TOP–NEST

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Hydrogen and fuel cells vehicles in Norway: value chain and path-dependence analysis

Case study: The HyNor project and Hynor Lillestrøm

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In this analysis we describe two case studies of fuel cell and hydrogen development projects in Norway. The first case, the HyNor project, is an initiative to implement hydrogen in road transport. The second case describes in particular the testing activities of the Hynor Lillestrøm project at Akershus Energy Park, demonstrating competence in integrated hydrogen energy systems. The Hynor Lillestrøm project develops a technology design which uses renewably-driven electrolysis (using solar PV panels on the roof of the facility) and reforming of landfill gas (since 2013) for producing hydrogen. The demonstration of second-generation carbon capture technology is integrated in the technology design.

These cases were selected for the following reasons: (1) the importance of hydrogen infrastructure for the fuel cell vehicle market, (2) to describe a promising technology design integrating different hydrogen production pathways into an integrated hydrogen system, and (3) for analysing the regional policy context in which the projects are embedded.

(1) The existence of hydrogen production and refuelling infrastructure is central for the fuel cell vehicle market (Adamson, Jerram, & Mackinnon, 2013). In Europe, the rollout of hydrogen refuelling stations over the next 2-3 years is concentrated in Northern Europe, including the Nordic countries, Germany and the United Kingdom.
(2) Norway has access to a broad range of renewable energy sources which can be exploited for the production of hydrogen. The abundance of hydropower can be exploited for the production of hydrogen not just hydropower. The case study on Akershus Energy Park shows how different production pathways are integrated into one energy system.
(3) In the NorWays project the development of hydrogen production and refuelling infrastructure was modelled at various spatial levels (Stiller et al., 2010). Results of this project have informed also this case study. The HyNor project is focussing on Southern Norway, encompassing Oslo, Grenland and Stavanger and fits very well for this case study (see also section Geographical scope).

1 Value chain characteristics

1.1 Main activities/segments of the value chain

HyNor is a development project, which promotes the use of hydrogen in the transport sector in *southern* Norway. It was established and was run by a manifold of actors from industry, local and regional authorities and central public authorities. The project is described by its owners as being the driving force for the preparation of hydrogen as a fuel in road transport in Norway as well as being a test bed for demonstration projects leading up to mass market introduction of hydrogen vehicles (HyNor webpages). The objectives of the HyNor project have changed over time (Sataøen, 2008), but the main goal has not changed. Initially the main activities concentrated on establishing a hydrogen refuelling network along the Oslo-Stavanger corridor including also Drammen, Notodden, Porsgrunn, Grimstad and Lyngdal (figure 1). In recent years a reorientation of activities has taken place and the main focus for the period up to 2015 is to expand the refuelling network in the Oslo region and to create a hydrogen link in collaboration with Sweden and Denmark.

Overview of the different phases of the HyNor project:

- Phase 1. 2003–2009: HyNor had the aim to demonstrate the technology by enabling hydrogen vehicles to drive and refuel along this road from Stavanger to Oslo;

- Phase 2. 2010–2012: HyNor aimed at an increasing density of refuelling stations in the capital region and at a larger fuel cell vehicle fleet;
- Phase 3. 2013–2015: HyNor will prepare the commercialisation of fuel cell vehicles in the Norwegian market, in cooperation with other projects in neighbouring countries.

Figure 1: The HyNor corridor according to initial plans.

Source: HyNor webpage

The HyNor project is still a 'pioneer' project which is dependent on the enthusiasm of the involved experts and the support from the authorities, and involved research organisations and firms.

1.1.1 Production of hydrogen

There are several options for the production of hydrogen: natural gas steam methane reforming (SMR), biomass gasification, electrolysis and by-product hydrogen from existing industry plants. The production can be localised onsite or in central production units (Stiller, et al., 2010). Norway has a long history of hydrogen generation by electrolysis through the use of hydro-power. By-product hydrogen is at the moment not a major resource in Norway (NorWays, 2009).

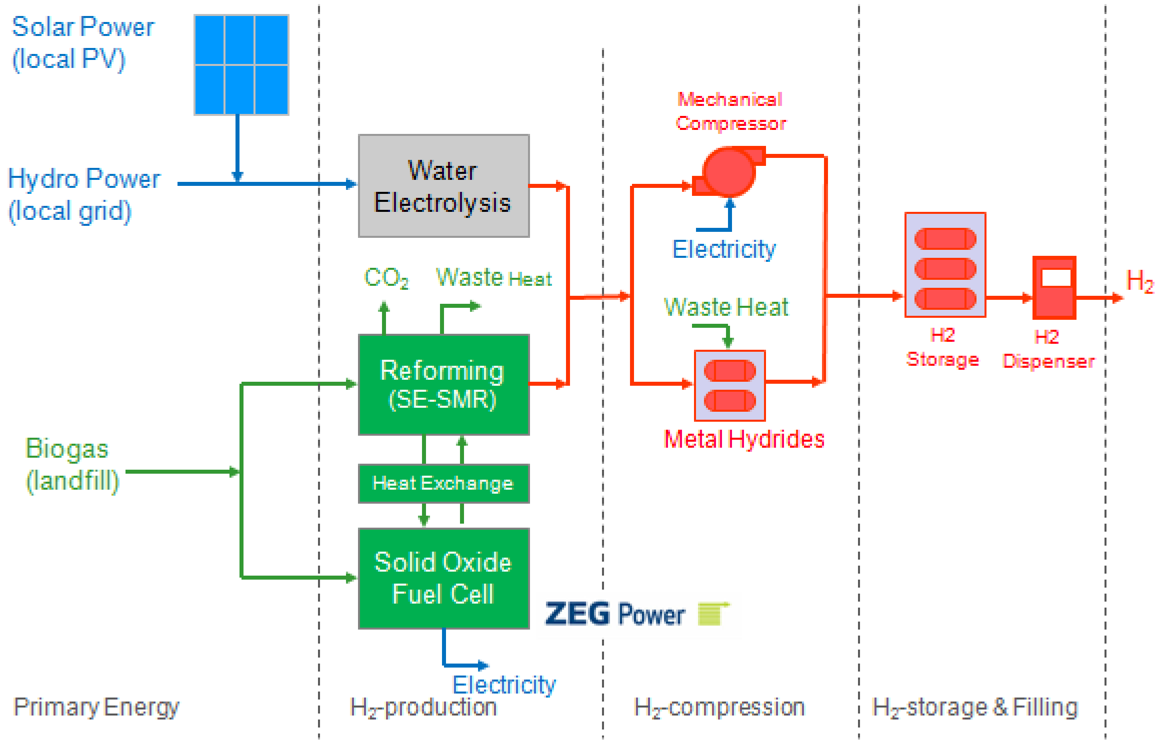
In Norway, we can see a clear shift in the dominating solutions for the production of hydrogen for transport from reforming natural gas towards producing hydrogen by electrolysers due to the availability of rather cheap hydropower. The reforming of biogas is not so usual, but will increase somehow in the future. Cambi AS, a technology provider for biogas facilities, has also plans to integrate hydrogen production into their concept of larger biogas facilities in the future. However, the required purity of hydrogen in fuel cells still favours electrolysed hydrogen.

The HyNor project had the objective to develop and demonstrate a broad variety of different hydrogen production technologies (Kårstein, 2008): electrolysis using hydropower or other renewable electricity sources; hydrogen production with biomass gasification; hydrogen production with natural gas as energy source, including CO_2 capture; and utilisation of the by-product hydrogen from existing industry plants (ibid.). The project was initially organised in different geographical nodes where different hydrogen production methods were demonstrated (figure 1). In the following section, we describe in particular the demonstration activities of the Hynor Lillestrøm project.

The Hynor Lillestrøm project is located at Akershus Energy Park. The project has the objective to establish a hydrogen refuelling station with on-site hydrogen production based on renewable energy sources and to be a test and demonstration centre for relevant locally developed hydrogen production and compression technology. The project will also be used for competence development, information and dissemination activities.

A sorption enhanced steam methane reformer (SESMR) system developed by the Institute for Energy Technology (IFE) is used to convert landfill gas (upgraded to biogas quality) to hydrogen. IFE is also the project leader, and is responsible for the overall system integration. A thermally-driven metal hydride hydrogen compressor developed by Hystorsys (Hydrogen Storage Systems AS), a spin-off company from IFE will also be demonstrated. The demonstration project cooperates with research environments in the Netherlands and in Denmark. The station integrates testing of landfill gas upgrading and hydrogen purification systems (dedicated the SESMR) from a Dutch supplier (HyGear) and a standardized small-scale hydrogen production, compression, and dispenser system supplied from the company H2 Logic in Denmark. The technological design, which is a zero-emission gas process (ZEG Power) has been developed and patented jointly by IFE and Christian Michelsen Research (CMR). The ZEG process will be installed in 2014. Figure 2 illustrates the basic principles of the Hynor Lillestrøm test station.

Figure 2: The principles of Hynor Lillestrøm.



Source: Gjerløw, Hynor Lillestrøm

1.1.2 Production of fuel cells for transportation means

There are only few companies producing fuel cells for transportation in Norway. Large parts of fuel cells are being imported. The Norwegian based company, Nordic Power System develops fuel cell systems for various applications. The company develops diesel fuel cell auxiliary power units (APU) that run on conventional fuels such as diesel and biofuels. The fuel cell generator is a viable power source for a variety of markets, both for mobile and stationary applications. The production facility is located in Sogn, Norway.

Another important company is Kongsberg Automotive which is a global supplier of the vehicle industry and develops systems for electric and hybrid vehicles. Its development company Epower provides R&D and design services for electric-, hybrid and fuel cell electric vehicles.

1.1.3 Production of equipment for storage and transport of hydrogen

The company Hexagon Raufoss (former Raufoss Fuel Systems) is a global supplier of high-pressurized composite tanks for storage and transportation of hydrogen and natural gas and biogas. The company provides storage systems for transit buses, trucks and passenger cars, gas transportation and stationary storage. Hexagon Raufoss is a member of Hexagon Composites Group registered with head office in Ålesund, Norway. The Group achieved a turnover of NOK 992 million in 2011. The hydrogen refuelling station in Lillestrøm uses tank systems produced by Hexagon Raufoss. Hexagon Hexagon participated also in the NorWays project.

A further company to mention is Hystorsys AS, a spin-off company from IFE, which develops metal hydrides for compression and storage of hydrogen.

1.1.4 Integration with other energy production technologies

A comparative advantage of producing hydrogen in Norway is the presence of abundant domestic resources from which it can be harvested. The possibility to integrate different resources is considered to be particularly promising relative to the production of hydrogen (NorWays, 2009). The HyNor project explores and demonstrates some of these different approaches (see figure 1).

Grid electricity in Norway is close to carbon free which has made the option of using electricity to drive water electrolysis (splitting water into hydrogen and oxygen) an interesting source of renewable hydrogen. The production of hydrogen from excess wind energy was demonstrated at the Utsira Wind and Hydrogen demonstration plant. The technology has the potential of adding value to wind energy as a source of vehicle fuel.

The production of hydrogen from natural gas stood in the past at the core of the Norwegian hydrogen strategy (Aam, 2004). The application of carbon capture technology has also been explored. Depending on the technology used the production of hydrogen from natural gas is a likely low cost option.

The production from gasified biomass such as wood or from biogas is an explored option, which may maximise the value of these underexploited resources where they are not needed for heat or electricity. The application is well suited for distributed, smaller-scale production at source (Matthey, 2013).

The Hynor Lillestrøm project at Akershus Energy Park, demonstrates competence in integrated hydrogen energy systems (see also section Production of hydrogen). The Hynor Lillestrøm project develops a technology design which uses renewably electricity as power for equipment at the plant, and for back-up power (UPS) and reforming of landfill gas (since 2013) for producing hydrogen. The demonstration of second-generation carbon capture technology is also integrated in the technology design. The hydrogen refuelling station comes in addition.

