The UK may also benefit from its excellent wind energy sources and build upon this position to develop distinctive competences on renewable hydrogen production systems. Furthermore UK's strengths in specialist applications, for example in offshore or military uses but also in high value markets may create in the short term a platform for the development of hydrogen powered niche products. But the UK has until now a relatively limited position in fuel cell vehicle development and in stationary fuel cell integration. Among demand side factors, regional initiatives (benefiting from the existing industrial base and expertise such as in Teeside, focusing on local air problems in densely populated and urbanised regions, supporting local regeneration of economic activities) could be key drivers in the early adoption of fuel cell and hydrogen applications. High fuel taxes (the highest in Europe) could also accelerate the adoption of innovative clean transport technologies such as fuel cells.