Nordic H₂ Energy Foresight

Building the Nordic Research and Innovation Area in Hydrogen

Summary Report

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Abbreviations

APU Auxiliary Power Unit
CHP Combined Heat and Power
FC Fuel Cell
IEA International Energy Agency
ICE Internal Combustion Engine
IPHE International Partnership for Hydrogen Economy
MW Mega Watt
NG Natural Gas
PEMFC Proton Exchange Membrane Fuel Cell
R&D Research and Development
SOFC Solid Oxide Fuel Cell
UPS Uninterruptible Power Supply

Executive Summary

The Nordic Hydrogen Energy Foresight was launched in January 2003 by 16 partners from academia, industry, energy companies and associations from all five Nordic countries. A wide range of additional Nordic and European experts from research, industry and governments have participated in the various steps of the foresight process.

The aim of the foresight is to provide decision support for companies and research institutes in defining R&D priorities and to assist governmental decision-makers in making effective framework policies for the introduction of hydrogen energy. The foresight exercise also provides a means for developing Nordic networks to gain critical mass in a wider international context. The overall intention is to find long-term and promising ways for Nordic stakeholders of exploiting hydrogen in the drive to meet the 3E's: energy security, economic growth and environmental protection. The diversity among the Nordic countries as well as established political and economic collaboration in research, innovation and energy represent some unique and interesting opportunities for exploring different pathways to the hydrogen economy. By setting ambitious targets for hydrogen in the Nordic energy system, we can best examine the future societal options and industrial opportunities available when being in the frontline.

Interaction between research, industry and government, and combination of judgemental and formal procedures, are essential features of the Nordic H_2 Energy Foresight. The foresight process includes a series of pre-structured interactive workshops (scenario workshop, vision workshop, technology roadmapping workshop, and action workshop), supported by systems analysis and assessment of technical developments.

Three external scenarios set the context for envisioning the introduction of hydrogen in the Nordic energy systems: B – Big Business is Back, E – Energy Entrepreneurs and Smart Policies and P – Primacy of Politics. These were combined with three alternative second-period developments ('hydrocarbon security-of-supply problems', 'undisputable CO_2 problems', 'a smooth path to the future'). Eventually, big visions for the hydrogen share of the total Nordic energy system in 2030 were made, ranging from 6-18% of the total energy consumption, except for industrial consumption.

Key technologies were prioritised by Nordic and international experts. The technology areas considered were:

- Hydrogen production based on reforming of natural gas, electrolysis with wind power and biomass gasification;
- Transport applications focused on hydrogen city buses and new private cars. Nordic opportunities might be in hydrogen fuel cell/electric drives for small specialised vehicles (fork-lifters, golf cars), storage of H_2 as methane or methanol for transport and methane driven fuel cell/electric engines for ships. Infrastructure equipment may also become a Nordic opportunity;
- Stationary applications focused on fuel cell systems for domestic and decentralised heat/power production and APU/UPS systems based on fuel cells and hydrogen (or similar fuels).

Roadmaps were developed for production, transport applications and stationary use of hydrogen and fuel cells. These roadmaps indicate the development of key technologies, Nordic equipment market opportunities and sizes as well as Nordic energy market opportunities and sizes from the present to 2030.

Action recommendations. The Nordic H_2 Energy Foresight suggests that the Nordic actors should take an active role in promoting the successful introduction of hydrogen energy

and thereby exploit the anticipated business opportunities in this area.

These **short and longer term business opportunities** are presented in the table.

Coordinated actions are needed to ensure that the long-term investments in hydrogen energy technology will contribute to common welfare in the form of more sustainable energy systems and new profitable businesses.

Recommendations for a Nordic **action strategy** for the Nordic research and innovation area in hydrogen are:

- Conduct coherent **information and awareness campaigns on hydrogen economy and relevant innovation.** The campaigns should be directed to decision-makers and the wider public.

- Closer **Nordic co-operation on research and development** in strategically defined key areas of hydrogen and fuel cell technologies where Nordic research and Nordic industry have the best opportunities. Publicly funded research should focus on areas where industry (of today or tomorrow) can utilise the results.

	Production and Transmission	**Transport**	**Stationary Use**
Equipment Market	• Natural gas reformers • Equipment for gasification of biomass (or biomass to biofuel) • Equipment and systems technology to system integrate wind power with H_2 production • Electrolysers • Infrastructure equipment; automation, compressors, pipelines In the longer term • Equipment for long distance transport of liquid H_2 (cryogenic tanks, etc.) • Maybe CO_2 sequestration equipment	• Special vehicles • Infrastructure equipment for hydrogen in transport sector • APU systems for the transport sector (ships and trucks) – this links to similar systems for stationary use. In the longer term • Marine use of hydrogen and fuel cells	• FC and FC systems for domestic CHP • FC-based power back up and APU units • FC APU units for remote power supply • FC-based decentralised CHP systems
Energy markets	• Natural gas • Biomass for energy • Electricity from wind • Other renewable energy sources In the longer term • Operation of a H_2 Nord Pool and trading with H_2 • Ship transport of liquid H_2	• New fuelling infrastructure In the longer term • Inclusion of transport and fuel production into emission trading after 2012.	• Stationary FC/H_2 systems as a regulatory technology in energy systems with fluctuating production (i.e. wind power)

- Promote innovation in Nordic industry through **demonstration projects, lighthouse projects and stimulation of niche markets** – forming an early home market for Nordic industry.

- **International co-operation.** Improve the Nordic countries' impact on the international agenda setting.

It has not been possible to address a number of topics and there are still depending challenges and problems. These concern the prospects of hydrogen compared to other energy carriers and the difficulty in making detailed technology roadmaps in a technological area that is undergoing rapid change and is subject to competing alternative technologies. Further analysis is also needed to properly analyse Nordic niches within the automotive sector and the consumer electronics industry, as well as more detailed systems analysis.

Introduction

Interest in the hydrogen economy has grown rapidly in recent years. Governments, industry and the capital markets have seized upon the promise hydrogen may offer in meeting the two main energy challenges: the need for security of supplies and climate change. These challenges require the development of new, highly efficient energy technologies that are either carbon neutral or low emitting technologies. Hydrogen as an energy carrier may contribute meeting the challenges by providing the flexibility in the energy system necessary for the high penetration of intermittent renewable sources and for a link to the transport sector.

Hydrogen is a clean, flexible energy carrier obtainable from fossil, renewable and nuclear energy sources. Hydrogen can be used in direct combustion to power vehicles. Partnered with fuel cells, it can provide electricity and heat for distributed generation in industrial and residential sectors as well as in transport sector. Its potential for turning intermittent renewable energies such as wind and solar power into a storable energy commodity makes it attractive for the future sustainable energy system in Europe.

The development of a hydrogen economy, with hydrogen produced from renewable energy sources, is a long-term objective of the European research and development agenda. However, there is still a debate about the various options and transition paths to make the hydrogen economy a reality in the long run. Since the 1970's, the EU has supported R&D in the area of hydrogen and fuel cell technologies. Funding has grown from 8 million € in the Second Framework Programme (1988–1992) to more than 130 million € in the Fifth Framework Programme (1999-2002) (EU Commission, 2003a). In the Sixth Framework Programme (2003-2006), the budget for sustainable development and renewable energies has increased to 2.1 billion €, of which 250-300 million € is expected to be earmarked to hydrogen and fuel cell related research and development over a four-year period. With the launch of two hydrogen Quick start Growth Initiatives in November 2003 – Hypogen and HyCom – with an indicative budget of 2.8 billion € over 10 years, the EU further aims at intensifying and aligning its R&D efforts with national and regional R&D programmes, science communities and industry.

The Northern European countries – Denmark, Finland, Iceland, Norway, and Sweden and the home rule governments of Greenland, the Faroe Islands and Åland – have a long tradition of co-operation within research, education, and innovation as well as within energy supply. This is a solid foundation for concerted action towards knowledge-sharing and sustainable developments, but does not suffice for building strategic intelligence, synergy and critical masses into Nordic R&D-activities to realise the business potentials of the hydrogen economy. The Nordic H_2 Energy Foresight aims at aligning research and development efforts at regional level – between the Nordic countries themselves and between the Nordic countries and the European Research Area. It is, thus, a middle-up contribution of smaller EU member and associated states to overcome the fragmentation and duplication of research efforts and to help create the European Research Area in the field of hydrogen and fuel cell technologies.

This report gives account of the Nordic H_2 Energy Foresight. A short description of the Nordic knowledge region is made, comprising the overall competitiveness of the Nordic countries, the research and development in new technologies, including hydrogen and fuel cells, and the diverse but interlinked energy systems. Then, focus shifts to the objectives and design of the foresight exercise. The main part reports on the scenarios, roadmaps and suggestions for action produced during the process as well as implications of the envisioned future development in terms of costs and emissions. Finally, the main conclusions and recommendations are made.

The Nordic Knowledge Region

Nordic co-operation rests on a long and shared history, which for centuries has influenced the political, economic and cultural ties among the Nordic countries. These ties foster shared values – values that are inherent in the Nordic welfare states – with their stable and well-functioning democratic institutions, highly developed economic sectors, and safe communities. Following the foundation of the Nordic Council (1952) and the Nordic Council of Ministers (1971), collaboration has developed in a range of areas, including a common labour market, a passport union, and research and educational activities.