1.1.5 Distribution of hydrogen for transportation means and related infrastructure

In the future the network of refuelling stations will differ regarding (1) the access to hydrogen, onsite hydrogen production, either electrolysis or SMR, or central hydrogen production, and (2) the delivery options to the refuelling stations, pipelines or gaseous hydrogen trucks. The representatives from HYOP AS and the Hydrogen Council assess that on-site production of hydrogen will dominate together with local bigger production units nearby which require short local pipelines. They do not see the need for longer hydrogen pipelines – eventual needed hydrogen, which is not produced locally, can be trucked in. They think that in the future fuel cells will be combined with batteries in hybrid vehicles. Then hydrogen stations will be placed outside the cities and will be bigger because the car users can switch between hydrogen and battery drift.

There are currently six hydrogen refuelling stations in Norway, of which four are located in the Oslo capital region. The fuelling stations serve today in total ca. 20 passenger cars and five hydrogen busses running in regular traffic in Oslo. The bus refuelling station in Oslo is part of the wider European project CHIC (Clean Hydrogen in European Cities) and the hydrogen is produced from electrolysis using renewable energy. The project is supported financially by the Oslo City Council and Akershus County Council and the public enterprise Transnova[1]. The infrastructure is provided and run by Air Liquide.

During the last couple of years there have been several uncertainties regarding the operability and maintenance of the hydrogen refuelling stations in Norway. In 2011, Statoil Fuel & Retail, which is now owned by Couche-Tard, announced it would terminate its hydrogen activities and to withdraw from operating the three stations under its operation at Økern in Oslo, in Drammen and in Porsgrunn.[2] Statoil Fuel & Retail have a clear commercial approach and will therefore not carry the costs for maintaining unprofitable operations. In 2012, the stations were taken over by HYOP (Hydrogen Operations), a firm owned by Kjeller Innovasjon AS in cooperation with actors involved in the hydrogen activities in the Lillestrøm area. That means that HYOP is still in a pre-commercial stage and needs public support for some time – the company receives support from Transnova and the regional authorities in Oslo and Akershus. First with the introduction of a larger fuel cell fleet this can become a profitable business.

An overview over the refuelling stations in Norway is given in Table 1.

Table 1: Overview over hydrogen refuelling stations in Norway

Location	Operated by	In operation	H_2 source
Oslo HyNor, Økern[3][4]	HYOP	May 2009	Trucked-in hydrogen from electrolysis
H2 moves Oslo Gaustad[5][6][7]	HYOP	November 2011	Electrolysis on-site
Oslo Bus station CHIC[8][9]	Air Liquide	April 2013	Electrolysis on-site
Drammen, Kjellstad[10][11]	HYOP	May 2009	Trucked-in hydrogen from electrolysis
Lillestrøm,	HYOP	June 2012	Electrolysis, steam reforming - on-site via solar PV;

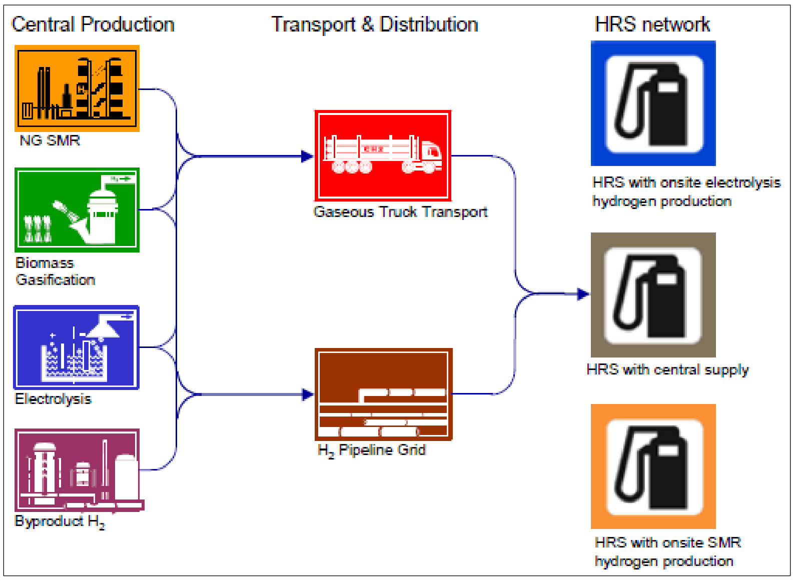
[1] Transnova provides grants and advice for pilot and demonstration projects that reduce CO_2 emissions in the transportation sector. Grants are mainly given to projects at a stage between R&D late phase and market introduction.
[2] http://www.nrk.no/ostlandssendingen/kutter-stotten-til-hydrogen-1.8354244
[3] http://www.netinform.net/H2/H2Stations/H2StationsDetail.aspx?ID=79
[4] http://www.klimabiler.no/fyllestasjon/hynor-oslo-bil/
[5] http://www.netinform.net/H2/H2Stations/H2StationsDetail.aspx?ID=386
[6] http://hynor-lillestrom.no/nyheter_1/h2_moves_stasjonen_pnet_/
[7] http://www.scandinavianhydrogen.org/h2moves/stations
[8] http://www.netinform.net/H2/H2Stations/H2StationsDetail.aspx?ID=384
[9] http://chic-project.eu/cities/phase-1-cities/oslo/oslo-refuelling/oslo-hydrogen-refueling-station
[10] http://www.netinform.net/H2/H2Stations/H2StationsDetail.aspx?ID=80
[11] http://hynor.no/prosjekter/drammen

Kjeller[12][13]			reforming of land fill gas
Porsgrunn, Herøya[14][15]	HYOP	June 2007	By-product from chlorine production delivered via pipeline
HyNor Stavanger[16]	Statoil	October 2006 – December 2011	CGH2 delivery by AGA from Sweden, based on electrolysis

At Sintef's location in Oslo Gaustad H2 Logic installed in November 2011 a new hydrogen refuelling station. The installation took just ten days in total and was co-funded by the EU project H2moves Scandinavia, Transnova and the Danish EUDP programme (Bünger, 2013).

Investment costs of a nationwide network of hydrogen stations have been calculated in the NorWays study on the establishment of a hydrogen refuelling infrastructure in Norway. According to its estimates of a nationwide hydrogen refuelling network, this would consist of 1,100 refuelling stations and would require in total investments at EUR 1.5 billion until 2050 (NorWays, 2009). However, hydrogen refuelling "infrastructure providers bear a high first-mover risk, making a heavy up-front outlay to build a retail station network that will not be fully utilized for some years" (Pütz & Nørbech, 2012).

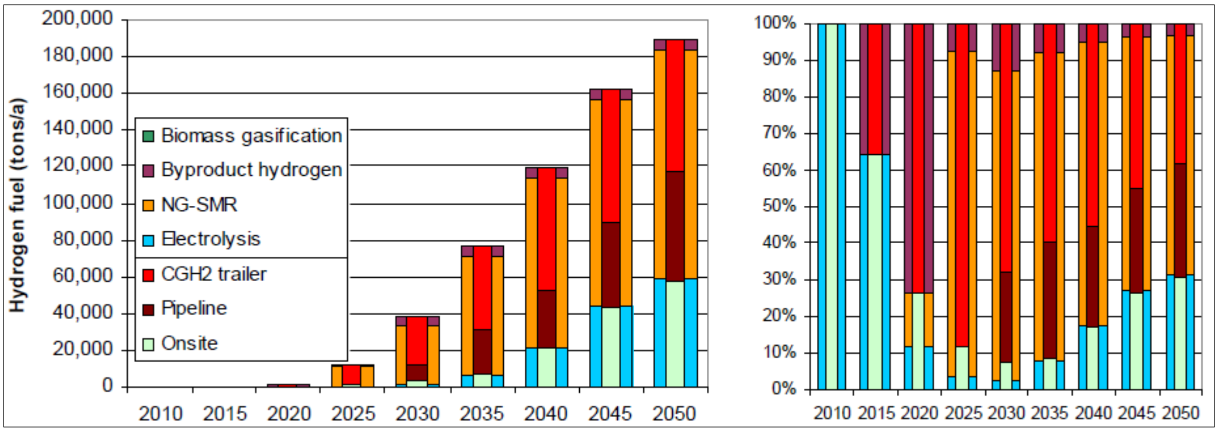
Figure 3: Options for production and distribution of hydrogen considered in the H2Invest modelling work (NorWays, 2009:10)



The NorWays project estimated the development of hydrogen production and distribution options with the help of a hydrogen infrastructure build-up simulation model (H2INVEST). The model was an economic model which did not take into account environmental concerns. The aggregated shares are shown in figure 4.

[12] http://www.netinform.net/H2/H2Stations/H2StationsDetail.aspx?ID=385
[13] http://hynor-lillestrom.no/
[14] http://www.netinform.net/h2/h2stations/H2StationsDetail.aspx?ID=81
[15] http://www.tu.no/motor/2012/02/09/fylkeskommunene-redder-hydrogenstasjonene
[16] http://www.netinform.net/H2/H2Stations/H2StationsDetail.aspx?ID=82

Figure 4: Aggregated shares of production and distribution options in the base case scenario of H2Invest (NorWays, 2009:10)



However, today, reforming of natural gas without CCS is not an option anymore in Norway. Therefore the results of this model have clear limitations.

Recently, the H2moves Scandinavia project analysed the experiences with hydrogen refuelling infrastructure and fuel cell vehicles in Norway and Denmark (Bünger, 2013). As a part of the project the certification and approval procedures for hydrogen refuelling stations and fuel cell vehicles in the Scandinavian countries was analysed. The report highlighted that requirements and approval procedures for H_2 refuelling stations are not harmonised with EU provisions, which can complicate the establishment of hydrogen infrastructure (ibid.). The project suggests therefore that stakeholders should develop guidelines and support authorities in the Nordic countries for the alignment of the provisions. The report addresses also the introduction of a harmonised European standard for hydrogen stations based on ISO 20100. ISO 20100 is a standard for hydrogen quality based on ISO/TS 14687-2, and an updating of MID Directive 2004/22/EC (Annex MI-002) on metering accuracy on hydrogen refuelling stations to apply for gas meters and volume conversion, and of OIML R139 on metering pressurised hydrogen (ibid.).

An appropriate regulative framework and the development of standards were also an important issue for the financial and technology outlook on the European fuel cell and hydrogen sector for 2014–2020 in the report of the New Energy World Industry Group (2011). These would contribute to remove barriers to commercialisation, and would create a strategic advantage to Europe in the global marketplace. The report suggests that the European industry should improve their effort to represent the sector at the international standard setting development authorities. The report highlights the ISO and SAE standards which provide globally harmonized requirements for: "hydrogen refuelling interface, hydrogen fuel quality, and hydrogen refuelling station safety and lay out requirements" (2011:32). They suggest that the ISO standards needs to be adopted as European standards, combining the interaction with EC regulation and the benefits of global harmonization. This was also supported by the HYOP representative. Regarding the European regulatory framework, the European regulation for the approval of hydrogen fuelled vehicles should be highlighted. The report requests as a new task to develop "an efficient EC framework supporting large scale deployment of hydrogen fuelling stations and the associated hydrogen production and supply systems" (2011). For the period up to 2020, the report estimates costs of €10 million for regulation, codes and standards coordination activities. The HYOP representative assessed that the standards for the refuelling infrastructure, like the hydrogen fuelling nozzle have been in place for some years, which is a different situation compared with charging infrastructure for battery electrical vehicles.

The government and local regulations for the approval of hydrogen refuelling stations were not so challenging in Norway as in other countries.

