FuelCellToday

The leading authority on fuel cells

Fuel Cells and Hydrogen in Norway

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The report is for the most part based on information available up to December 2012.

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Summary

Due to the considerable petroleum resources of its continental shelf, Norway is one of the largest energy producers in the world, ranking in the top ten oil exporting countries and in the top five natural gas exporters.

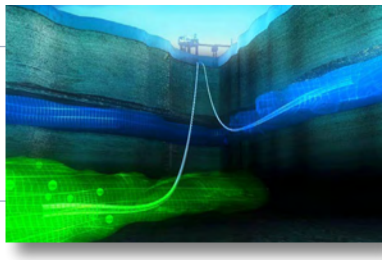
Almost half of its domestic energy consumption is met by electricity and electricity is about 95% based on hydropower, leading to a high proportion of renewable energy in Norway's energy supply.

Norway has pledged to cut domestic GHG emissions by 20% by 2020 and to be carbon neutral by 2050. Subject to international reciprocity, the 2020 cuts may be increased by 10% and carbon neutrality may be brought forward to 2030.

The country faces a challenge in finding significant emissions reduction opportunities. As its electricity supply is already largely decarbonised, the transportation sector must supply a substantial proportion of emissions cuts.

Hydrogen will have a key role to play in decarbonising transportation. There are practical limits on the use of electricity and biofuel, so fuel cell vehicles are considered the best solution for at least 50% of Norway's passenger transportation.

Norway has abundant resources for the production of hydrogen: by water electrolysis driven by renewable electricity, from natural gas (potentially with CO_2 capture), industrial byproduct hydrogen, and from some biomass and biogas.



There is also an economic opportunity for Norway here: as an early adopter developing expertise in and technology for producing, storing, distributing and using hydrogen, this can be exported. The country can also become a leading producer of sustainable hydrogen.

In 2003 the Norwegian government appointed a committee to develop a national hydrogen programme and a national hydrogen strategy was formulated, intended to position Norway to profit from an emerging global hydrogen economy.

The new 'Action Plan 2012–2015' from the Norwegian Hydrogen Council sets out recommendations for Norway to retain its pioneering role in hydrogen and benefit from value creation. The total cost for implementation is around NOK 1.6 billion (~€ 218 million).

New technology for producing environmentally-friendly hydrogen is being developed in Norway, including new electrolyser technology and novel processes for producing hydrogen from methane with integrated carbon capture.

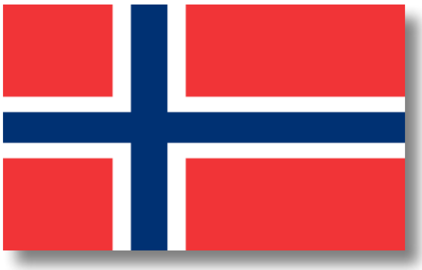
The HyNor project was started in 2003 to demonstrate hydrogen in transportation. It facilitates creation of refuelling infrastructure, the acquisition of hydrogen vehicles, and the provision of carbon-dioxide-neutral hydrogen, such as from the above processes.

Statoil has pulled back from hydrogen to focus on its core business, and a new company called HYOP was formed in 2012 to drive the development and operation of hydrogen infrastructure from the demonstration phase through to commercialisation.

Norway has six operational hydrogen stations, five established under HyNor and one under the H2moves Scandinavia project. The HyNor Oslo Buss station falls under the FCH JU CHIC project. HYOP is currently operating three of these hydrogen stations.

Norway's hydrogen activities have attracted the involvement of vehicle OEMs and the country has emerged as one of the candidate early markets for the commercial rollout of FCEV. Five fuel cell buses and seventeen fuel cell cars have been deployed so far.

1. Introduction



Snapshot

Capital: Oslo
Member of the EEA; non-member of the EU
Indexed GDP per capita (EU27=100): 181
Population: 5 million; urbanisation 77%
Area: 385,252 sq. km; 7% under water; 33% forested
Key renewable energy: hydroelectricity

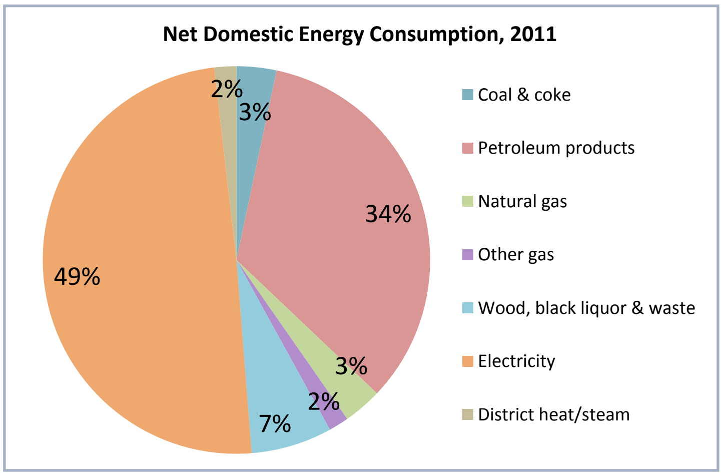
When it comes to energy, Norway has a high international profile: it is among the top oil and gas exporters in the world and yet, at the same time, has taken one of the most progressive stances on emissions cuts among the developed nations. For both these reasons, energy developments taking place in Norway have broad relevance – as this report seeks to show, this is particularly true in the discussion of hydrogen as an energy carrier. The report first examines Norway's energy context, then looks at the opportunities for hydrogen and fuel cells within that, and summarises some of the latest developments and deployments that have taken place in the country.