The Nordic region has consolidated its participation in the European co-operation. Denmark, Finland and Sweden are members of the European Union while Iceland and Norway are associated members. Since 2001, the Nordic countries have been seeking to strengthen co-operation between the Nordic EU members and at the same time involve the two Nordic associated countries in consultation and knowledge-sharing in order to signal a more pro-active joint EU-line. The aim is to maintain and develop Nordic influence on European co-operation at a time of EU expansion from 15 to 25 member states (Nordic Council of Ministers, 2003a: 23). A joint Nordic regional EU approach is not meant to be a closed Nordic bloc policy, but rather to bring Nordic co-operation closer to the EU agenda and organise supplementary co-operation structures that fit in with the EU co-operation (Ibid: 24).

The Nordic countries build their research co-operation on strong national priorities as well as the EU research system. According to a newly published White book, the weaknesses are the lack of sufficient critical mass, visibility and attractiveness, and groundbreaking innovations (Nordic Council of Ministers, 2003b: 5). The White book recommends the establishment of the NORIA (Nordic Research and Innovation Area) with well-established and leading networks and partnerships, high R&D investments, high mobility and international higher education systems and structures (Ibid: 5).

Competitiveness of Nordic Countries

The Nordic countries are among the most competitive countries in the World. In the Global Competitive Report 2004, the five Nordic countries are among the top-20 nations in rankings of Growth Competitiveness as well as Business Competitiveness. Finland tops the rankings for growth competitiveness and comes second only to the United States in business competitiveness. All five Nordic countries are ranked in the top-ten of the Growth Competitiveness Ranking.

The Nordic countries with more than 24 million inhabitants are wealthy and have large research and development resources. On average, the Nordic countries invest over 2.7% of GDP on R&D and are well placed as far as the most important indicators for research and innovation are concerned. The R&D expenditures for Finland and Sweden exceed already today the EU target of 3% by 2010, primarily due to considerable investment from industry. Iceland, the smallest of the Nordic countries, stands out with the largest government financed R&D

Figure 1. Competitiveness of Nordic countries according to World Economic Forum 2004

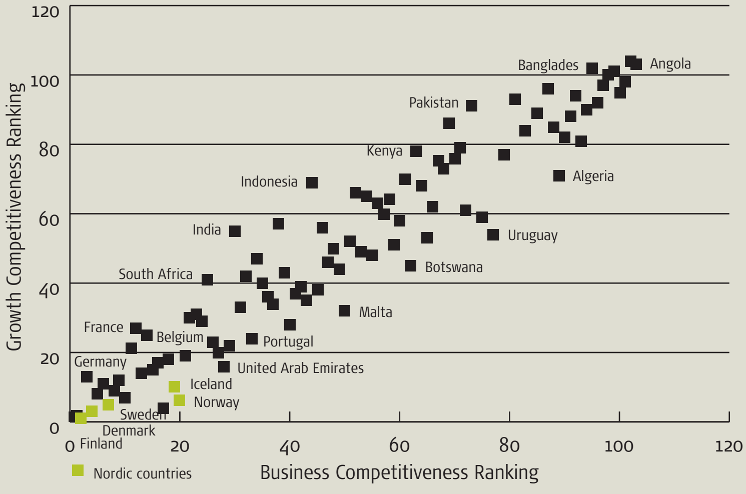


Table 1: Population and R&D expenditure in the Nordic Countries. Source: Nordic Statistical Yearbook 2002; OECD, 2002.

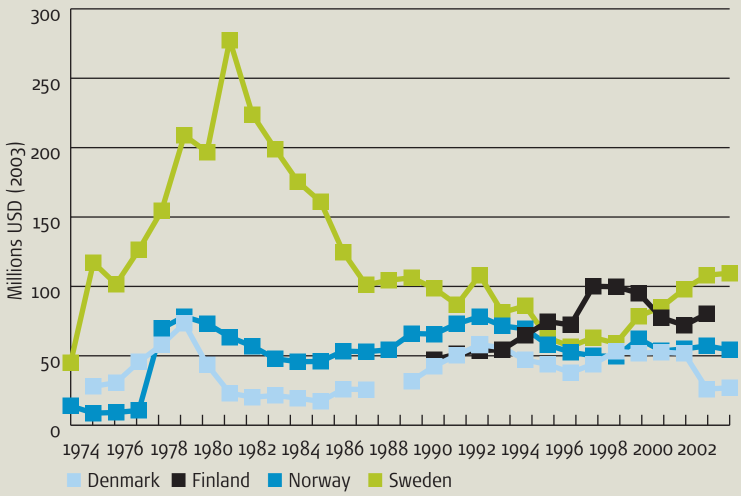
	Inhabitants	GDP Bill. US$ 2002	Total R&D Exp./GDP % 1999	Public R&D/GDP % 1999	Private R&D/GDP % 1999
Denmark	5,368,000	172.2	2.09	0.68	1.21
Finland	5,194,000	131.5	3.22	0.94	2.16
Iceland	286,000	8.7	2.33	0.96	1.01
Norway	4,524,000	193.0	1.70	0.72	0.84
Sweden	8,909,000	240.3	3.78	0.93	2.56
Total	24,251,000	745.7	2.74	0.81	1.71
EU-15	–	–	1.86	0.65	1.03

expenditure. Norway has the lowest R&D expenditure of the Nordic countries, but in terms of government financed R&D, Denmark is at the bottom end.

Research and Development in New Energy Technologies

When it comes to energy research, the Nordic countries seem to follow the trend of the other International Energy Agency (IEA) countries with increasing R&D resources following the first oil crisis, a peak in the early 1980's and hereafter decreasing R&D funds. The total IEA uses approximately 8.9 billion $ in 2001 on governmental energy R&D, a substantial decrease from the peak-year of 1980 with 14.7 billion $. Among the Nordic countries, Sweden has the highest governmental energy R&D expenditure with approximately 108 million $ in 2002 followed by Finland with approximately 80 million $. The Norwegian government invests 57 million $ while the Danish governmental energy R&D dropped to 26 million $ in 2002.The development of governmental energy R&D is illustrated in Figure 2.

Figure 2. Public energy R&D funds in the Nordic countries (in 2003 USD)



Source: IEA database 2004

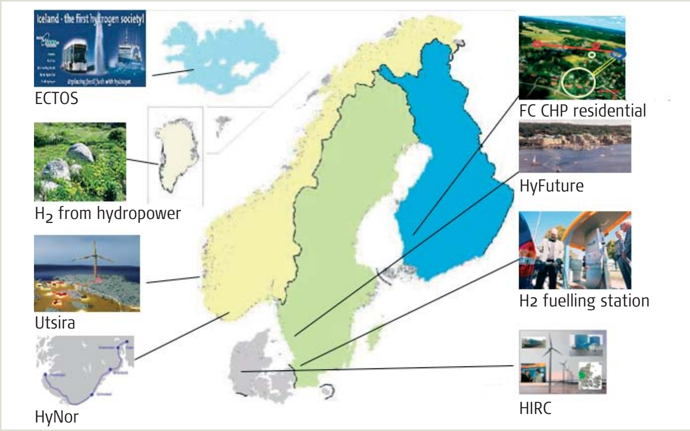
The Nordic investment in hydrogen and fuel cell technologies is increasing along the whole hydrogen value chain. During 1998-2002, at least 96 projects were launched with total budgets of more than 72 million € (Jørgensen, 2003). The largest action field in terms of both funds and number of projects was fuel cells with 37 projects and more than 39 million €. But also production and storage were well represented in some Nordic countries (Norway and Sweden). The sample did not include R&D on CO_2 capture and sequestration.

In a recent IEA study on public R&D in hydrogen and fuel cell technologies, Nordic highlights include (IEA, 2004):

- Danish R&D strategy for fuel cells with total annual investment of approximately 18 million € (2003).
- Finnish focus on distributed hydrogen-related energy systems and R&D in fuel cells.
- Norwegian efforts on CO_2 sequestration in the North Sea and priority to investigate hydrogen production from abundant, domestic natural gas resources.
- Swedish Consortium for Artificial Photosynthesis with focus on basic R&D on artificial photosynthesis using sunlight to produce hydrogen from water. In addition, several R&D programmes related to stationary and transportation fuel cell applications.

Also at European level, Nordic stakeholders are well represented in European research and demonstration projects within fuel cells and hydrogen. In the period 1999-2002, Nordic partners were represented in 40% out of 70 projects supported by the Fifth Framework Programme on Energy Environment and Sustainable Development (EESD), representing total project funds of more than 120 million € (excluding 11 projects where no information is available on budget) (EU Commission, 2003a; Jørgensen,

Selected demonstration projects in the Nordic countries



- The **Icelandic ECTOS-project** (Ecological City Transport System) tests three FC-buses from Evobus and a fuelling with on-site electrolysis based on hydropower in Reykjavik. It has been the model for the ambitious Clean Urban Transport for Europe (CUTE) project in nine European cities, including Stockholm.
- In the **Greenlandic idea catalogue** on hydrogen, one project is about hydrogen production from glaciers and ice cap. The other project is about hydrogen production in Nuuk by using the excess energy from the hydropower plant in Kangerluarsunnguaq/Buksefjorden.
- The **Utsira Hydrogen Wind project** demonstrates an autonomous energy system in the small island of Utsira. The plant is operated as a stand-alone unit serving 10 households on an isolated grid, where wind power represents the main power supply and hydrogen produced from excess power from wind energy will secure a stable and uninterrupted power supply.
- The **HyNor** project plans to build several hydrogen filling stations in southern Norway during 2005-2008 along the 540 km long route between Oslo and Stavanger and to operate a number of buses and cars using hydrogen as a fuel.
- Following a regional foresight on hydrogen energy, the **Hydrogen Innovation and Research Centre (HIRC)** was established in 2004 in the Western part of Denmark. The centre is a catalyst for bringing together stakeholders in hydrogen and fuel cell development and demonstration projects.
- The **Malmö Hydrogen Station** is located next to a natural gas fuelling station and has on-site production of hydrogen based on green certificate power (wind). Besides being able to fill up cars with pure hydrogen at 200 bar and 350 bar, the station provides hythane, a mixture of natural gas and hydrogen, to the city buses.
- **HyFuture** is a joint initiative by industry, universities and local government in the West Sweden region. The goal is to establish a platform for dissemination of knowledge and demonstration of hydrogen as an energy carrier and use the hydrogen surplus from the petrochemical industry in Stenungsund.
- The Finnish community of **Äetsä** has long experience of hydrogen production, storage and distribution and the related knowledge and know-how. This includes a PEMFC CHP system for housing, distribution of hydrogen produced as a by-product of a local chemical plant and new steam boiler facilities fueled by pure hydrogen.