Hydrogen refuelling stations based on onsite H_2 production for fuel cell electrical vehicles can be combined with fast charging stations for battery electrical vehicles, especially in the corridors between the larger cities (Econ Pöyry, 2012). Both the H_2 refuelling stations and the fast charger need a huge power source – hydrogen could be produced during night time when there is less demand for charging. There are dialogues going on this topic. By such initiatives the efforts for establishing infrastructure for both sustainable vehicle fleets could be combined and synergies could be achieved.

1.1.6 Marketing and sales of hydrogen and fuel cell cars

A number of niche markets are emerging for various hydrogen technologies. Examples of Norwegian companies investing in a hydrogen technology are in the areas of hydrogen storage (Hexagon Raufoss, Hystorsys), fuel cells (Nordic Power Systems), hydrogen production (NEL Hydrogen, ZEG Power, GasPlas, and RotoBoost) and refuelling station solutions (NHC, 2012).

NEL Hydrogen of Norway (previously owned by Statoil) delivers large scale electrolysers to the global industrial market, and has recently demonstrated a new type of electrolyser that can follow a fluctuating load, e.g., from wind power. NEL Hydrogen supplied the electrolyser for the first commercial hydrogen station, which opened in Iceland in 2003 (Matthey, 2013).

Beyond these, there are only a few small and medium-sized enterprises (SMEs) and start-up companies. Currently the large, national energy companies are absent and show reluctance to become engaged in hydrogen activities (Norwegian Hydrogen Council, 2012).

However, important car manufacturers from Japan and South Korea, such as Toyota, Nissan, Honda and Hyundai have decided that they will accelerate the introduction of fuel cell cars in the Scandinavian market in the coming years. For this purpose they signed in October 2012 a memorandum of understanding together with representatives from hydrogen infrastructure companies – HYOP As from Norway and H2 Logic and Copenhagen Hydrogen Network from Denmark, and the NGOs for hydrogen and fuel cells – HyNor from Norway, Hydrogen Sweden, Icelandic New Energy, and the Hydrogen Link Denmark Association. The memorandum has been supported actively by the Scandinavian Hydrogen Highway Partnership.

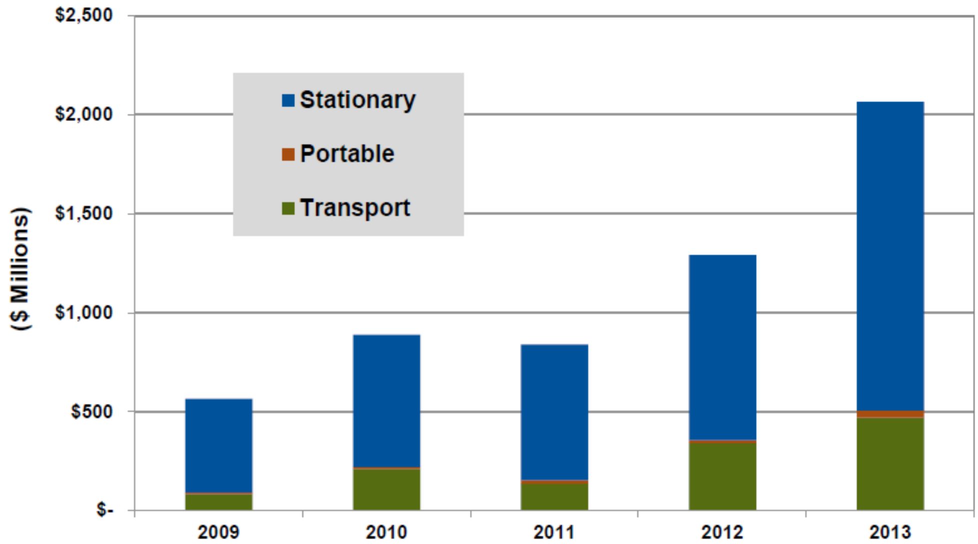
With the establishment of such infrastructure in Norway, Sweden, Denmark and Iceland the car manufacturers plan to move from demonstration of fuel cell vehicles to their commercialisation. This will require engagement of national energy companies and investors, but also stable policy incentives to foster such a coordinated roll-out of the necessary infrastructure. According to this memorandum following cooperative tasks are envisioned by the car manufacturers to ensure a successful market introduction (citation):[17]

- "Joint pursuit of introduction of FCEVs and establishment of hydrogen infrastructure in the Nordic countries starting around year 2014 to 2017
- Advocating for establishment of necessary public financing and support mechanisms for the FCEVs and the hydrogen infrastructure
- Engagement of key national dealerships of the car manufacturers
- Engagement of key national energy and infrastructure companies

[17] http://www.scandinavianhydrogen.org/shhp%5D/news/toyota-nissan-honda-hyundai-sign-mou-on-market-introduction-of-fuel-cell-vehicles-in-no-0

- The car manufacturers will endeavour for a market launch of the FCEVs in 2015 or later provided that sufficient infrastructure has been introduced
- The Infrastructure Companies will endeavour to introduce the hydrogen infrastructure starting around year 2014 to 2017
- The efforts of the Parties are subject to establishment of public financing and support mechanisms for the FCEVs and the hydrogen infrastructure" (MoU, 2012).

Figure 5: Fuel Cell Systems Revenue Generated by Application, World Markets: 2009-2013 (Adamson, et al., 2013: Chart 2.2)



Source: Navigant Research

Navigant Research has assessed the revenues generated by fuel cell system applications, including stationary, portable and transport applications (Adamson, et al., 2013). Figure 5 shows increasing revenues from fuel cell system applications which in 2013 amounted to over 1 billion USD. Most of the revenues come from stationary applications, but also transport applications have increased their revenues, especially over the last two years.

The public procurement of fuel cell vehicles for public authorities and services is seen as a valuable market introduction option for expanding the number of available fuel cell vehicles which require hydrogen from the refuelling infrastructure.

1.2 Main supporting activities

1.2.1 RD&D undertaken in companies

Since the 1980s and 1990s Norwegian companies have engaged in R&D on different fuel cell types, hydrogen production technology and hydrogen storage, with Statoil, Norsk Hydro and Kværner as the most prominent companies (Godoe & Nygaard, 2006; Klitkou, Nygaard, & Meyer, 2007). In the 1990s, despite clear interests in exploiting abundant natural gas as feedstock for solid oxide fuel cells and co-funding from the public research funding agency, NTNF, these big industrial R&D projects – NorCell I and II and Mjøllner – failed (Godoe & Nygaard, 2006). While Statoil was mainly interested in using natural gas for producing hydrogen, Norsk Hydro was focussed on electrolysis. Norsk Hydro owned a subsidiary specialised in electrolysers for water hydrolysis, Hydro Electrolysers (former Norsk Hydro Electrolysers AS) (Godoe & Nygaard, 2006). The firm is located in Notodden in Telemark and is a world leader for hydrogen technology. The alkaline electrolysers had been further developed and tested by NEL Hydrogen at the Energy Park in Porsgrunn, but these activities are now terminated. The aim was to produce electrolysers that have flexible load operation with faster response time. An alternative design is tested by the start-up company RotoBoost. The company has patented a rotating stack electrolyser, a design which is supposed to bring capital costs down significantly.

In the decade from 2001 to 2010 Det Norske Veritas (DNV) worked on several projects regarding hydrogen for road transport, especially related to the definition of safety procedures for hydrogen refuelling stations, starting in 2001 with the European Integrated Hydrogen Project, Phase 2 (EIHP2), later collaborating within the IEA Hydrogen Implementing Agreement (HIA), Annex 19 on hydrogen safety, and two EU projects, such as HySafe and HyApproval.

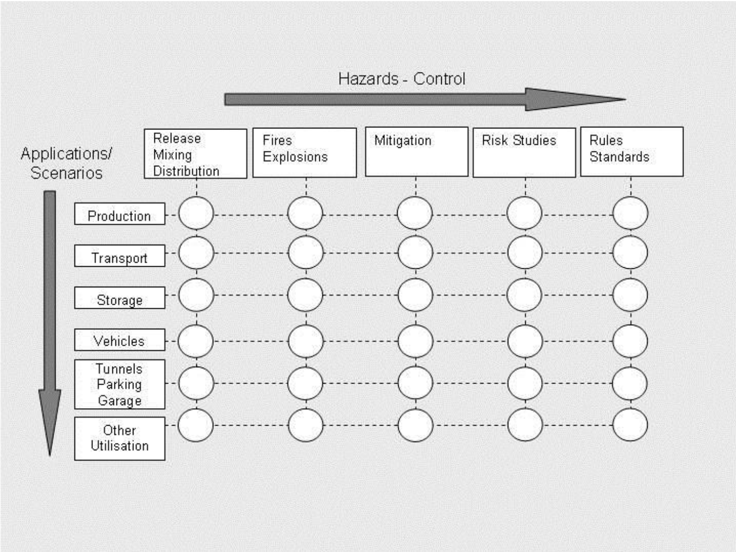
EIHP2 started in 2001 and ended in 2004. EIHP2 had among others the goal to "undertake comparative risk and safety analyses with respect to the release of hydrogen in confined and semi-confined environments, such as tunnels, inner-city streets and garages".[18] These analyses should provide input to definitions of hydrogen related standards and regulations. 21 partners from nine European countries participated in EIP2, from Norway DNV, Norsk Hydro ASA and Raufoss ASA (now Hexacon), and from Sweden participated Volvo.

Task 19 in HIA started in 2004 and ended in 2010. The purpose of HIA in general was to facilitate the implementation of hydrogen as an energy carrier and the focus of Task 19 was on hydrogen safety. This included to develop risk assessment methodologies and to systemize the experimental programmes going on to gather more knowledge about hydrogen. In the work for Task 19 DNV collaborated with partners from Europe, Northern America and Japan, but also with Norwegian partners: GexCon AS and the Telemark University College. While the University College performed experiments GexCon improved its software tool FLACS for explosion modelling and explosion risk modelling. The development of risk assessment methodologies was challenged by limited access to such report caused by secrecy and proprietary knowledge in this field. Such problems emerged also in other projects and made it necessary to transfer accessible knowledge from other sectors, such the offshore oil and gas sector and the chemical industry.

The European Network of Excellence, HySafe,[19] started in 2004 and ended in 2009. It aimed to develop best practice for estimates of hydrogen *leak frequencies* and for hydrogen *ignition probabilities*, and to develop the *Hydrogen Incident and Accident Database*, HIAD. Also here it was difficult to get good data on incidents and accidents because of the unwillingness of companies to share knowledge. The project ended up with using hydrocarbon practice and discussed what properties of hydrogen would increase or decrease the probabilities in a worst case. Here 25 partners from 12 European countries and Canada participated, including from Norway DNV, Norsk Hydro ASA and GexCon AS. The project analysed possible hazards to develop rules and standards for different applications, such as hydrogen production, transport, storage, hydrogen vehicles, usage of hydrogen in tunnels, parking and garages, and other applications (compare Figure 6).

[18] www.eihp.org/
[19] http://www.hysafe.org/

Figure 6: HySafe Activity Matrix



Source: [HySafe]

HyApproval

Today, fuel cell R&D undertaken by companies is not so visible anymore. With the regard to R&D on hydrogen there are some start-ups which have great potential, such as GasPlas and RotoBoost. They attracted investors and get support from the Norwegian Hydrogen Forum. The lack of industrial demand for such products has been a bottleneck for such companies. This might be changed with the entrance of a larger fuel cell vehicle fleet.

1.2.2 RD&D undertaken by public research organisations

The most important public research organisations in the field of FC and hydrogen are the NTNU – Norwegian University of Science and Technology, the University of Oslo, Sintef, and the Institute for Energy Technology (IFE) (Klitkou, et al., 2007). They cover a wide range of H2/FC research fields.