2. Energy in Norway

2.1 Supply, Consumption and Emissions

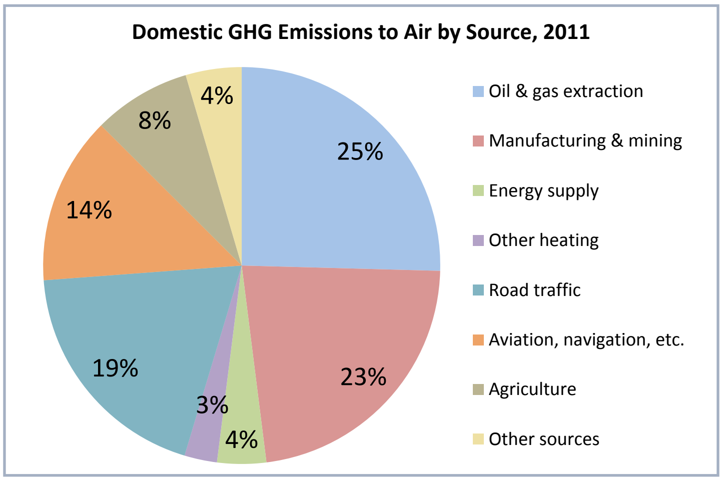
Norway is not a country that faces challenges in energy security. Due to the considerable petroleum resources of its continental shelf it is one of the largest energy producers in the world, ranking in the top ten oil exporting countries and in the top five natural gas exporters[1]*. This has been successfully commuted into wealth and a better quality of life for its citizens (through free healthcare and universities, for example), but the country uses relatively little oil and almost no natural gas domestically. Norway has the highest per capita consumption of electricity in the world after Iceland[2]; almost half of its total energy consumption is met by electricity (see figure below[3]) and electricity production is almost all based on hydropower.

Hydropower is thus the single largest source of energy in the country's total primary energy supply (TPES) and is almost solely responsible for the high proportion of renewables in the TPES: this averaged 44% over the decade to 2011 (or 56% excluding the energy sector)[3], one of the highest levels among the OECD member countries. However, Norway has recognised the need to improve flexibility in the energy supply and diversify into renewables other than hydropower, which will struggle to support sustained growth in demand and is vulnerable to annual variations in precipitation.



Having said this, the country is more than a decade past peak oil and output is in decline. For the moment, most of this export loss is being filled by increased production of natural gas, sales of which are expected to peak in 2020.

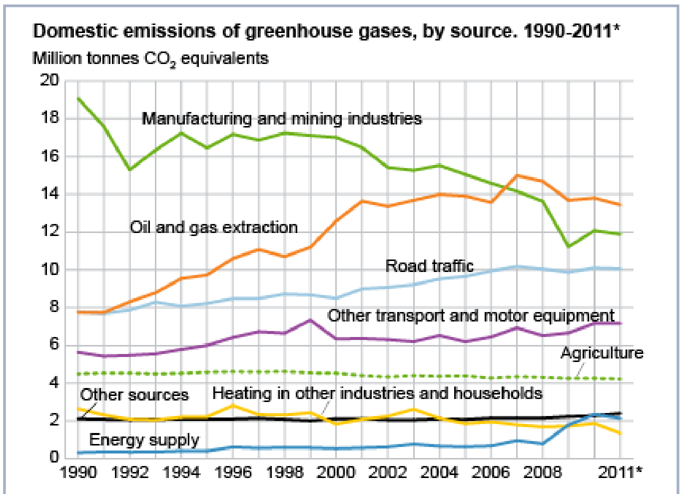
Norway's per capita consumption of energy is relatively high (6.39 tonnes oil equivalent per head in 2010, compared to the OECD average of 4.40)[4]; demand is boosted by its cold climate, the size of the country and the low population density, but especially the prevalence of energy-intensive industry – particularly the oil and gas sectors themselves, plus light metal and other electrochemical production. Energy data from the 1970s onwards show that energy consumption increased quite rapidly up to 2000 and more slowly since; however, this increase has tracked economic growth as energy intensity (energy use per unit of GDP) declined to 2000 and has now plateaued[4].



The country's offshore oil and gas production and its manufacturing industry are substantial contributors to overall greenhouse gas (GHG) emissions, but are offset to a degree by minimal emissions from electricity production (included under 'energy supply' in the figure alongside[6]). Transportation is the single largest source of domestic emissions, contributing 19% from road traffic and 14% from other forms such as shipping and aviation[3]. Not included in these figures is international sea and air traffic, which constitutes around a fifth of Norway's overall GHG emissions[6].