Table 2. Total energy consumption and electricity overview in the Nordic countries, 2002. Source: www.nordel.org, www.ssb.no, www.ens.dk, www.stem.se

	Denmark	Finland	Iceland	Norway	Sweden	Nordic
Total energy consumption TJ	**829 281**	**1 328 146**	**142 300**	**1 138 800**	**2 260 700**	**5 699 227**
Breakdown of energy						
Crude oil %	42	26	25	35	31	
Natural gas %	23	11	–		4	
Hydro energy %	–	4	17	49	10	
Nuclear fuel %	–	18	–	–	33	
Coal and coke %	21	12	–	15[7])	4	
Geothermal %	–	–	55	–	–	
Other[1]) %	13	27	3	1	18	
Electricity						
Installed capacity, MW	12 632	16 866	1 474	27 960	32 223	91 155
Generation, GWh	37 260	71 938	8 404	130 591	143 361	391 554
Hydropower, GWh	32	10 636	6 968	129 735	66 046	213 417
Nuclear power, GWh	–[2])	21 443	–	–	65 572	87 015
Thermal power, GWh	32 349	39 793	3	783	11 185	84 113
– condensing	–	12 875	–	215	1 026	14 116
– CHP[3]), district heat	30 232[4])	14 635	–	–	5 425	50 292
– CHP, industry	2 117	12 268	–	371	4 699	19 455
– gas turbines etc.	–	15	3	197	35	250
– other renewable power[5])	4 879	66	1 433	76	558	7 012
Imports, GWh	9 047	14 577	–	5 330	20 108	49 062
Exports, GWh	11 102	2 654	–	15 003	14 750	43 509
Total consumption, GWh	35 205	83 861	8 404	120 918	148 719	397 107
Total consumption per capita, kWh	6 519	16 127	28 013	26 871	16 710	16 342
Breakdown of electricity generation						
Hydropower, %	0[6])	15	83	99	46	55
Nuclear power, %	–	30	–	–	46	22
Other thermal power, %	87	55	0	1	8	21
Other renewable power, %	13	0	17	0	0	2

1) Wind energy, biomass, peat 2) None nuclear power production 3) Combined heat and power
4) Includes production in condensing power plant 5) Wind power, geothermal power in Iceland
6) 0 = less than 0.5 % 7) Includes natural gas

2003). In the Sixth Framework Programme after the calls for proposals in 2003-2004, Nordic partners were represented in 59% out of 29 projects, representing total project funds of more than 87.8 million € (EU Commission, 2004). Nordic partners are, for example, Norsk Hydro, Volvo, Risø National Laboratory, Technical University of Denmark, Kungl. Tekniska Högskolan, IRD Fuel Cells A/S, Icelandic New Energy, Sydkraft, VTT, Wärtsilä and Det Norske Veritas.

The Nordic Energy Systems

The Nordic countries have a wide diversity of primary energy sources. These comprise fossil fuels, nuclear power and renewable energy sources such as hydropower, wind power and biomass, and peat. As illustrated in Table 2, energy sources of electricity likewise vary between the countries. The share of renewable energy sources in electricity production is more than 55% in the Nordic area. Hydropower is the dominating renewable energy source in Norway and Iceland and also plays an important role in the Swedish and Finnish electricity supply. Wind power only plays a significant role in the Danish electricity supply where at the same time coal is the dominant source. Nuclear power plays an important role in Sweden and Finland, but while the Swedish nuclear power plants are planned to close, a new nuclear power plant is being built in Finland.

Industrial energy consumption is large due to high energy intensity in, for example, pulp and paper and metal industries. Because of cold climate, the share of space heating is high in overall energy consumption. However, the overall efficiency in energy production is high, since more than 80% of thermal power is produced in combined heat and power plants (CHP). More than half of these plants are connected to the district heating systems of communities. Since 1990, total electricity consumption in the Nordic countries has risen by an average 1.2% annually (Swedish Energy Agency 2003). In 2002, the demand of electricity in the Nordic area was 397 TWh. The total energy consumption in the Nordic countries totalled 5700 PJ in 2002. Table 2 presents an overview of energy sources used in the Nordic countries, together with the corresponding capacity and consumption figures.

In addition to renewable energy resources, Norway and Denmark have a considerable production and export of oil and natural gas. In 2002, Norway produced about 160 million tons of oil and 74 billion m^3 of natural gas. For Denmark, the corresponding figures were 18 million tons and 8 billion m^3. These two countries together accounted respectively for 4.9% and 2.9% share of the World's total in oil and gas production (BP, 2004).

International electricity grids are well developed in the Nordic countries and allow for transmission of electricity over long distances as illustrated in figure 3. Please notice that the map does not include recent planned investments.

Denmark, Finland, Norway and Sweden form a common electricity market area with the Nord Pool power exchange. In addition to interconnections of electricity in the Nord Pool area, connections also exist to Germany, Russia and Poland. As a consequence of deregulation, there has been a revolutionary restructuring of the whole energy sector in the Nord Pool countries. On average, the prices of electricity have decreased following the closure of old production capacities until 2002. However, in the short term the yearly variation in hydropower production has the highest impact on the market prices of electricity. Due to low electricity market prices, no new production capacity (except wind power and small, decentralised CHP) has been built. The planned closing of the Swedish nuclear power plants and implementation of climate policies will most likely force electricity market prices up again unless new investments are made.

Figure 3. Energy systems and connections in some Nordic countries

The natural gas network is well developed only in Denmark. In Finland and Sweden, the network covers the southern part of the country. In Norway, the explored natural gas is mainly exported via offshore pipelines and the on-shore natural gas grid practically does not exist. However, new pipelines have been planned both in Norway and Finland. The World's longest offshore pipeline ever planned is to deliver Russian gas to Continental Europe via Finland and the Baltic Sea. The pipeline would pass through the Baltic Sea from Vyborg to the German coast. The North Transgas (NTG) project is included in the Quick start projects of the Growth Initiative and is expected to cost 5 billion € and be finalised in 2010 (EU Commission, 2003b).

Objectives and Design of the Nordic H_2 Energy Foresight

The Nordic H_2 Energy Foresight exercise was launched January 2003 by 16 project partners from academia, industry, energy companies, and associations from all five Nordic countries.

The diversity among the Nordic countries as well as well established political and economic collaboration in research, innovation and energy represent some unique and interesting opportunities for exploring different pathways to the hydrogen economy. In short, the Nordic H_2 Energy Foresight has the following objectives:

- To develop socio-technical visions for a future hydrogen economy and explore pathways to commercialisation of hydrogen production, distribution, storage and utilisation.
- To contribute as decision support for companies, research institutes and public authorities in order to prioritise R&D and to develop effective framework policies.
- To develop and strengthen scientific and industrial networks.

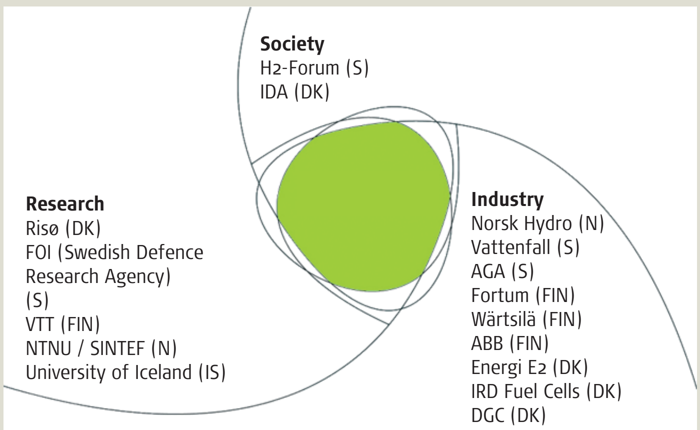
The foresight process has been managed and facilitated by a team of specialists in energy systems and technology foresight from Denmark (Risø National Laboratory), Finland (VTT) and Sweden (FOI Swedish Defence Research Agency).

The Nordic H_2 Energy Foresight puts equal weight on process and content, both for the intrinsic quality of the outputs of the process and for the networking and commitment it creates. Therefore, the project has centred on a sequence of four workshops, bringing together project partners and experts from industry, energy companies, research, and governmental authorities. Expert judgements and discussions in these workshops are assisted and challenged by formal quantitative systems analysis and technology assessment. The Nordic H_2 Energy Foresight is thus essentially an iterative process where the final output is formed by the qualitative and quantitative input from project partners, external experts and literature during the various steps of the project. In particular, the process contains the following central, interactive steps:

The *Scenario Workshop* at the University of Iceland in Reykjavik discussed the external conditions around the hydrogen society. General issues that cannot be affected by a hydrogen technology policy but that are likely to affect introduction of H_2 Energy in the Nordic energy system were considered. The scenario workshop produced three scenario sketches for Nordic H_2 energy introduction (see Eriksson, E.A., 2003a).