The failure of the big industry projects NorCell and Mjøllner had also consequences for the public research organisations (Godoe & Nygaard, 2006: 1707). Currently the main challenge is that there is no domestic industry which wants to back up the research going on in the public research organisations. A number of relevant projects have been stopped because they are dependent on support from industry which is lacking.

The research focus of the research organisations located in Trondheim is on membranes, bipolar plates and other sub-components of fuel cells, electrolysers and reforming of hydrogen combined with pre-combustion CO_2 capture. The Norwegian Institute for Scientific and Industrial Research (Sintef) is a leading actor for hydrogen RD&D, especially for the development of PEM electrolyser and membranes (Godoe & Nygaard, 2006). Sintef is focusing its attention on the so called NEXPEL design, a Proton Exchange Membrane (PEM) electrolyser for sustainable hydrogen production intended for use with wind or solar power. The design has been tested at the Energy Park in Porsgrunn. Sintef has frequently undertaken contract R&D for Statoil, Kværner and often in cooperation with IFE on hydrogen storage (Godoe & Nygaard, 2006). Sintef has received substantial funding for H2/FC research from the Research Council of Norway (RCN) and is actively involved in several EU funded projects in the public-private programme Fuel Cells and Hydrogen Joint Undertaking.

The Norwegian University of Science and Technology (NTNU) is engaged in hydrogen research but is mainly focusing on fundamental R&D. The main areas of research are electro-catalysis for PEM fuel cells and water electrolysis (PEM and alkaline). The Department of Chemistry has a number of facilities relevant for hydrogen and fuel cells, such as stations to test PEM fuel cell performance.

Important RD&D is also undertaken by IFE and CMR who currently collaborate on testing hydrogen technology based on methane reforming. IFE is an independent research foundation performing research on hydrogen production, storage of hydrogen in metal hydrides and compression of hydrogen, fuel cells and integrated hydrogen energy systems. CMR AS is a technology research company that focusses on commercial R&D. Activities on fuel cells and hydrogen are undertaken in the subsidiary companies Gexcon AS and Prototech AS.

The University of Oslo has developed expertise and has on-going research in ceramic proton conducting materials for fuel cells.

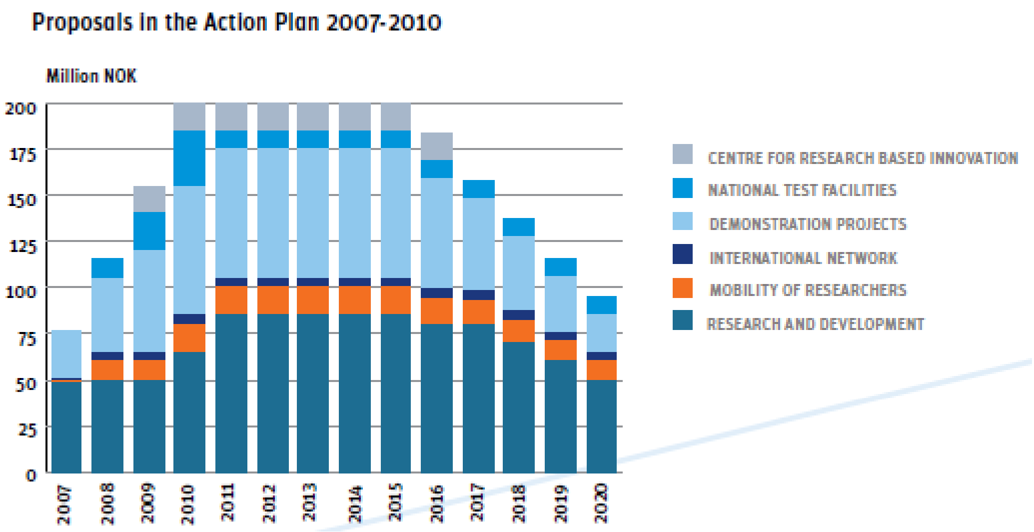
1.2.3 RD&D funding support by public agencies

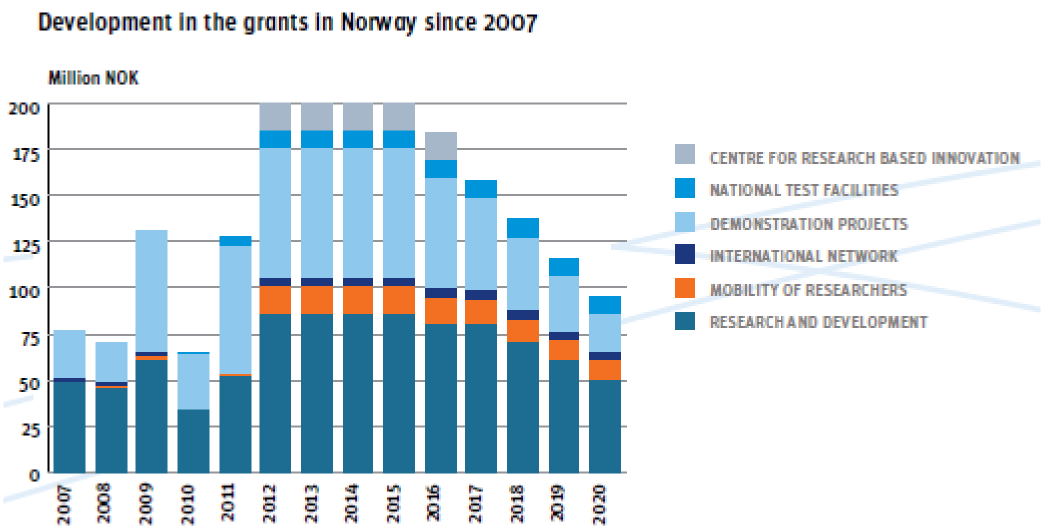
After the failure of the mentioned industry projects, public funding on fuel cells was downscaled, which “disabled the nation to reap potentially high knowledge benefits from the investments it had made, in the future” (Godoe & Nygaard, 2006:1707). The basic funding of the research institutes is with 5% also rather low which makes them dependent on contract research from industry and competitive grants from RCN.

RCN has run programmes in which considerable hydrogen-related research has been funded from application-oriented basic research toward applied research. During past years the levels of funding for open basic research has declined and it has had a negative effect on several fields including hydrogen and fuel cells (Norwegian Hydrogen Council, 2012).

The first action plan of the Norwegian Hydrogen Council for 2007–10 (2006) suggested to step up public funding for the period 2010–2015, from 76 million NOK in 2007 to200 million NOK annually in 2010-2015 (Bunzeck et al., 2008). This goal could not be achieved (see Figure 5).

Figure 5: Comparison of proposed funding development in the action plan 2007–10 and actual development of public funding for hydrogen as reported for 2007-11 in the action plan 2012–2015 (2012)





The establishment of the public enterprise Transnova has led to increased funding to demonstration activities for alternative fuels and more efficient propulsion technologies, including hydrogen and fuel cells. About eighteen hydrogen demonstration projects have been granted financial supports from Transnova in the period 2009–2014, which corresponds to an amount of NOK 52 million (see table A in the appendix).

During the last decade, RCN has supported hydrogen and fuel cell research, mainly under the RENERGI programme supporting research projects on renewable energy (2004-2012)[20]. About 23% of the programme budget was dedicated to research projects in hydrogen and fuel cells. The programme was launched in 2004, at a time when hydrogen was a prioritised policy area in Norway (see section 5). However, after some years the interest declined primarily as a consequence of the reduced activities on hydrogen within large industrial actors. Initially, projects under the HyNor initiative dominated RENERGIs portfolio. Concerning funding, the project portfolio increased during the programme period from NOK 45 mill in 2006 to NOK 60 mill in 2011. Large energy companies such as Statoil and Hydro, Statkraft and DNV were the most important industrial actors taking part in the programme. These actors have, however, since 2009 terminated their hydrogen activities. Other companies that have received funding under the programme are Elkem, NEL-Hydrogen, Nordic Power Systems and other smaller companies. In general, there are fewer SMEs which are active within hydrogen and fuel cells research in Norway compared to Denmark and Sweden (RCN, 2012).

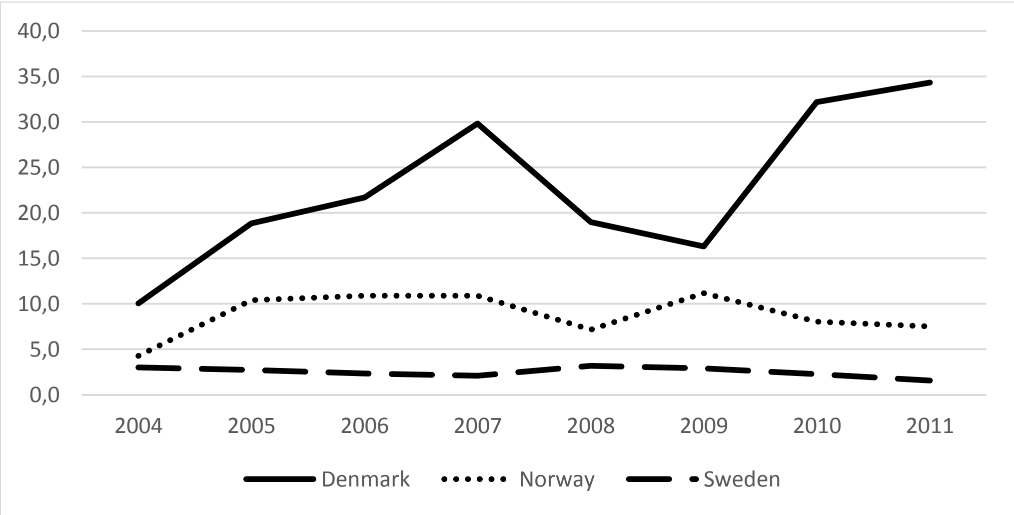
Another relevant RCN programme supporting hydrogen and fuel cells research is NANOMAT – on Nanotechnology and new materials (2006-2011). Energy and environment, including hydrogen technology have been a prioritised investment area. A new programme, NANO2021 was launched within the same field in 2012. Two projects on fuel cells receive funding under the programme after the first call for proposals. The projects are led respectively by the University of Oslo (*Biogas operated proton ceramic fuel cells with novel S-tolerant functional materials*) and by SINTEF (*Functional oxides for clean energy technologies: fuel cells, gas separation membranes and electrolysers*).

[20] The RENERGI-programme (Clean Energy for the Future) has been the Research Councils large-scale programme for energy research from 2004 – 2012. The RENERGI-programme is now in its final phase. The Research Council will continue the energy research and has established a new large programme: The ENERGIX-programme (Large-scale programme for Energy Research).

Innovation Norway (IN) is the Norwegian Government's instrument for innovation and development of Norwegian enterprises and industry. IN supports hydrogen and fuel cell projects mainly under its Environment Technology Scheme (Miljøteknologiordningen).

Figure 3 illustrates the trends in government RD&D budgets on hydrogen and fuel cells in the three Scandinavian countries since 2004.[21] Amongst the Nordic countries, Denmark had the highest public expenditures in the period 2004–2011. While Danish expenditures in 2011 were EUR34.3 million Norwegian and Swedish budgets were significantly lower at 7.5 million EUR and 1.6 million EUR respectively. In the period 2004–2011 Denmark spent around 68 per cent of the expenditures on fuel cells while 72 per cent of public expenditures in Norway were directed towards hydrogen. This picture may indicate differences in industrial specialisation in the two countries.

Figure 6: RD&D Budgets for Hydrogen and fuel cells for Denmark, Sweden and Norway 2004–2011. Total RD&D in Million Euro (2011 prices and exch. rates). Source: IEA/OECD



Note: There is no data for Finland in the IEA database.

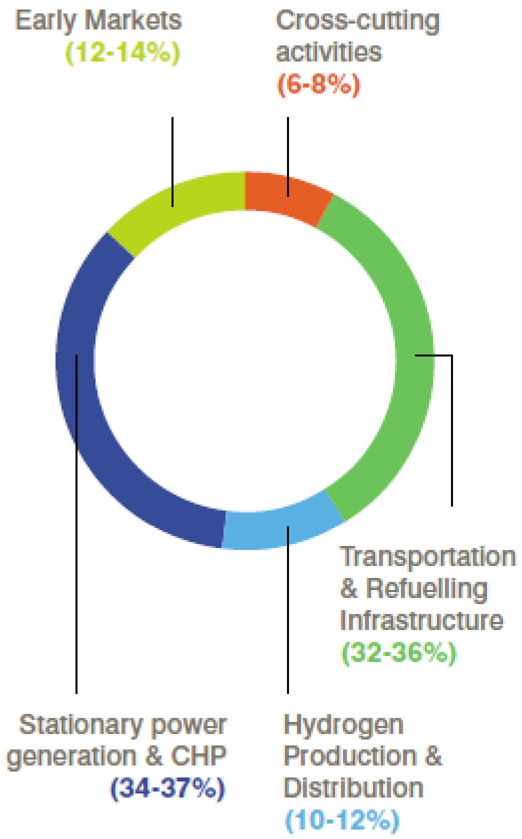
It should be mentioned that the data on demonstration budgets has many gaps, especially for Norway and Sweden, where such data are not reported consequently (Klitkou, Scordato, & Iversen, 2010). For Denmark the IEA data report on average a share of 13 per cent demonstration funding, with peaks in 2007 and 2008 with 29 and 39 per cent.

The funding of a National Centre for Pilot Testing of Hydrogen Technologies has been proposed by the Norwegian Hydrogen Council (2012) and has been supported by RCN.

Beside the national RD&D funding programmes European initiatives are also important to mention. In 2003, the European Commission established the European hydrogen and fuel cell technology platform. It was estimated that around €7.4 billion for the period 2007–2015 were required for achieving the objectives of this technology platform (New Energy World Industry Group, 2011, 21). In 2008, the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) was created as an Industrial Initiative under the EU SET Plan and had a "total budget of €940 million between 2008 and 2013, funded half by FP7 and half by industry and research contributions" (ibid.). About one third of the budget goes to transportation and refuelling infrastructure.

[21] There are no figures on expenditures on hydrogen and fuel cells for Finland.

Figure 7: Funding areas of the Fuel Cells and Hydrogen Joint Undertaking



Source: New Energy World Industry Group (2011, 21)

Projects funded under FCH JU include H2Moves Scandinavia (total budget € 19.5 million, EC funding € 7.8 million) and Clean Hydrogen in European Cities (CHIC) (total budget € 81.9 million, EC funding € 26 million). The New Energy World Industry Group estimates that the total joint financial effort for transport and refuelling in Europe is estimated at around €12.1 billion for the period 2014–2020 (ibid.). This will contribute to the introduction of 500,000 Fuel Cell vehicles and at least 1,000 hydrogen refuelling stations.

1.3 Companies/actors involved in each segment of the value chain

1.3.1 Value chain governance structure

The value chains for hydrogen and fuel cells are clearly decentralised, with firms specialised in different elements of the value chains and not one leading firm capturing the whole value chain. For hydrogen and fuel cell vehicles their respective value chains have to be developed and coordinated. However, these different value chains are currently not integrated nor coordinated by one lead firm.

Figure 8 visualises the upstream and downstream elements of the hydrogen value chain. The figure starts with primary energy sources, including renewable electricity, biomass, nuclear power, natural gas and other fossil energy sources, goes to the production, storage, and transport of hydrogen, then the distribution of hydrogen. In Norway, some of these sub-value chains are or are planned to be more coordinated than others. Here, primary energy sources are mainly renewable electricity and natural gas. Over the last decades there was more focus on the exploitation of natural gas, while nowadays renewable energy sources have become more deployed. There are also experiments with biomass gasification, but no nuclear energy or other fossil fuels than natural gas are used. The production is often on-site, but also central production exists and hydrogen is also a by-product of the chemical industry. Hydrogen production is less centralised more distributed at the country or region level, often related to local energy sources or as a by-product of industrial processes. There are a number of firms engaged in different solutions for onsite hydrogen production. In this way, centralised hydrogen production and long transport distances may be avoided. Transportation of hydrogen is mostly done with trucks, but shorter pipelines are also in use. Hydrogen is stored in compressed tanks at the production sites and at refuelling stations. Equipment for storage and transport of hydrogen in compressed tanks is produced by Hexagon, a Norwegian firm operating on the global market. In recent years, Hexagon has faced some institutional challenges on the European market, such as safety regulation for transport of gas, the heavy weight of huge compressed tank trailers and the length of these trailers (Baldwin & Newhouse, 2013; Heggem, 2013).

Figure 8: Value chain for hydrogen

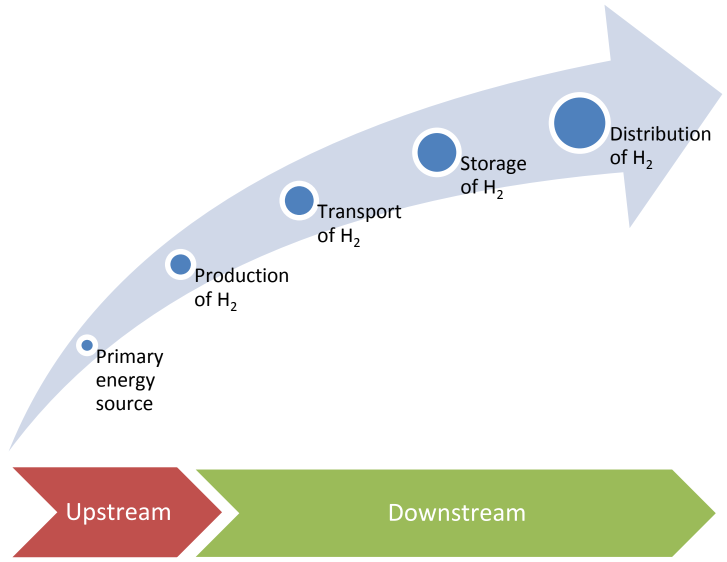
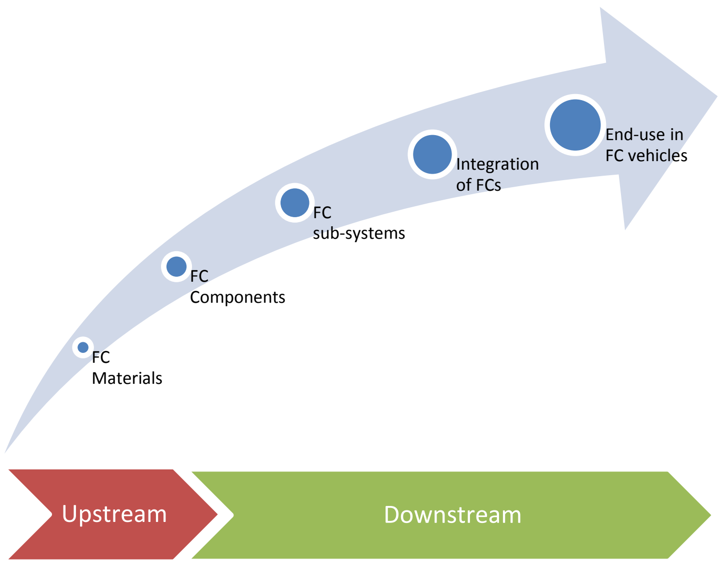


Figure 9: Value chain for fuel cell vehicles



On the fuel cell side we can distinguish between following elements of the value chain: materials, components, fuel cell sub-systems, integration of fuel cells and the end-use in fuel cell vehicles (figure 9). The value chain starts with required *materials* for the fuel cells, such as “catalysts, electrodes, membranes, polymers and gas diffusion layers” (Milburn & Adamson, 2012; Nygaard, 2008, 34). These materials belong to several sectors and not only to fuel cell vehicles. They are an input to the necessary *components* and their assembly in fuel cell *sub-systems*. Regarding components we can distinguish between following components for PEMFC: membrane electrode assembly, bi-polar plates, gas flow channels, and end plates.

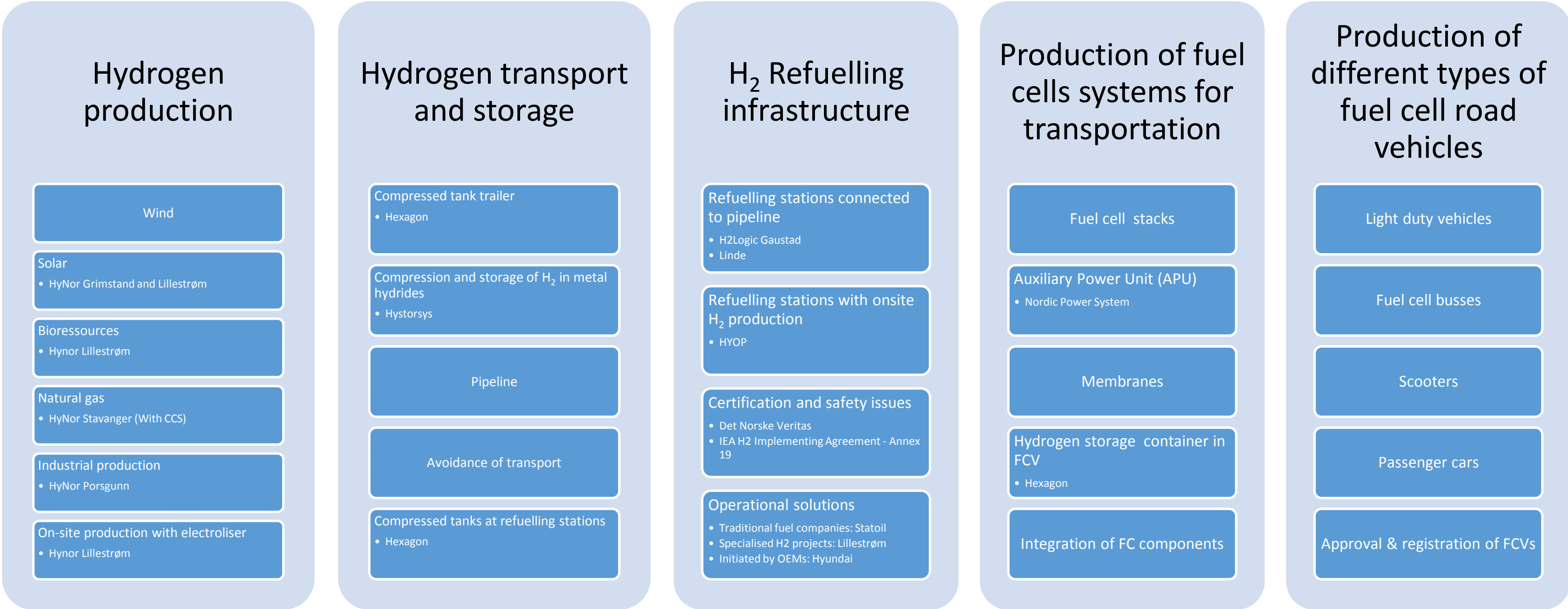
Fuel cell stacks, sensors, hydrogen storage tanks, fuel systems, heat exchanger, power conditioner and power inverters are elements developed in a fuel cell subsystem (Nygaard, 2008, 35). Fuel cell stacks are produced by a number of firms all over the world, but they will probably merge into a lower number of firms (Milburn & Adamson, 2012). Hydrogen storage containers in FC vehicles are produced by the same globally operating firm as hydrogen storage mentioned above (Heggem, 2013). Then, the sub-systems and components get *integrated* in PEM fuel cells, and, finally, the fuel cells are used in different types of vehicles. There are some important OEMs which are committed to produce passenger FCV in the near future, such as Hyundai, Toyota, Honda, Renault-Nissan, Ford and Daimler. While Hyundai, Toyota and Honda will go for the Scandinavian market by 2015, Renault-Nissan, Ford and Daimler announced in 2013 a partnership to jointly develop fuel cell stack and other central system components for fuel cell vehicles by 2017.[22] However, passenger cars will not be the first larger market for fuel cell vehicles, but scooters and light duty vehicles, such as forklifts, will be deployed much earlier (Jerram & Adamson, 2013). FC scooters need much less hydrogen, but they will compete with battery electric scooters. Norway has developed into an early market for the commercial rollout of fuel cells electric vehicles (FCEV) and a number of original equipment manu-facturers (OEMs) of vehicles are currently involved in Norway’s hydrogen activities (Matthey, 2013).