At the *Vision Workshop* at FOI in Stockholm, experts discussed hydrogen technology visions in the Nordic context. Contrary to the Scenario Workshop, the Vision Workshop addressed issues that can be affected by Nordic actors. Also at the Vision Workshop, preliminary focusing was made on the most important issues – those with the highest technical feasibility today and the largest future Nordic market potential. The views were collected with the

Figure 4. Project partners

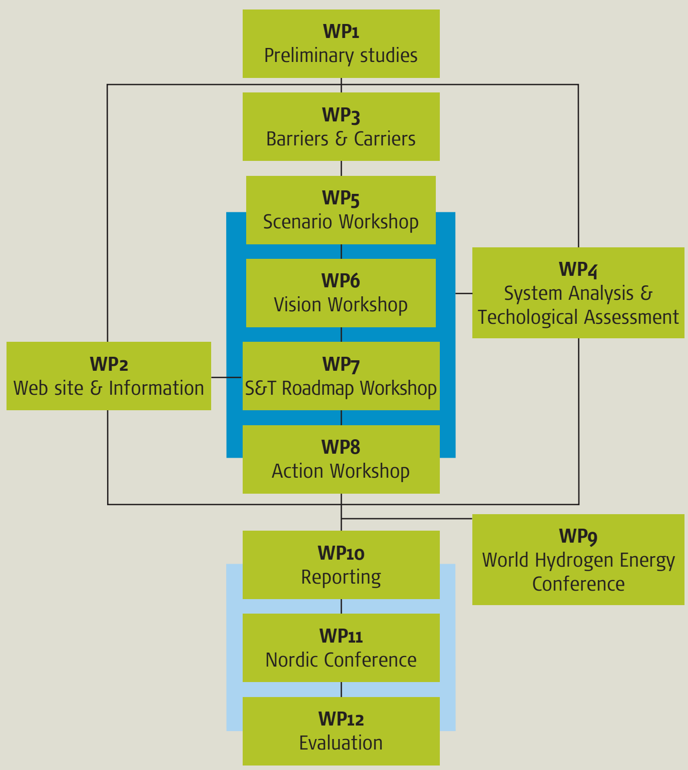


help of a questionnaire on the vision list developed in a brainstorming session (see Eriksson, E.A., 2003b).

The *Roadmap Workshop* at Risø in Roskilde outlined the sequence of implementation and mutual interdependence of the hydrogen technology visions from today and until 2030. Furthermore, barriers, needs and drivers for realising the visions were discussed in relation to Science and Education (needs for scientific research, needs for competences) and Government (energy and industry policy, public R&D, early market stimulation, standardisation, safety) (see Dannemand Andersen, P. et al., 2004).

The *Action Workshop* at VTT in Helsinki discussed the actions needed to overcome barriers and to realise the Nordic hydrogen energy visions and roadmaps. Focus was on three development areas that are of importance when introducing hydrogen energy to the Nordic energy market: 1) hydrogen production and distribution, 2) hydrogen use in transport, and 3) stationary use of hydrogen. In addition, generic cross-cutting issues and conditions and possibilities of utilising new business opportunities were discussed (see Eerola, A., 2004).

Figure 5. Project flow



The *Systems Analysis* analysed technological end economical feasibility of different hydrogen technologies in different scenarios with a linear programming method. The created model is a representation of the flows of energy (energy carriers) and technological alternatives in the hydrogen energy system. The input data has been collected from project partners and extensive literature search. However, many inputs are associated with uncertainty, especially in the longer term. Often, information found from literature does not include assumptions, such as discount ratio, assumed fuel prices, etc. Therefore, the quantitative results are meant to be broad illustrations of different scenarios, technology development paths and policy choices (see Koljonen et al., 2004).

An important part of the project is to bring the discussions and the knowledge on hydrogen energy closer to the public. Therefore, a website – *www.h2foresight.info* – informs on ongoing hydrogen-related activities, both in the Nordic countries and elsewhere and publishes results generated during and after the foresight process.

Finally, an *evaluation* of the foresight will be made in July 2005 by the end of the project. Since the start of the project in January 2003, Nordic and other international stakeholders have met and discussed expectations concerning the hydrogen economy, visits have been made to outstanding demonstration projects and R&D facilities in the Nordic countries, some have even made business and networking has paved the way for future collaboration.

Making the Future

Early Expectations

At the beginning of the foresight process, a number of explorative interviews were carried out to analyse the expectations to build a Nordic knowledge area in hydrogen.

On the positive side, academic experts pointed to high levels of general energy research in the Nordic countries, research which to some extent also was complementary among the countries with the Danish advancement in wind energy research and research on SOFC. Norway had special knowledge on advanced water electrolysis and large-scale production of silicon and solar cells, and Sweden and Finland had special knowledge on biogas and bio energy. In the field of renewables, the Nordic region had early adopters. Governmental officials expressed a positive attitude to the Nordic co-operation, as this might be a promising way to strengthen hydrogen R&D activities. However, the question was if the Nordic countries would be interested in taking joint initiatives at EU level. But, as one official expressed it, the Nordic countries had an obligation to be at the forefront of the hydrogen economy based on each of the Nordic countries' overall high level of development – technological, economic, social, and political. If the Nordic countries could not succeed, who could? An industrial expert thought that it was an advantage that the Nordic countries had so diverse energy systems and at the same time common interests in research and development.

On the sceptical side, experts also noticed that there seemed to be a slow progress of political will regarding the hydrogen economy among the Nordic countries, at least compared to other countries as, for example, Japan and USA. Some scepticism was also voiced regarding the different motivations to introduce hydrogen energy due to different energy systems and problems in the Nordic countries (hydropower in Iceland and Norway, nuclear power in Sweden and Finland, wind energy and CHP in Denmark, etc.). This might, however, also be regarded as a possibility as there were several development tracks to choose between and the consequences would be different regarding the options.

One of the main challenges of the foresight process was hence to create more coherent and agreed views on building a Nordic knowledge area in the hydrogen.

External Scenarios

At the Scenario Workshop, external scenarios were developed for Nordic hydrogen energy introduction. On the basis of brainstorming and group discussions, a matrix of three *first-period scenarios* (2003-2015) set against three *second-period scenarios* (2015-30) was constructed. The general rationale for considering external scenarios is that many conditions of great importance to Nordic H_2 energy introduction are beyond the control of Nordic decision-makers. Furthermore, the energy sector is marked by particularly strong inter-temporal links, mainly due to the strong infrastructural element. This motivates the non-standard two-period approach to external scenarios where the first-period scenarios set the socio-economic stage for the second-period scenarios focusing on major energy-related challenges. The three first-period external scenarios that derive from the scenario workshop can be described as:

- **B – Big Business is Back** is a globalised economy dominated by US multinationals and US big business-oriented policy approaches. Major physical investments are not particularly helped by the prevailing quarter-to-quarter capitalism. There is very little interest for global environmental issues. Oil prices are moderate. However, H_2 energy is still believed to be a likely component in future energy systems.

- **E – Energy Entrepreneurs and Smart Policies** is a globalised economy dominated by entrepreneurs and venture capitalists,

Figure 6. The external scenarios produced on the basis of the scenario workshop

Developments 2015-30 / External scenarios 2003-15	1. Hydrocarbon security-of-supply problems	2. Undisputable CO_2 problems	3. A smooth path to the future
B: Big Business Is Back			B3 Big vision 6%
E: Energy Entrepreneurs and Smart Policies	E1 Big vision 15%		
P: Primacy of Politics		P2 Big vision 18%	

The colour indicates the ease of Nordic H_2 introduction: Green: easy. Yellow: intermediate. Red: difficult
'Big Vision' indicates hydrogen's share of the total Nordic energy system in 2030, except for industry consumption.

and with policy actors apt at harnessing the power of innovation for societal purposes. The energy sector is characterised by a tendency towards decentralisation. There is some interest for global environmental issues. Oil prices are moderate.

- **P – Primacy of Politics** is a Europe-centric economy characterised by co-operation between governments and big business and with a great interest in large-scale investments in, for example, energy and transport systems. There is some interest for global environmental issues. Oil prices are high due to security-of-supply problems and the high oil price is an important driver for energy sector change.

Combining this with three alternative second-period developments (1. 'hydrocarbon security-of-supply problems', 2. 'undisputable CO_2 problems', 3. 'a smooth path to the future'), we finally got the following 9 scenarios. Scenarios B3, E1 and P2 were chosen to form the framework for the subsequent work. See Figure 6.

Visions for Hydrogen in the Nordic Countries

The participating experts at the Vision Workshop were asked to assess an ambitious but realistic "big vision" for hydrogen by 2030. Hence, hydrogen's share of the total Nordic energy system by 2030 was assessed as follows:

Scenario B3:	6%-7%	6%
Scenario E1:	14%-16%	15%
Scenario P2:	16%-19%	18%

In the systems analysis, these expert estimates were further analysed. Energy consumption in the Nordic area was divided in four main types: electricity, transport, space heating and "others". The fourth type covers use of heat energy in the industrial sector (see Figure 7a). In energy production, the changes in the existing systems are very slow due to long life times of generating plants. Also, hydrogen as an energy carrier would compete with other sustainable energy systems like electricity generation from renewable energy sources. In systems analysis and assessment of external scenarios, it is assumed that hydrogen technologies will not replace existing energy technologies in the industrial sector. Therefore, future hydrogen demand in the Nordic area is only divided into stationary use (electricity production, space heating) and transport use. Further, hydrogen's share for stationary applications, i.e., electricity and heat production, is assumed to be approximately the half of the "big visions" (see Figure 7b).