Table B in the annex lists Norwegian actors, such as companies, research institutes, universities and university colleges, public research funders, interest organisations and service providers that are active in different segments of the hydrogen value chain. The overview allows us to characterise the technology innovation system for hydrogen in Norway. Actors are classified according to their role relative to main activities (commercialisation, component development, R&D, services) type of hydrogen application (portable, stationary, transportation) and along the hydrogen chain (control system, distribution, FC/ICE, production, storage, system integration). The list is an adapted version of an overview presented in the Norwegian hydrogen guide 2012 published by the Norwegian Hydrogen Forum.[23]

Figure 10 summarises the value chain elements for H_2 production, transport and storage, and for H_2 refuelling infrastructure, FC systems for transportation and FCVs and respective Norwegian actors.

[22] http://www.technologyreview.com/view/510416/ford-daimler-and-nissan-commit-to-fuel-cells/
[23] http://www.hydrogenguiden.no/hydrogenguide/portal/portal_list_companies_view

Figure 10: Value chain segments for H_2 production, transport and storage, and for H_2 refuelling infrastructure, FC systems for transportation and FCVs



2 Key technologies and assessment of their technological development stage (dominant design, disruptive or incremental)

Fuel cells and hydrogen technologies are inter-related technologies that can provide energy to a diverse set of products. They are generic technologies with application possibilities in a broad range of sectors ad markets.

The basic principle of these technologies is an electrochemical reaction between hydrogen and oxygen that produces electricity and water (Nygaard, 2008). Water is the only emission in the energy conversion process. Hence, a wide application of hydrogen and fuel cell technologies in products and processes may contribute to the move towards less GHG emissions locally and globally. While the technologies have improved rapidly during the last years and the distance between costs and revenues is decreasing, many uncertainties remain about scientific solutions, technological applications and market development

2.1 Technologies for hydrogen production, distribution and storage

A challenge related to the production of hydrogen is the way it is obtained. Hydrogen does not exist in a pure form but must be extracted from a source involving the use of energy. There is hence a sustainability aspect related to the production of hydrogen. Other challenges are related to the costs of production.

Hydrogen can be extracted from different source and different production methods can be used Here we list some of the most common methods:

- Steam methane reforming from fossil raw materials, mainly coal and natural gas
- Bio-mass and solar-thermal for direct production of hydrogen
- Electrolysis of water with electricity from renewable sources such as wind, solar and hydro
- Electrolysis of water with electricity from nuclear power
- Directly from nuclear heat (Nygaard, 2008)

Steam methane reforming (SMR) from natural gas and electrolysis of water are the two dominant production methods. SMR is commonly used for industrial and transport applications. Some of the most important challenges related to this technology are high temperatures, the use of costly materials and the need to include complex carbon monoxide removal systems.

With hydrogen electrolysis, it is possible to use a renewable energy source (Nygaard, 2008). A cost effective alternative is hydrogen produced from electrolysis by so called “peak shaving”. This method makes use of the electrical energy otherwise lost when the grid is not able to consume the electric energy from the power plant (wind, nuclear, etc.). By connecting hydrogen electrolysers to the power production unit, hydrogen can be stored and the energy later fed back into the grid or used as a transport fuel. Another way to use hydrogen cost effectively is to use the hydrogen that is produced as a by-product from the chemical industry (Nygaard, 2008). A further way is the production on demand.

2.2 Technologies for fuel cells

The fuel cell is a technology that enables production of electricity by a chemical reaction between hydrogen and oxygen. When hydrogen and oxygen react in the fuel cell, they combine and produce electricity, with water as the only exhaust (Nygaard, 2008). The no-emission effect occurs when the fuel cell is run with pure hydrogen but when other hydrogen-rich fuels are used such as methanol, biogas or natural gas some level of emissions of CO_2 are involved.

Fuel cells have a high efficiency and therefore decrease energy consumption. A further characteristic is that a fuel cell is a highly complex product and its design can differ considerably depending on type and application. There are mainly four different types of fuel cells that firms are working with today, classified according to the electrolyte they use. They are normally distinguished on the basis of whether they are high-temperature or low-temperature fuel cells and the specific areas of application vary accordingly (Nygaard, 2008).

- Polymer Electrolyte Membrane Fuel Cell (PEMFC) - used for transportation purposes
- Direct Methanol Fuel Cell (DMFC) - designed for consumer electronics
- Solid Oxide Fuel Cell (SOFC) - used for stationary combined heat and electricity plants
- Molten Carbonate Fuel Cell (MCFC) - used in electricity production in large plants

For all types of fuel cells there are particular technological and market-related barriers. Briefly, the main barriers are linked to *costs, reliability, durability and infrastructure*. Many see costs as the largest barrier for commercialisation of fuel cells as they cannot yet compete in price with other technologies such as batteries of the combustion engine in cars. Production volumes are still low and the use of expensive materials such as platinum is a problem that producers are trying to tackle (Nygaard, 2008). The lack of infrastructure is also seen as a major barrier.

Norway has well-developed research environments for fundamental R&D in material sciences and electrochemistry. Both fields are active in fuel cell research. During the 1980s and 1990s there were four large fuel cells development projects carried out by big Norwegian enterprises engaged in oil and gas (Statoil, Norsk Hydro and Kværner). Three of the four projects were designed to develop solid oxide fuel cells (SOFC). Besides the large enterprises, there were also several research institutes active in patenting in this field: The most important once were the Norwegian Defence Research Establishment (FFI), SINTEF Group and the Institute for Energy Technology (Klitkou, 2007).

Today, the fuel cell technology is ready to be commercialised for the application in vehicles. There are still high potentials for reductions in size and cars, but they can be achieved with a market introduction of fuel cell vehicles. Therefore, the mentioned large OEMs start now to build factories for fuel cell vehicles. To use fuel cells is still rather unknown – therefore the largest barrier is not technology but the lack of knowledge about the technology.

3 Market characteristics

The market for hydrogen is still limited, but will grow very fast after 2015 with the announced introduction of fuel cell passenger cars on the Scandinavian market by OEMs from Asia. The market for FC vehicles is still limited, but niche market opportunities exist for FC scooters, busses and light duty vehicles (Jerram & Adamson, 2013).

Several policy studies on the introduction of hydrogen as an energy carrier in the Norwegian transportation sector have found hydrogen to be essential if Norway is to cut its emissions in the transportation sector in the long run (NorWays, 2009). Studies have concluded that hydrogen could be competitive at around 5% market penetration, which has been forecasted to be potentially achieved by 2025. According to these scenarios the hydrogen supply base would consist of a mixture of on-site electrolysis, natural gas and by-product hydrogen and gasified biomass (Matthey, 2013).

Norwegian policy incentives which favour zero emission vehicles, the high share of renewable energy in domestic electricity production and the active support by regional and local authorities are important reasons for the car manufacturers' interest in delivering FCEVs to Norway. This makes Norway to an ideal test bed for fuel cell vehicles.

Also some few small and medium sized enterprises are engaged in the hydrogen technology field, such as the producers of small electrolysers for onsite production of hydrogen or hydrogen compression with metal hydrides technology, applied on the storage of hydrogen. Beside hydrogen production technologies the storage of hydrogen in compressed tanks has become a valuable market opportunity for some industrial players, in Norway especially Hexagon, which is operating globally. However, there are no Norwegian firms providing integrated hydrogen fuel cells solutions.

There can be some future market niches in specialised vehicles for transport in harbours, ferries and other maritime vehicles. Here the cooperation with the other Nordic countries is a good possibility.

4 Geographical scope

Norway is a rather long stretched country with huge differences regarding population density, traffic volume, access to renewable electricity and natural gas, and availability of by-product hydrogen from existing industry plants and of biomass as feedstock for hydrogen production. Therefore, a regional approach is necessary to take hold of the regional options for supply and demand of hydrogen (Stiller, et al., 2010). The NorWays project compared the options of the different Norwegian regions and concluded that Oslo as the capital of Norway with a half million inhabitants with no major industry and own energy resources available will be the earliest user centre for hydrogen fuel cell cars. Oslo will be followed by Telemark, which is a centre of metallurgic and chemical industry and has access to hydropower. The region of Rogaland in Western Norway is also foreseen as a potential centre for hydrogen users with access to hydropower and wind power and a landing place for natural gas (Rosenberg et al., 2010). Interestingly, the modelling of the transition to hydrogen fuelled transport showed a faster introduction for Telemark and Rogaland in comparison to Oslo. Reasons are the available hydrogen industry by-product in Telemark and the access to surplus renewable electricity in Rogaland (ibid.).

HyNor, while being a national development project it is geographically organised in local projects along the highway from Stavanger over Grimstad, Porsgrunn and Drammen to Oslo. These local projects are rather autonomous from the ventral HyNor organisation (Kårstein, 2008, 84). Currently, hydrogen refuelling stations are operating in Porsgrunn (Grenland), Drammen, Lillestrøm and Oslo. In 2006, the first Norwegian refuelling station was opened in Forus, Stavanger. The station was based on cooperation between Statoil and AGA, and was operated by Statoil. In 2011, the Stavanger station closed down because Statoil Fuel & Retail had no interest in pursuing this pathway further on (read also section Distribution of hydrogen for transportation means and related infrastructure).

The geographical orientation has recently shifted towards establishing a refuelling network primarily in the Oslo region. There were several reasons for this shift: (1) the introduction of fuel cell vehicles was not as fast as anticipated, (2) because of the withdrawal of the larger companies the HyNor project had to focus efforts on the most promising region, and (3) the other hydrogen projects were concentrated in the capital region and provided synergy effects and the possibility to build up a hydrogen cluster in the capital region. The attempted development of a hydrogen highway was good for publicity, but not for introducing the technology because it is too risky economically. Several of the sub-projects could not achieve financing and had to be terminated over the last years. There are plans for local initiatives to establish hydrogen infrastructure in Bergen and Stavanger. HyNor encourages such initiatives which are supported by the local authorities.

In addition, HyNor is embedded in a global niche market for hydrogen and fuel cells, cooperating with international partners, in the US (California Fuel Cell Partnership) and in Scandinavia (Scandinavian Hydrogen Highway Partnership) to open up a “hydrogen link” between Norway, Sweden and Denmark. The Scandinavian Hydrogen Highway Partnership was founded in 2006. And the establishment of this partnership was one of the major efforts of the HyNor project (Sataøen, 2008).

Interesting political initiatives to introduce hydrogen in the transportation sector are being pursued at the regional level in the Akershus County. The Akershus County Council (ACC) recently launched a long-term strategy for the introduction of hydrogen in the transportation sector for the period 2013-2025 and has shown political leadership. The strategy supports the Counties overall climate goals to reduce greenhouse gas emissions. The goal for transport is to reduce climate emissions from road traffic with 20% compared to the 1990 level by 2030. During past years the county has allocated around EUR9.2 mill to development and maintenance of a hydrogen infrastructure and for the establishment of a FC bus fleet in the Oslo metropolitan area. As illustrated in figure 3 the hydrogen infrastructure in Eastern Norway currently consists of six hydrogen fuelling stations and 23 test FCEVs. According to plans, a common H_2 strategy will be launched with Oslo City in 2014. The ACC strategy is supported by a project group including research institutes, industry, public financial bodies and interest groups:

- Research & development: Institute of Energy Technology (IFE), Institute of Transport Economics (TØI), Hynor Lillestrøm;
- Industry, H_2 producers: Akershus Energi, AGA-Linde, HYOP;
- Automotive industry: Mercedes, Toyota;
- Interest / Environmental organizations: Norwegian Automobile Federation (NAF), Zero; Emissions Resource Organization (Zero), Norwegian Hydrogen Forum;
- Public bodies: Oslo City, Transnova, Ruter (Public transportation of Oslo and Akershus).

Figure 11: The Eastern Norway hydrogen infrastructure 2013.

Source: Akershus County Council hydrogen strategy.

There have been a number of activities promoting the deployment of fuel cell vehicles, such as open exhibitions, workshops and demonstrations of such vehicles.

Figure 12: FCVs at the Exhibition "Fossil free travel opportunities" near the City Hall of Oslo (2013).

Source: Klitkou

5 Institutional context

At the national level, initiatives on hydrogen started in the early 2000'. The White Paper on natural gas from 2002 (Report to the Storting no.9 (2002-2003) *Om innelands bruk av naturgass mv*.,) describes the government's plan for an increased investment in hydrogen and for the establishment of a national hydrogen programme. The (renewed) international interest for investing in hydrogen as an energy carrier may explain the launching of initiatives on hydrogen in Norway. The HyNor project was launched in light of these policy processes.

In 2003, the Norwegian government appointed a hydrogen committee (also known as the Aam-committee) to develop a national hydrogen programme and a national hydrogen strategy. The committee conclusions were presented in the Official Norwegian Report NOU 2004:11 – *Hydrogen som fremtidens energibærer*, a central document which initiated the government's activities on hydrogen. The report presents three main arguments for pursuing a Norwegian hydrogen initiative: Norway's large natural gas resources, the environmental aspects, and the potential for national industrial development. These arguments illustrate the main official rationales for the political support for hydrogen in Norway:

- the exploitation of Norwegian natural gas for production of hydrogen;
- industrial hydrogen development;
- potential environmental gains from the usage of hydrogen;
- participation in international research at the forefront (Kårstein, 2008).

It was in light of these policy processes that the HyNor project was launched. Other important policy documents in this context are listed in table 3. According to the representative of the Norwegian Hydrogen Council, currently Norway lacks a visionary policy favouring hydrogen as an important energy carrier to overcome the lock-in on oil and gas – this is not prioritised by the Norwegian Ministry of Petroleum and Energy. Policy should push more in that direction to create a public demand for such technology and to build the necessary hydrogen infrastructure. This could trigger industrial engagement as the example of CCS has shown.

At ministerial level hydrogen initiatives are driven by the Ministry of Petroleum and Energy and the Ministry of Transport and Communications. These ministries established jointly the Hydrogen Council in 2005, with the mandate to act as an advisory board to the Ministries in matters related to hydrogen. The Council consists of representatives from industry, research, education and organisations. The Norwegian Hydrogen Council has so far issued two Action Plans for the periods

2007–2010 (2006) and 2012–2015 (2012). In December 2006, the Norwegian Hydrogen Council published the first action plan (2006). Recommendations in the first Action Plan have been implemented, such as equal incentives for fuel cell and battery-electric vehicles and public funding to the demonstration of fuel cells in ships. Furthermore, the recommendation of establishing Transnova was realized in 2008 through the Climate Agreement (Klimaforliket). This has led to increased public funding to alternative fuels and more efficient propulsion technologies, including hydrogen and fuel cells. In 2012, the council published the second action plan (2012). This action plan included again a number of recommendations, such as an incentive scheme for operating hydrogen refuelling stations, strengthened policy instruments to ensure efficient phase-in of zero emission vehicles, improved public budgets for transport R&D and demonstration projects, exploration of hydrogen export potentials from Norway, and public procurement of zero emission vehicles (Norwegian Hydrogen Council, 2012; Pütz & Nørbech, 2012).

In recent years, several reports and policy documents highlight the importance of hydrogen as an essential energy carrier which will help cut emissions in the Norwegian transportation sector (Climate Cure 2020[24] and NOU 2012:9 of the Energy Committee[25]). The section on hydrogen in the passenger car fleet in the *Climate Cure report 2020* (*Measures and Instruments for Achieving Norwegian Climate Goals by 2020*) gives an account of the current and future situation for hydrogen development in Norway. Up to the period 2030 a greater technological advancement and falling costs is expected. A slow market introduction is assumed from 2016 corresponding to the car manufacturers' launch strategies. It is also being recognised that only a limited amount of cars will be available for the Norwegian market during the first few years after the commercial roll out in 2015 and up to 2020. After 2020, growth is expected to remain slow until costs reach an acceptable level. The scenario is based on the assumption of a breakthrough on the last remaining technological problems for hydrogen cars. One of the greatest challenges perceived is related to costs of hydrogen relative to the costs of electrification. In the same time the advantages of hydrogen, such as rapid filling speed coupled with range over electricity is recognised (Norwegian Public Road Administration, 2010).

The White paper on climate policy stated that Norway will continue to have a leading internationally to facilitate the use of electrical and hydrogen vehicles (Miljøverndepartementet, 2012). The White paper listed a number of the policy instruments mentioned above which support the phase-in of electrical and hydrogen vehicles, such as free municipal parking, free access to bus lanes, and no charges on toll roads or state ferries. In 2012, Norway ratified the EU Renewables Directive, which means for Norway a share of 67.5 per cent of gross final consumption of energy from renewable sources and 10 per cent from renewable energy sources in transport fuels by 2020 (Utenriksdepartementet, 2011). Table 3 gives a short overview over the relevant official policy documents on hydrogen and fuel cells in Norway.

[24] The Climate Cure2020 process was an initiative launched on behalf of the Ministry of Environment the Climate and Pollution Agency. In cooperation with the Norwegian Water Resources and Energy Directorate (NVE), Statistics Norway, the Norwegian Public Roads Administration and the Norwegian Petroleum Directorate they prepared a list of specific measures to reduce domestic CO2 emissions in Norway by 2020 and produced an analysis of how to implement the measures. The final report formed the basis of the government's assessment of Norwegian climate policy.

[25] The Energy Committee who was established with the mandate to evaluate the energy and power balance in Norway until 2030 and 2050.

Table 3: Overview of Norwegian official documents on hydrogen and fuel cells. Source: NIFU

Date	Title	Organisation	Type of document
1998	NOU 1998: 11 Energi- og kraftbalansen mot 2020	Commissioned by the Ministry of Petroleum and Energy	Official Norwegian Report
2002	NOU 2002:7 Gassteknologi, miljø og verdiskaping	Commissioned by the Ministry of Petroleum and Energy	Official Norwegian Report
2002	Report to the Storting no.9 (2002-2003) - *Om innenlands bruk av naturgass mv.,*	Ministry of Petroleum and Energy	White paper
2004	NOU 2004:11 – *Hydrogen som fremtidens energibærer*	Commissioned by Ministry of Petroleum and Energy and Ministry of Transport and Communication	Official Norwegian Report
2005	*Strategi – Satsing på hydrogen som energibærer innenfor transport og stasjonær energiforsyning*	Ministry of Petroleum and Energy and Ministry of Transport and Communication	Policy strategy
2006	*Norsk storsatsing på hydrogen – Handlingsplan for perioden 2007-2010.*	Norwegian Hydrogen Council	Action plan
2008	*Energi21- National strategy for Research, Development, Demonstration and Com-mercialisation of New Energy Technology*	Energi21/by mandate from the Ministry of Petroleum and Energy	Official strategy
2012	*Norway a global leader in Hydrogen. Action Plan 2012-2015. How to maintain our pioneering role*	Norwegian Hydrogen Council	Action plan
2010	*Climate cure 2020 -Measures and Instruments for Achieving Norwegian Climate Goals by 2020*	Ministry of the Environment and Climate and Pollution Agency	Official advisory report
2011	Proposisjon til Stortinget: Samtykke til fornybardirektivet	Ministry of Foreign Affairs	Ratification of Renewable Directive
2011	*Energi21- National Strategy for Research, Development, Demonstration and Commercialisation of New Energy Technology- revised strategy*	Energi21/by mandate from the Ministry of Petroleum and Energy	Official strategy
2012	NOU 2012: 9 Energiutredningen – verdi-skaping forsyningssikkerhet og miljø	Commissioned by the Ministry of Petroleum and Energy	Official Norwegian Report
2012	St. meld. 21 (2011–2012) Norsk klimapolitikk	Ministry of the Environment	White Paper

Energi21 is the collective R&D strategy for the energy sector in Norway and it sets out the desired course for research, development and demonstration of new technology for the 21th century. The Energi21 initiative was launched with a mandate from the Ministry of Petroleum and Energy. The initial Energi21 strategy report was presented in February 2008, marking the first time that energy stakeholders in Norway were unified behind a collective research, development and demonstration (RD&D) strategy in the energy sector (Energi21, 2008). The mandate has been restricted to the stationary energy sector and energy consumption and carbon capture. Hydrogen and fuel cells is not a priority area in the new strategy (Energi21, 2011). The board of Energi21 has recommended the government to enlarge the mandate of Energi21 to also include the transportation sector. The Hydrogen Council has put forward the same recommendation (Hydrogen Council, 2012).

To reduce emissions from the transportation sector a number of policy support measures and incentives are in place. In Norway biofuels, biogas, CNG and hydrogen are all subject to lower or exempt from, fuel and CO_2 taxes. All electric cars, including fuel cell electric vehicles[26] benefit from a number of incentives: they are exempt from purchase tax and VAT, receive a 90 % discount on

[26] According to regulations adopted by the Norwegian Storting in 2010 hydrogen vehicles powered by electricity generated by fuel cells are defined as electric vehicles. See: http://www.lovdata.no/for/sf/sv/td-20091127-1499-004.html

annual road tax, pay no toll or municipal parking fees, qualify for free ferry passage and have access to bus lanes and public charging points.

6 Path dependencies

The initial conditions for the transition to hydrogen and fuel cell in transport systems in Norway are characterised by path dependencies related to hydropower and the large oil and gas sector. Table 4 summarises the key processes for a greater deployment of hydrogen and fuel cell technology in Norwegian road transport: initial path dependent conditions, possible path creation process, new path establishment processes, barriers to new path creation and envisioned landscape change outcomes.

Hydrogen production and natural gas

Over the last decades the existing hydroelectric power generation and offshore oil and gas production have secured Norway's economic success, but at the beginning of the 2000's there was, according to an OECD study on the deployment of hydrogen and fuel cell technology in Norway, a growing interest in exploiting the natural gas resources for hydrogen production, to act on environmental concerns and to see hydrogen as a market opportunity for the Norwegian industry (OECD, 2006). The report pointed out that the Norwegian society needed a hydrogen supply infrastructure and that collaboration with the global automotive industry were still too weak (OECD, 2006, 211). There exist many possibilities to produce hydrogen, either by using electrolysis from renewable electricity, reforming of natural gas or biogas, or exploiting by-product hydrogen. In the 1990s and 2000s there was more focus on the exploitation of natural gas to produce hydrogen, while nowadays renewable energy sources have become more deployed, both renewable electricity and biomass gasification.