The evolution of the hydrogen as an energy carrier is assumed to grow exponentially from 2005 to 2030. It is important to emphasize that the aim of these Nordic hydrogen visions is not to predict what may likely happen in the future. It is rather to set out challenges that could bring the Nordic countries to the forefront of hydrogen development and challenge our mental models of the future.

Hydrogen is not an energy source in itself. Hydrogen has to be produced from a basic source of energy. For the Nordic countries as well for the rest of Europe, the main energy source for hydrogen production over the next 25 years will be natural gas – especially in the B3 scenario. In the two other scenarios, natural gas might play a smaller but still important role. Renewable energy sources will provide most of the rest. The renewable energy sources available for hydrogen production in the Nordic countries over the next 25 years are hydro power, geothermal, biomass and wind energy. Most of the Nordic countries' large-scale hydro resources are exploited by now, and only remote Iceland and Greenland have non-exploited feasible resources (up to of 1000 MW in each country). Only Iceland has geothermal energy resources. Nuclear energy is expected to play an important role in Finland. Still, at Nordic level natural gas, wind energy and biomass will apparently be the major sources for added energy (hydrogen) production.

Figure 7a. The estimated consumption of energy in the Nordic area until 2030 (Eurelectric 2002, EU 2004)

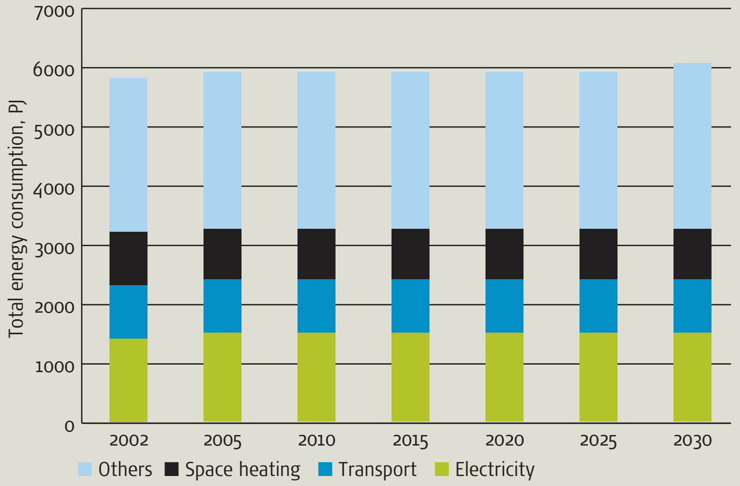
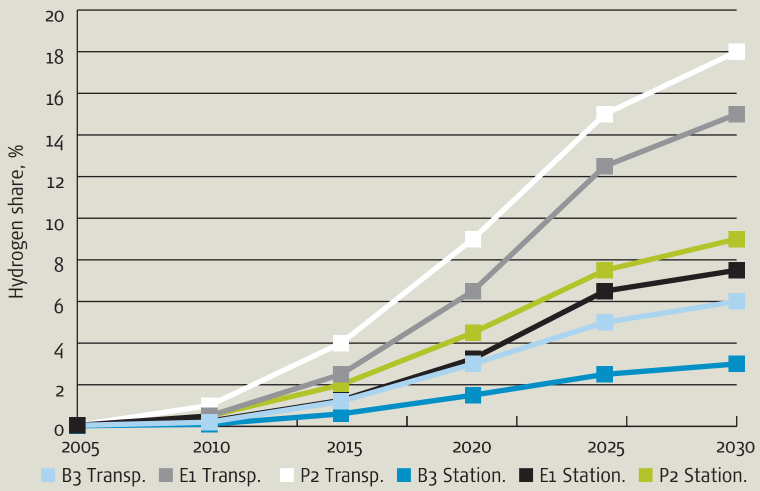


Figure 7b. Hydrogen demands for the transport sector and stationary applications of the base case scenarios B3, E1 and P2.



The considerations behind the large role of natural gas are that the demand for energy and especially electricity will increase over the next decades and that all economically feasible renewable energy sources might be utilised to fulfil this need. Hence, this will decrease the renewable sources available for hydrogen production. Furthermore, the Nordic area has an abundance of natural gas and this combined with CO_2 sequestration gives unique

How do our visionary scenarios relate to international visions, expectations and projections?

A. A paper from IIASA (Barreto et al., 2003) presents a scenario storyline for hydrogen energy in the global energy system. In this scenario (defined as the "B3-H2 Scenario"), hydrogen is expected to have a global market share of approximately 10% among the different energy carriers. Hydrogen used in the transport sector constitutes in that study approximately 5% by 2020 and 25% by 2050. The percentages for hydrogen in what is defined as "residential and commercial markets" are 8% by 2020 and 38% by 2050.

B. The European HyNet study "Towards a European Hydrogen Energy Roadmap" has set up some scenarios for possible cumulative European hydrogen vehicle populations by 2020. The scenarios vary from 1 million (approx. 1%) to 9 million (approx. 5%) vehicles by 2020.

C. The European Deployment strategy has made what is called key assumptions on hydrogen and fuel cell applications for a 2020 scenario. These can be seen from the table below.

	Portables (<100W)	Portables/other niches (1-4 kWe)	Micro CHP (<50 kWe)	Industrial CHP (200-500 kWe)	Road Transport
Estimated H_2/FC market share	50%	n.a.	15%	n.a. (multiple markets)	0.5-5%

opportunities. In the Vision Workshop, the energy sources for hydrogen production by 2030 in the three scenarios were settled by 2030 to:

Scenario B3: Natural gas: 70%; Renewable (and nuclear): 30%
Scenario E1 & P2: Natural gas: 50%; Renewable (and nuclear): 50%

A total of 66 hydrogen technology visions were assessed in terms of technical feasibility today (2003) and Nordic market potential by 2030. Based on the assessment, the most interesting were selected (see Table 3).

Hydrogen and fuel cell systems in consumer electronics have a strong Nordic interest, as large telecom companies such as Nokia are located here. Nevertheless, it was decided to exclude this area from the further analysis. There were two reasons for this. First, the technology and solutions on consumer electronics are believed to be of such a different kind that there will be very limited spill-over effects or early market effects affecting transport and stationary (heat & power) use of H_2 and fuel cells. Second, the use of H_2 and fuel cells in consumer electronics will only have a marginal effect on the overall energy systems. The key issue here is not concerning energy but concerning functionality. It is, however, often mentioned that consumer electronics may be an application area where consumer early can become acquainted with hydrogen technologies.

Roadmapping and Systems Analysis

Through a participative roadmap exercise the sequence of implementation and the interdependence of the hydrogen technology visions from today and until 2030 were roughly outlined. Furthermore, the experts discussed business opportunities for Nordic equipment industry and energy market opportunities for the energy companies in the Nordic countries.

This was carried through for each of the three areas:

1) Production and production related transmission/distribution of hydrogen;

2) Hydrogen used in the transport sector (including related distribution and retail); and

3) Stationary use of hydrogen (including related distribution and retail).

The result of the roadmap exercise is outlined in the roadmap schemes 1-3 on pages 22-24.

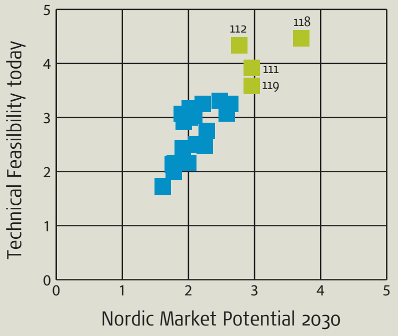
The systems analysis and assessment of technological alternatives was carried out with a linear programming method. The model includes mathematical representations of those emerging technologies for hydrogen production, transmission and energy conversion, which were selected for the roadmap exercise. In the model, the annual costs are accumulated into the milestone years by linearisation and discounting. The minimised total cost includes all the investment and operating costs from the present to the final year of the scenario. The technical parameters include efficiencies, loss factors, plant life times, etc. The energy and hydrogen balances of the model ensure that the demands of electricity, heat and transportation fuel will be covered.

In the scenario calculations, several constraints were set for the base case calculations in order to introduce all the technologies in the first place. Therefore, the minimum of biomass gasification, electrolysis, and steam-reforming with CO_2 capture were all set to 10% of centralised hydrogen production, and the minimum of road transport was set to 5% of total

Table 3: Ranking of hydrogen technology visions – based on vision workshop

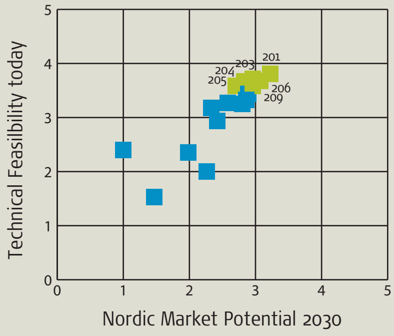
Production

Production and distribution of H2



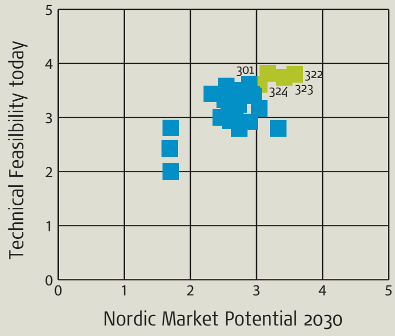
Transport

H2 in transport



Stationary use

Stationary use of H2



Top rank of 23 technical visions:

- H_2 produced from steam- reforming of natural gas
- H_2 produced via electrolysis with wind power
- Gasification of biomass

Top rank of 17 technical visions:

- H_2 driven FC/ electric city buses
- H_2 FC/electric drives in new cars
- H_2 FC/electric drives for small specialty vehicles
- Pressurised tanks for H_2
- H_2 storage as methane or methanol
- Methane driven FC/electric engines for ships

Top rank of 26 technical visions:

- Natural gas driven fuel cells for domestic heat & power
- H_2 and FC in decentralized CHP plants
- Power sources for mobile communication
- Market opportunities for portable electronics

decentralised hydrogen production. The share of fossil fuels in hydrogen production was assumed to be 50-70% of total hydrogen production according to the scenario definitions and the share of renewable energy sources and nuclear energy in hydrogen production was 30-50%. The investments of electrolysis and fuel cells were also assumed to be subsidised by 30-50% in the scenarios E1 and P2. Renewable energy sources were also favoured in these scenarios due to a CO_2 tax, which was set to 8-10 €/MWh for natural gas.

Figure 8 shows the investment costs for hydrogen production, distribution and for heat and power production. The discount ratio used in the calculations was 5% and it should be noted that the selection of discount ratio has a remarkable effect on the total costs. For example, the decrease in discount ratio to 3% increased the total costs about 35% in 2020 and about 60% in 2030. As shown in the figure, the investments in the hydrogen infrastructure seem to be the highest.

Hydrogen Production and Transmission

According to the model calculations, steam reforming and biomass gasification seem to be the most competitive technologies for hydrogen. The competitiveness of biomass gasification is greatly affected by biomass fuel price, which is a local energy source. Electrolysis seems to be the most competitive in decentralised systems, if the price of electricity is low enough. With the scenario assumptions, the needed capacity (MW H_2 out from production units) of steam-reforming, biomass gasification and electrolysis units in 2030 were 1200-12000 MW, 1300-4000 MW, and 400-1300 MW, respectively. The approximated Nordic market sizes in 2030 for the base scenarios varied from 1000 million € to 3000 million € for hydrogen production, and from 4000 million € to 12000 million € for hydrogen transmission.

Figure 8. Investment costs (in million €) of milestone periods in energy production, hydrogen production and hydrogen distribution for the scenarios B3, E1 and P2

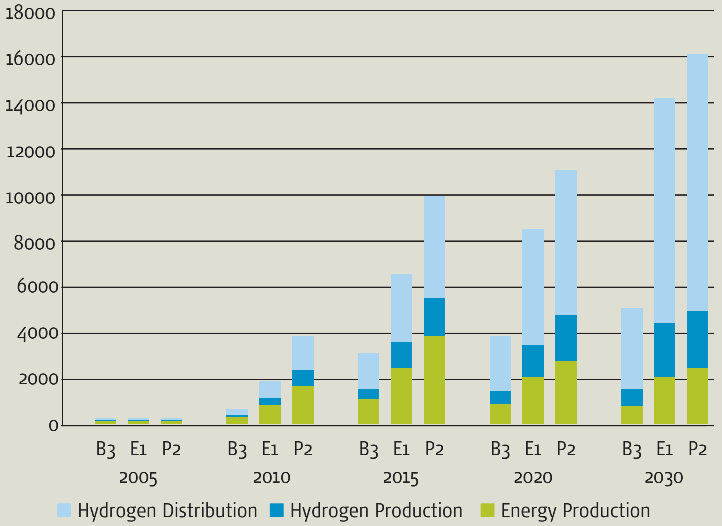
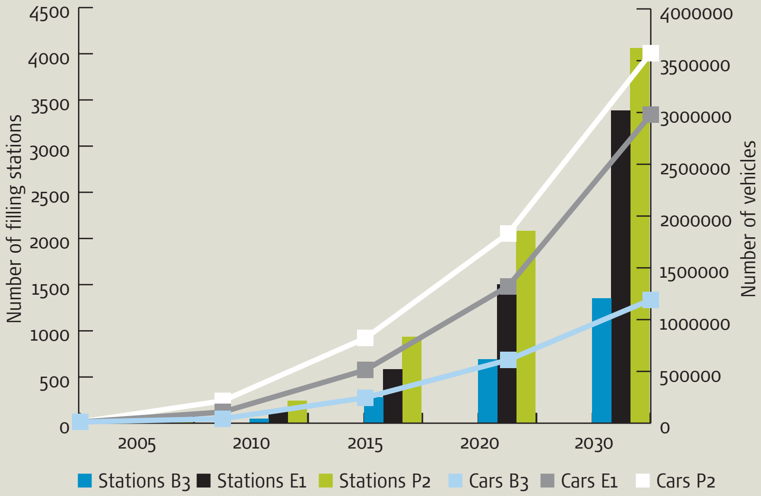


Figure 9. Number of filling stations and hydrogen fuelled vehicles for three scenarios



Stationary Use

Niche applications of hydrogen/fuel cell based APU (Auxiliary Power System) and UPS (Uninterruptible Power Supply) form some of the first steps on the road. Both hydrogen and natural gas driven fuel cells for domestic and decentralised CHP (combined heat and power production) are seen as important steps towards the hydrogen economy in the Nordic countries. In the longer term, hydrogen driven CHP must be implemented in large-scale to arrive at the visions for 2030. In the scenario calculations, FC CHP seem to be the most competitive for heat and power production in the long-term. The heat and power production with hydrogen fuelled fuel cells in 2030 is 2200-6700 MW, while with gas engines the maximum energy production capacity is 200-300 MW only. The Nordic market sizes in 2030 for the base scenarios vary from 1000 to 4000 million € for stationary applications.

Transport

Introduction of hydrogen in the Nordic transport sector will follow the same paths as in the rest of Europe. The first steps will be special vehicles, busses and fleets. A special Nordic issue might be the use of hydrogen in the marine sector, but this is very difficult to include in our energy systems calculations. Therefore, the focus is on road transport in our estimated market sizes. Another Nordic niche might be special vehicles where H^2/FC systems can improve the functionality of these vehicles. In 2020, about 0.5-2 million hydrogen vehicles and in 2030 about 1-4 million hydrogen vehicles are needed to fulfil the 'big visions' for hydrogen energy in the Nordic transport sector. The number of fuelling stations needed in 2020 is estimated to 500-2000 and in 2030 to 1000-4000, respectively. These scenarios for hydrogen supply per station are based on the assumption that 50% of the vehicles are ICE-powered and 50% are equipped with a fuel cell drive train.

Roadmap: H_2 production and transmission

Timeframe	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030
Technology	• Demonstration of decentralised H_2 production from natural gas and decentralised storage in pressure tanks • Demonstration of electrolysis at local filling stations • Demonstration of gasification of biomass to H_2 • Demonstration of H_2 mixed in existing NG grid	• Demonstration of H_2 production from NG with CO_2 sequestration • Expansion of natural gas grid • Early market for H_2 from electrolysis at local filling stations • Early market for gasification of biomass to H_2 • Demonstration of electrolysis and storage as a buffer for wind energy	• Further expansion of natural gas grid • Build-up of H_2 grid and filling stations • Large-scale plants for gasification of biomass to H_2 • Large-scale plants for centralised reforming of NG to H_2 with CO_2 sequestration	• Nordic H_2 grid is further expanded • H_2 NordPool is established • Large-scale H_2 production from NG reforming, biomass gasification and electrolysis (water & solid oxide) • Large-scale hydropower dedicated for liquid hydrogen production established in Greenland and Iceland • SOEC electrolysis for production of H_2, methanol or methane	• First large-scale commercial storage of hydrogen • Early production of H_2 from PV + electrolysis • Advanced H_2 production directly from photochemical and biological processes
Nordic equipment market opportunities	• Natural gas reformers • Equipment for gasification of biomass (or biomass to biofuel) • Equipment and systems technology to system integrate wind power with H_2 production • Electrolysers (water electrolysis and solid oxide electrolysis SOEC) • Infrastructure equipment; automation, compressors, pipelines, pressure tanks • Maybe CO_2 sequestration equipment			• Equipment to long distance transport liquid H_2 (cryogenic tanks, etc.)	
Technical data & market sizes	• Demonstration projects and early niche markets	• Niche markets	• 500-3600 MW NG reforming • 500-3000 MW biomass gasification • 200-600 MW electrolysers		• 1200-12000 MW NG reforming • 1300-4000 MW biomass gasification • 400-1300 MW electrolysers
Nordic energy market opportunities	• Natural gas • Biomass for energy • Electricity from wind • Other renewable energy sources			• Operation of a H_2 Nord Pool and trading with H_2 • Ship transport of liquid H_2	
H_2 in Nordic energy system	• H_2 introduced as energy carrier	• 0-2% H_2 in Nordic energy system	• 1-3% H_2 in Nordic energy system	• 2-7% H_2 in Nordic energy system	• 5-8% H_2 in Nordic energy system

Roadmap: Use of H2 in transport

Timeframe	2005-2010	2010- 2015	2015 - 2020	2020 - 2025	2025 - 2030
Technology	• Special vehicles • Demonstration of bus and taxi fleets using H_2 in fuel cells and internal combustion engines • Demonstration of APUs in trucks, ships and aircraft	• Demonstration of marine & train FC • Introduction of H_2 vehicles in bus fleet • Early market introduc-tion of H_2 FC and ICE passenger cars • Early market introduc-tion of FC APUs in trucks, ships and air-craft	• H_2 FC and ICE vehicle mass market • FC APUs standard equipment in trucks, ships and aircraft • Early market introduc-tion of marine fuel cells	• High H_2 vehicle pene-tration • Markets for FC in marine appli-cations	• H_2 vehicles commer-cially avail-able in road transport, marine, rail and aviation
Nordic equip-ment market opportunities	• Special vehicles (functionality market) • Infrastructure equipment for hydrogen in transport sector • APU systems for the transport sector (ships and trucks) - this links to similar systems for stationary use.			• Marine use of hydrogen and fuel cells	
Market sizes	• Demonstration projects and early niche mar-kets	• 0.2-0.8 million H_2 vehicles	• 0.5-2 million H_2 vehicles • 500-2000 stations		• 1-4 million H_2 vehicles • 1000-4000 stations
Nordic energy market oppor-tu-nities	• New fuelling infrastructure			• Inclusion of transport and fuel production into emission trading during 2010.	
H_2 in Nordic transport sector	• H_2 introduced as ener-gy carrier in the trans-port sector	• 1-4% H_2 in Nordic transport sector	• 3-9% H_2 in Nordic transport sector	• 4-16% H_2 in Nordic transport sector	• 6-18% H_2 in Nordic transport sector