Refuelling stations and localised hydrogen production

Traditionally there has been a lock-in on the use of natural gas, but with the experiences from the most recent hydrogen projects, such as HyNor or NorWays, also other technology options have been improved and companies have emerged which are specialised in electrolyser, H_2 refuelling stations, H_2 storage and compression solutions. This has contributed to the establishment of a limited refuelling infrastructure in the greater Oslo area. However, there were only limited connections to the global automobile industry and the acquisition of fuel cell vehicles was hampered by the fact that they were not available or the available cars were too expensive. This was the reason why commercial retailers of hydrogen could not maintain the established refuelling stations – the costs for operation and maintenance were too high compared to the income from a very low number of FC vehicles. The distribution of hydrogen remains somehow still a barrier. The lack of Norwegian companies providing integrated hydrogen fuel cell solutions is also a barrier for the faster commercial deployment of this technology.

Political framework conditions

Political framework conditions have contributed to more favourable conditions for fuel cell vehicles compared to other countries. Fuel cell cars and battery electrical cars are treated equally in Norway regarding taxes, parking, road tolls, free ferry use, use of bus lanes etc., which means rather favourable conditions compared to internal combustion vehicles. However, a visionary political focus on replacing oil and gas with hydrogen is lacking, which also includes the funding of the development of a national infrastructure for hydrogen as an important energy carrier.

Technological barriers

Demonstrations of the fuel cell vehicles and of fuel cell refuelling stations have shown that there are no major technological barriers for the wider deployment of hydrogen and fuel cell vehicles.

Industrial actors

After the failure of the big industrial projects in the early 2000s and the withdrawal of bigger industrial players, there exist today only a very limited number of companies, which are engaged in H2/FC technology and which could support R&D of public research organisations.

Market possibilities

The market penetration by fuel cell vehicles in 2025 in the greater Oslo area is estimated to be about 55.000 FCV and 30 H_2 refuelling stations. However, larger investments are needed for the establishment of this refuelling infrastructure – about 100–220 million € in greater Oslo area until 2025. There are several possible path establishment processes: public procurement of fuel cell vehicles for car fleets (postal delivery, road authorities, renovation service etc.) in public services and strengthening of niche markets, such as fuel cell scooters, bus fleets and light duty FCVs.

Table 4: Path dependencies and path creation processes for H2/FC in Norway (addapted from Simmie, 2012)

Initial conditions	**Path creation process**	**New path establish-ment processes**	**Barriers to new path creation**	**Landscape change outcome**
Path-dependencies: hydropower and oil and gas sector – large energy companies are reluctant to engage in H_2 activities Many possibilities to produce H_2: electrolysis from renewable electricity and reforming of natural gas, and by-product hydrogen Lacking infrastructure for distribution of H_2 Technology advantage in electrolysis from renewable electricity and reforming of natural gas, but also creating lock-in, especially regarding natural gas Limited connections to global automotive industry and too low number of vehicles produced globally.	Subsidies for procurement of FC busses and passenger cars Local projects integrating different H_2 production methods Regional hydrogen strategy in Oslo-Akershus Establishment of H_2 refuelling infra-structure Tax exemption for fuel cell vehicles in parallel to electrical vehicles Engagement of environmental NGOs, firms and researchers in hydrogen society Fulfilment of EU directive for alternative fuels is a target.	Connection of Norwegian H_2 infrastructure with other Nordic countries to allow travels throughout the Nordic region and to Germany Strengthening of niche markets: - Conversion of major city bus fleets - Introduction of FC scooters - Deployment of light duty FC vehicles Public procurement of FC vehicles for car fleets in public services Market penetration in 2025: 55.000 FCV and 30 H_2 refuelling stations in greater Oslo area Cost of H_2 is calculated to reach a competitive level of 15€/kg by about 2019 and of 8-9 €/kg by 2024-25 (Pütz & Nørbech, 2012)	Basic economic barriers: Delivery costs of FC vehicles remains high No strong investors for H_2 refuelling infrastructure - high first-mover risk Too high operation and maintenance costs for H_2 refuelling stations when low number of FC vehicles H_2 costs vary substantially with demand, therefore cost levelling measures will be required Institutional barriers: Standards, codes and regulations on hydrogen quality, metering at refuelling stations and transports on roads are not harmonised and do not support deployment of H_2/FC technology Lack of political leadership by the	2025: H_2 may be cost competitive and subsidies should not be required thereafter (NorWays, 2009) 2040: 1.760,000 FC vehicles (Pütz & Nørbech, 2012) 2050: nationwide H_2 infrastructure with 1.100 stations (NorWays, 2009) 2050: total investment in a nation-wide H_2 refuelling station infrastructure: 1.5 billion €$_{2005}$ up to 2050 = 850€ per car (NorWays, 2009) McKinsey study: cost of 1000–2000 € per car or approx. 5% of the overall costs of FCEV's (McKinsey & Company, 2011) Domestic renewable fuels (H_2, electricity, biofuels) cover all transportation fuel needs.

		Total investment in H_2 infrastructure: 100-220 million € in greater Oslo area until 2025.	government Too low funding available for demonstration projects Social/cultural barriers: Competition between fuel cell vehicles and battery electrical vehicles.	

7 Conclusions

Concluding we can say that the major barriers to new path creation are as following:

- *economic barriers,* such as high delivery costs of FCVs, high investment costs for H_2 refuelling infrastructure and high operation and maintenance costs for this infrastructure as long as there are only few FCVs;
- *industrial barriers,* such as lacking strong industrial actors engaged in fuel cell and hydrogen technology, backing up public R&D on this technology;
- *market entrance barriers,* such as lacking refuelling infrastructure compared to charging points for battery electrical vehicles and high prices for FCVs;
- *political barriers,* such as lacking political leadership at the highest political level to ensure the necessary infrastructure for the deployment of hydrogen as an important energy carrier and to overcome the existing lock-in on oil and gas;
- *institutional barriers,* such as lacking European standards, codes and regulations on hydrogen quality, metering at refuelling stations and transports on roads are not harmonised, too low public funding for R&D and operation and maintenance of refuelling stations; and
- *social/cultural barriers*, such as competition between fuel cell vehicles and battery electrical vehicles, lack of knowledge on fuel cells and fears for hydrogen accidents.

Appendix

Table A: Hydrogen demonstration projects supported by Transnova

Project leader	Name of project	Financial support NOK	Project period
GasPlas AS	Mobile H2 Plasma Reactor	9 000 000	2010 - 2012
Hynor Lillestrøm	Introduksjon av hydrogen som drivstoff, basert på lokal produksjon fra fornybare energikilder	4 900 000	2010 - 2012
Kunnskapsbyen Lillestrøm	NextMove – samarbeid med Sverige og Danmark om nullutslippskjøretøy	330 000	2011 - 2013
Kunnskapsbyen Lillestrøm	Hydrogen Gardemoen – mulighetsstudie	300 000	2011
Prototech	Videreutvikling av framdriftssystemer for skip basert på hydrogen og brenselceller	1 750 000	2010
RotoBoost H2 AS	Kompakt hydrogenproduksjon	2 800 000	2012 - 2014
Ruter	Demonstrasjon av hydrogenbusser	12 000 000	2010 - 2011
SINTEF	H2moves Oslo	12 000 000	2010 - 2012
SINTEF Materialer og kjemi	Hydrogen til transport fra fornybar energi i Midt-Norge	250 000	2012 - 2013
Transportøkonomisk Institutt (TØI)	Tiltakskatalog for transport, miljø og klima	500 000	2011
Veolia Transport Bane as	Utvikling av trippelhybrid buss	50 000	2010
Zero	Miljøvennlige drivstoff og kjøretøy	1 275 000	2010 - 2011
Zero	Zero Emission Rally 2010	400 000	2010
Zero	Første del av HyNor fase 2	3 600 000	2009 - 2011
Zero	Zero Emission Rally 2011	500 000	2011
Zero	Tilleggsfinansiering av Next Move	1 950 000	2012 - 2014
Zero	Virkemidler for å bygge hydrogenstasjoner	60 000	2012
Zero and Green Highway	Zero Emission Rally 2012	700 000	2012
Total grants		***52 365 000***	

Table B: Overview of Norwegian actors in the hydrogen value chain, adapted from the Norwegian hydrogen guide 2012

NORWEGIAN ACTORS	ACTIVITIES				APPLICATION			HYDROGEN CHAIN					
	Commercialisation	**Components**	**R&D**	**Services**	**Portable**	**Stationary**	**Transportation**	**Control systems**	**Distribution**	**FC/ICE**	**Production**	**Storage**	**System integration**
Government agency													
Innovation Norway	x	x	x	x	x	x	x	x	x	x	x	x	x
Research Council of Norway		x	x	x	x	x	x	x	x		x	x	
Interest organisations													
Bellona			x	x		x	x		x		x		
ZERO				x		x	x						
Member and consumer organisation													
Norwegian Automobile Federation				x			x						
Private companies													
AGA AS	X	x	X						X		X	X	X
Air Liquide Norway AS	X	X	X						X		X	X	X
Akershus CountyCouncil				x			x		x		x		
Akershus Energi AS	x			x					x		x	x	
Bertel O. Steen AS/Mercedes-Benz		x					x						
Birkebeinerlaugets Bedriftsutvikling AS				x									
Carbontech Holding AS	x	x	x			x					x		
CerPotech			x		x	x	x		x	x	x		x
Det Norske Veritas AS	x	x	x	x		x	x		x		x	x	
Eidesvik Offshore ASA			x	x			x			x			
GasPlas AS	x		x		x	x	x				x		x
GexCon	x	x	x			x	x	x	x		x	x	
Hynor Lillestrøm AS	x	x		x			x		x		x	x	x
HydrogenPartners AS	x	x	x	x		x	x	x	x		x	x	x

HYOP AS	x			x			x	x	x		x	x	
Hyundai Motor Norway AS	x						x						
Hystorsys AS	x	x	x			x	x					x	x
Kongsberg Automotive	x	x	x				x	x		x			
Lillestrøm Centre of Expertise				x									
Lindum AS	x		x				x				x		
Lyse Neo				x			x		x		x		
NEL Hydrogen	x	x	x	x		x	x	x	x		x	x	x
Nordic Power systems	x	x	x		x	x				x			x
Norges taxi							x						
n-Tec	x		x									x	
Protia AS	x	x	x								x		
Prototech AS	x	x	x		x	x	x	x			x	x	
Raufoss Fuel Systems AS	x	x	x	x		x	x		x			x	x
RotoBoost AS			x		x	x	x				x		x
Ruter AS	x			x			x		x				
Scatec AS	x		x			x						x	
Scanpower AS	x	x	x	x		x	x		x		x	x	
SVAFAS Stavanger Valve & Fitting AS	x	x		x				x					x
Vardar AS			x				x		x	x	x		
Westcon Power & Automation	x		x				x	x					x
ZEG Power AS	x	x	x			x					x		x
Public enterprise													
Enova SF				x		x							
Gassnova SF	x	x	x	x		x					x		
Transnova	x			x			x						
Public transport executive													
Ruter				x			x						
Research centre													

Lillestrøm Centre of Expertise				x			x						
Research institutes													
Christian Michelsen Research AS			x		x	x	x		x	x	x		x
Institute for Energy Technology (IFE)		x	x		x	x	x	x	x	x	x	x	x
Norwegian Defence Research Establishment (FFI)			x		x		x	x		x		x	x
SINTEF		x	x	x	x	x	x	x	x	x	x	x	x
Tel-Tek			x				x						
Western Norway Research Institute			x	x			x						
Trade organisation													
Energy Norway			x	x		x							
Universities and university colleges													
Buskerud University College		x	x				x	x					
Norwegian University of Life Sciences (UMB)			x										
NTNU Department of Chemical Engineering			x		x	x	x	x		x	x		
NTNU Department of Chemistry			x		x	x	x				x		
NTNU Department of Material Sciences and Engineering			x		x	x	x				x		
University of Agder		x	x							x	x		
University of Bergen		x	x			x	x	x					
University of Oslo			x						x		x	x	

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