Roadmap: Stationary use of H2

Timeframe	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030
Technology	• Demonstration of FC and FC systems for domestic and decentralised CHP • Early market introduction of FC based power back up and APU units • Early market introduction of FC for remote power supply	• Early market introduction of NG fuel cells for CHP (SOFC) • Market for H_2 FC (PEMFC) • Market for FC based power back up and APU units • Market for FC for remote power supply	• Market for NG fuel cells for CHP • High penetration of FC in power back up and APU markets • High penetration of FC in remote power supply market	• Commercial markets for H_2 PEMFC FC and NG SOFC in decentralised and domestic CHP markets	• Fuel cells commercially available for domestic, decentralised and centralised CHP
Nordic equipment market opportunities	• H_2 & NG FC and FC systems for domestic and decentralised CHP • FC based power back up and APU units • FC for remote power supply • Natural gas driven SOFC fuel cells • Components for infrastructure			• SOEC fuel cell electrolysers and reversible fuel cells	
Market sizes	• Early demonstration phase for FC and FC systems	• 350-1200 MW H_2 FC	• 700-2300 MW H_2 fuel cells		• 2200-6700 MW H_2 fuel cells
Nordic energy market oppor-tu-nities	• Stationary FC/ H_2 systems as a regulatory technology in energy systems with fluctuating production (i.e., wind power)				
H_2 in Nordic power and heat system	• H_2 introduced as energy carrier and energy source in stationary CHP and APU and power back up systems	• 0-2% H_2 in stationary applications	• 1-5% H_2 in stationary applications	• 2-7% H_2 in stationary applications	• 3-9% H_2 in stationary applications

Towards the Nordic Research and Innovation Area in Hydrogen

The Nordic Energy Foresight cannot predict the future, but the foresight participants have concluded a process, which is intended to help create the future, to strengthen the shared knowledge creation and strategic intelligence, and to find the best business options and pathways for the hydrogen economy in a Nordic context.

The Nordic countries are all highly developed knowledge societies that are competitive in terms of technological readiness, public institutions and macroeconomics. The Nordic countries offer unique and interesting opportunities to be at the forefront of the hydrogen economy. There exists a solid foundation on which a Nordic research and innovation area (NORIA) and with bridges to the European Research Area (ERA) on hydrogen technology can be established:

- Hydrogen and fuel cell technologies are new promising energy technologies in which Nordic research, industry and energy companies have developed strong international competences. This is a good starting point for bringing those technologies to the market place.

- The Nordic energy systems offer diverse and competitive framework conditions for the introducing hydrogen as a strong new energy carrier along with electricity. This will further increase the robustness and flexibility of the energy system in the liberalised European energy market.

- A Nordic hydrogen-based energy system will increase the opportunity to use renewable energy in the transport sector. This will increase the diversity of energy sources and reduce overall greenhouse gas emissions.

- The Nordic markets offer an excellent arena for developing competitive, user-oriented, publicly accepted and safe hydrogen and fuel cell technologies for a future hydrogen economy. Nordic industry (technology providers and users) may contribute to set prenormative standards for further international collaboration in these fields.

On the basis of the various steps of the foresight project, the **Nordic H_2 Energy Foresight suggests that the Nordic actors should take an active role in promoting the successful introduction of hydrogen energy.** Further actions are needed to ensure that the long-term investments in hydrogen energy technology will contribute to common welfare in the form of more sustainable energy systems and new profitable businesses. A Nordic action strategy to consolidate the position of the Nordic knowledge and innovation area in hydrogen and fuel cell technologies can be summarised in four headings:

1. Conduct coherent **information and awareness campaigns on hydrogen economy and innovation.** The campaigns should be directed to decision-makers and the wider public.

2. Closer **Nordic co-operation on research and development** in strategically defined key areas of hydrogen and fuel cell technologies where Nordic research and Nordic industry have the best opportunities. Public research should focus on areas where industry (of today or tomorrow) can utilise the results.

3. Promote innovation in Nordic industry through **demonstration projects, lighthouse projects and stimulation of niche markets** – forming an early home market for Nordic industry. Again focus should be set on areas where Nordic industry has the best business opportunities.

4. **International co-operation.** Improve the Nordic countries impact on the international agenda setting.

Table 4 summarises where this project has identified potential Nordic business opportunities in the short and the long term.

1. Information and Awareness Policies towards Decision Makers and the General Public

A successful introduction of hydrogen energy to the Nordic market depends on proper information dissemination and awareness rising among decision makers in the private and public sectors and among the general public. During the last couple of years, increased focus has been put on the prospects of hydrogen energy, often with detailed technical focus. We recommend that comprehensive information activities are further developed and disseminated to decision makers and the general public. Useful information include:

- *Information and presentation material* on hydrogen energy technologies and the longterm impacts on economy, environment and society (including comparisons to other energy alternatives). Work done by independent Nordic research groups – in the form of Nordic and European cooperation – is valuable in this respect. The information should be distributed through public authorities, covering the entire democratic system.

Table 4 Potential Nordic business opportunities in short and long term

	Production and Transmission	**Transport**	**Stationary Use**
Equipment Market	• Natural gas reformers • Equipment for gasification of biomass (or biomass to biofuel) • Equipment and systems technology to system integrate wind power with H_2 production • Electrolysers • Infrastructure equipment; automation, compressors, pipelines In the longer term • Equipment for long distance transport of liquid H_2 (cryogenic tanks, etc.) • Maybe CO_2 sequestration equipment	• Special vehicles • Infrastructure equipment for hydrogen in transport sector • APU systems for the transport sector (ships and trucks) – this links to similar systems for stationary use. In the longer term • Marine use of hydrogen and fuel cells	• FC and FC systems for domestic CHP • FC-based power back up and APU units • FC APU units for remote power supply • FC-based decentralised CHP systems
Energy markets	• Natural gas • Biomass for energy • Electricity from wind • Other renewable energy sources In the longer term • Operation of a H2 Nord Pool and trading with H_2 • Ship transport of liquid H_2	• New fuelling infrastructure In the longer term • Inclusion of transport and fuel production into emission trading after 2012.	• Stationary FC/H_2 systems as a regulatory technology in energy systems with fluctuating production (i.e. wind power)

- Compiling and communicating convincing and informative *'true stories'* on hydrogen energy and society. The 'true stories' should illustrate the potential of hydrogen energy and the conditions under which it may be successfully introduced to the Nordic market.

- Providing interesting *showcases* for schools and other educational purposes. Universities and other educational institutes should take an active role in producing common Nordic material available in all important languages that are spoken in the Nordic countries.

- Develop a *Nordic hydrogen economy* website, possibly in relation to the Nordic programme for large scale experiments. Such a site should also have a virtual educational showroom for school children with interactive sites and informative cases. The *www.h2foresight.info* may be used as a first starting point.

2. Nordic Co-operation on Research and Development

The Nordic countries have already today a well-developed cooperation in higher education, research and development in new energy technologies. Key institutions are Nordic Innovation Centre, Nordic Energy Research Programme and Norfa. This is a good starting point for further actions and synergies, in which a technology-oriented approach is combined with a user oriented approach. Among the most important actions, we recommend the following:

- Intensifying *R&D in areas with special Nordic potentials.* Such R&D should be aligned with starting a number of Nordic demonstration and lighthouse projects. There should be a careful sequencing of laboratory verification, early field tests, demonstrations and projects. Nordic companies and research institutes are in key position when defining appropriate R&D priorities and demonstration projects.

R&D priorities

Based on the Roadmap and the Action workshops the following list of technical research and development of special Nordic opportunities was established:

- New reforming technologies
- More efficient electrolysis processes
- Gasification of biomass and gas purification
- Long term research in new methods for hydrogen production using renewable energy sources
- New and efficient processes and technology for CO_2 capture from natural gas based systems and CO_2 storage.
- Fuel cell technology and material science for fuel cells (incl. high temperature and reversible fuel cells)
- Small and medium scale H_2 storage (incl. composite tanks)
- Hydrogen based auxiliary power units (APUs)
- Industrial balance of plant components (BOP)
- Distribution/infrastructure technology

- Facilitating *problem-oriented research* that crosses traditional disciplinary boundaries. The universities, research institutes and funding organisations in the Nordic countries should support cross-disciplinary approaches and international networking that promote problem solving in important areas of hydrogen energy technologies and their various applications.

- Creating *Nordic networks of excellence.* Nordic universities and research institutes, together with the Nordic companies actively developing hydrogen energy technologies and their applications, should create Nordic networks of excellence that support the development of important Nordic areas by pooling together frontline knowledge and expertise and by providing them an opportunity to discuss and further develop the ideas.

- Carrying out adequate and multifaceted *technology assessment studies and cost-benefit analyses* on the impacts of hydrogen energy. This includes safety and security in hydrogen production/utilisation and also lifecycle assessment and environment impact of hydrogen technologies (i.e. emissions to the atmosphere). The work can be done as Nordic and European cooperation by multidisciplinary research groups and technology assessment experts.

- *Annual Nordic research summer schools* in areas of relevance to hydrogen and fuel cell technologies and the hydrogen economy. Such an annual event could be hosted by alternating Nordic universities and with teaching contributions from other Nordic and international R&D institutions. Ph.D. students to be invited should include not only Nordic students, but also for the best Ph.D. students from International Partnership for Hydrogen Economy (IPHE) member states.

- *Mobility grants* for Ph.D. students and researchers working in the field of hydrogen and fuel cell technologies and related fields are a classical incentive to widen the knowledge base in areas subject to highly international developments and breakthroughs and should be prioritised to intensify linkages to IPHE member countries.

- *Development of new type of public financing instruments for longterm industrial R&D* should be considered. The Nordic funding organisations should align their activities accordingly. This issue also includes harnessing of Nordic and international venture capital for creating new hydrogen related businesses.

3. Demonstration Projects, Lighthouse Projects and Stimulation of Niche Markets

To stimulate industrial interest for the potential business opportunities within hydrogen and fuel cell technologies as well as to stimulate the creation of early markets, it is useful to perform largescale sociotechnical experimentation. Such demonstrations and lighthouse projects can address issues such as testing technologies in real life conditions; standardisation and system architecture; training; public acceptance; legal and regulatory issues; security, safety and insurance; business models and financing, etc.

Special focus should be on learning and feedback from demonstrations to R&D programmes. Close cooperation with research institutes or universities is especially needed in those fields where there still are major research elements included as, for example, fuel cells, system integration, etc.

The Nordic countries offer good test conditions for new technologies. New technologies can be tested and demonstrated in diverse climate zones (from mild to very cold), in areas characterised by diverse population density (from sparsely populated and remote areas to densely populated areas) and in areas with a critical mass in competences and infrastructure and well-functioning public and business institutions.

Likewise, the Nordic countries offer a good learning environment with good access to universities and research institutes, a well-qualified labour force, well functioning public institutions and a good business environment. This suggests good prospects for success from a coordinated Nordic programme of largescale sociotechnical demonstrations of hydrogen and fuel cell technologies for a future hydrogen economy.

Demonstrations and lighthouse projects. The Nordic countries have already today a number of ongoing and planned demonstrations. A next step could be promoting a limited number of hydrogen communities made up by a different technological applications and specialisations. These communities could constitute the first building blocks of largescale comprehensive hydrogen demonstrations.

- *Transport and stationary applications in an urban context.* Demonstrations may comprise a number of hydrogen fuelled buses as we see today in Reykjavik, or in areas with natural gas they may comprise a number of hythanefuelled buses as we see in Malmö. The stationary applications may include small CHP in public buildings or in residential houses similar to the CHP in Äetsä. The hydrogen needed may be produced in different ways, ranging from electrolysis of fresh water using renewable power as at the fuelling station in Reykjavik, reforming of natural gas as planned in some HIRC-projects and in some nodes of HyNor, or using surplus from the chemical industry as already done in Äetsä in Finland and as planned in the Swedish HyFuture.

- *Stationary and transport applications in remote areas and islands* similar to the Utsira demonstration project is a key area for testing and demonstrating an autonomous energy system. Such aspirations exist even in Greenland and the Faroe Islands with hydrogen produced from hydropower or wind.

- A third important application is the *marine use of hydrogen and fuel cells.* Such applications are foreseen in the Swedish HyFuture in Gothenborg and in Iceland.

Stimulation of markets for hydrogen and fuel cell technologies beyond demonstration is also important. Even if adequate technology for the hydrogen society would be available, it is difficult to start new businesses based on these new technologies without any intervention that supports the creation of the market. The following tools should be considered by the Nordic actors:

- Developing *incentives for decentralised energy systems and the use of renewable energy sources.* For instance, subsidiaries and economic incentives (emission fees, tax reductions, etc.) that support the adoption of hydrogen energy technology should be considered at Nordic and national level. Nordic Council of Ministers on Environment, Transport, Trade and Industry, together with national level authorities are the key actors here.

- Creating a common *Nordic hydrogen energy market* and specific Nordic business clusters. Nordic-level policy actors, together with industrial and national-level organizations should take an active role in this respect.

- Developing appropriate *certification systems* for hydrogen (including fuelling, vehicles, equipment and services). Nordic standardisation and certification organisations should play an active role in this at Nordic, national and European level.

- *Larger public procurement programmes* of hydrogen applications and services (e.g. for public transportation, governmental buildings, schools, hospitals). Actors responsible for public procurement in each Nordic country should be well informed and equipped for the purpose (includes even political legitimation for the purpose).

4. International Co-operation

The Nordic players can influence various international institutions and agreements that are needed for successfully introducing hydrogen energy to the European and global markets.

In fact Nordic key players have already today prominent positions in international institutions of relevance to hydrogen energy, in particular, the International Partnership for Hydrogen Economy where Iceland and Norway are direct members as well as the International Energy Agency and key Implementing Agreements. These international agreements define some important framework conditions for the international and also Nordic developments. Both political agreements (between governments, etc.) and voluntary agreements by industry and the wider development community should be considered and paid attention for already in the early phase of the transition process. In particular, the following actions are recommended:

- Nordic companies and research organisations, together with Nordic standardisation and certification organizations, should join their efforts to get more weight to Nordic viewpoints in European and international negotiations on *standards, codes and norms* concerning hydrogen energy technologies and their application.

- Active participation in the *development of EU directives and corresponding international agreements* that have an influence on the introduction and adoption of hydrogen energy. For example, the Nordic countries could take the first step for including the traffic sector in the world-wide emission trading system. For the purpose, the politicians and officials responsible for EU and other international affairs in the Nordic countries should be well-informed of hydrogen energy and its potential impacts. Assistance by Nordic experts on relevant fields is needed.

- *Anticipation of Nordic level impacts of international agreements.* Nordic actors should actively follow the development of international agreements and their potential influence with regard to the introduction of hydrogen energy into the Nordic energy market and the development of hydrogen-based Nordic businesses. Nordic experts and analysts should cooperate with politicians and officials with relevant information in order to cover all relevant aspects.

Challenges and Problems

This project is left with some unsolved challenges and problems because of the design and the resources of the project, a rapid technological development, and other reasons. The most important of these are listed in this box.

Hydrogen or other energy carriers? The point of origin for this project was to illustrate the prospects for a future hydrogen society. Several new studies suggest that the well to tank efficiency of an elemental hydrogen economy would be very low. Rather than an elemental hydrogen economy, these studies propose to shift the focus to a "synthetic liquid hydrocarbon economy". The Nordic H_2 Energy Foresight takes such considerations into account by leaving the discussion open regarding hydrogen or hydrogen rich energy sources such as, for example, methane or methanol to be used on the path to the hydrogen economy. But the project has not carried out any comparative analyses (economical, energy or environment) to further clarify this issue.

Technology roadmaps in a rapidly developing area. New technological possibilities still appear. In the period from the initiation of this project and until now, the international interest for hydrogen technologies has almost "exploded" and numerous new ideas and technologies have been suggested internationally. There is a variety of competing technologies and applications for hydrogen and other hydrogen rich fuels. As none of the technologies can be pointed out as the most promising, this has made it very difficult to settle at a more detailed roadmap towards a "hydrogen economy", and we have not outlined "the Nordic H2 roadmap". But based on input from workshop participants, examples of roads have lead to the identification of Nordic business opportunities where hydrogen-based systems are competitive in the short-term and with a Nordic industrial potential in the longer-term goals.

Improved alternative technologies. Also the commercially available technologies that hydrogen based technologies are likely to compete with are rapidly developing. For example, hydrogen based engines are to compete with new hybrid diesel engines for private cars.

Hydrogen business opportunities for Nordic automotive industry. The Nordic automotive industry is concentrated in few subsidiaries of very large international manufacturers. This has lead to this project's lesser focus on business opportunities within hydrogen in the automotive sector. But it is an outstanding issue to further analyse Nordic niches within the automotive sector.

Hydrogen business opportunities for Nordic consumer electronics industry. Hydrogen and fuel cell systems in consumer electronics have a strong Nordic interest. For reasons mentioned in this report it was decided to exclude this area from the further analysis. Nevertheless, this area is important and should be included in future Nordic innovation programmes.

Detailed systems analysis. The systems analysis in this study is a quite rough approach for qualifying other parts of the project. A more detailed and comprehensive systems analysis is planned by the IEA Hydrogen Coordination Group to take place in 2005. Country specific analysis for selected EU Member States is also conducted by HyWays – A European Hydrogen Energy Roadmap (www.hyways.de).

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Nordic Energy Research

Nordic H_2 Energy Foresight

Building the Nordic Research and Innovation Area in Hydrogen

Summary Report

January 2005

The Nordic Hydrogen Energy Foresight is co-financed by the Nordic Energy Research and the Nordic Innovation Centre, which operate under the auspices of the Nordic Council of Ministers. The Nordic Energy Research and Nordic Innovation Centre initiate and finance research and development projects and activities that create synergy between the actors in the Nordic research and innovation system. The project aims to contribute to the competitiveness of the Nordic business sector and to facilitate sustainable development through the creation of a Nordic knowledge market.

Nordic Hydrogen Energy Foresight is a strategic project, involving 16 organisations from the five Nordic countries, focusing on the prospects for moving towards a hydrogen economy within the next 20-30 years. The overall intention is to find long-term and promising ways for Nordic stakeholders of exploiting hydrogen technologies in the drive to meet the 3Es: energy security, environmental protection and economic growth.

Project partners

Denmark: Risø National Laboratory, Energi E2, DGC, IDA.

IRD Fuel Cells A/S

Finland: VTT, Wärtsilä, ABB, Fortum

Iceland: University of Iceland

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