Norway's carbon dioxide (CO_2) emissions from fuel combustion per capita have been increasing steadily over the last 40 years and have now overtaken the European average. This can be largely ascribed to increased industrial output as CO_2 intensity (weight of emitted CO_2 per unit of GDP) dropped significantly up to 2000, as for many other OECD countries, and although it has plateaued it is still low by European standards[5].

The increases derive primarily from oil and gas extraction; by contrast, GHG emissions from other industries have declined (*right*), partly due to reduced production. Emissions from transportation have also grown, with emissions from road traffic up by 30% since 1990 because of increased passenger vehicle use and emissions from other forms of transport having increased by a similar proportion[6]. Emissions from heat and electricity generation increased sharply after 2007 as some natural gas was introduced into the supply (hydroelectricity consumption remained flat in the same period)[3].



Source: Emission inventory from Statistics Norway and the Climate and Pollution Agency.

2.2 Facilitating Transformation

2.2.1 Targets

In 2009, Norway pledged to reduce GHG emissions by the equivalent of 30% of its 1990 domestic emissions by 2020 and to be carbon neutral by 2050 (including accounting for natural carbon sinks such as forests). Subject to international reciprocity, the 2020 cuts may be increased to 40% and carbon neutrality may be brought forward to 2030[7]. Two-thirds of the cuts will be made domestically, bringing Norway's emissions in line with EU targets[8], while the rest will be emissions reductions elsewhere, such as in developing nations, facilitated by Norwegian investment. A variety of means will be used to achieve these cuts.

Norway's renewable energy strategy is formulated on the terms of its adoption of EU Directive 2009/28/EC on renewable energy. Although Norway is not formally subject to European Union directives, its policy is strongly influenced by them through its obligations under the European Economic Area (EEA) Treaty. To be in line with the Directive, Norway has agreed to increase its current ~58% renewables share* in total energy use to at least 67.5% by 2020[9]. The Directive also sets a blanket target for the EU of 10% transportation energy to derive from renewable sources by 2020, which Norway has adopted.

2.2.2 Challenges

Norway is facing the challenge of having to make absolute cuts to its GHG emissions, while for the last decade economic growth appears to have been coupled to both energy consumption and emissions. To break this link, energy efficiency must be increased and more renewable sources must be introduced into the energy supply – where possible. For many countries, decarbonising the electricity supply is the first angle of attack on emissions. Norway, however, with electricity that is already over 95% renewable[10], will have to look elsewhere for significant reduction opportunities.

Unlike the majority of fossil fuel producers, Norway acknowledges an obligation to contribute to emissions cuts beyond its borders. The country is thus also in the difficult position of being 'climate conscious' while at the same time the oil and gas sector is of crucial importance to its economy. It needs to find the means to implement an energy transformation with minimal economic impact – or better yet, one which adds economic value. This apparent dichotomy can only be addressed by significant innovation and new technology that allows for 'sustainable' use of its natural gas.

The government recognises the challenge: its budget for research, development and demonstration (RD&D) in renewable energy, energy efficiency and carbon capture and storage (CCS) stood at NOK 800 million (€109 million) in 2011, up from around NOK 200 million (€27 million) in 2007[11]. The IEA recently reported that Norway's per capita public funding for clean energy RD&D is now among the highest of the IEA member countries[7]. Investment in energy transformation remains on an upward trajectory: for example, the 2013 budget is establishing a new climate and energy fund to support innovation in energy technology, augmenting the existing fund that supports energy efficiency and renewable energy implementation by enterprises[12]. These measures and others adopted by the government to stimulate investment in alternative energy are discussed further below.

2.2.3 Carbon Taxes and Trading

Norway has had a CO_2 tax since 1991, when it was applicable to ~68% of CO_2 emissions (about half of total greenhouse gas emissions); it varies for each sector and some are exempt. Although overall GHG emissions have grown since the tax was introduced, the evidence is that it has helped to cap energy intensity and has led to modest reductions in emissions from certain industrial sectors[13]; significantly, it stimulated investment by Statoil in carbon sequestration during offshore gas upgrading which has been taking place at the Sleipner gas field since 1996[14] – the first such operation in the world. The tax has also led to diesel and

**The share of renewables in gross final energy consumption is calculated differently for the EU renewable energy directive.*

petroleum pump prices which are much higher than would be expected in an oil-producing nation. For the 2013 National Budget, the Norwegian government has announced a near-doubling of the CO_2 tax on North Sea oil and gas extraction from the 1st of January. It is also increasing the CO_2 element in the car purchase tax[12]. In 2008, Norway joined the EU GHG emissions trading scheme, and this now covers 40% of Norwegian emissions. Quotas apply to emissions from energy production, oil refining, aviation, and production of a number of commodities[15].

2.2.4 Clean Energy RD&D

In 2008, the Ministry of Petroleum and Energy launched a national strategy for energy research and development, called Energi21. Its mandate is limited to stationary energy production/consumption and carbon capture, and there are twin aims: the development of 'climate-friendly' energy systems while creating economic value and internationally competitive expertise. The strategy was revised in 2011 and recommended focusing activities in six priority areas within fourteen technology areas[16]; these are:

- Solar cells (industrial development in the supply chain for the export market);
- Offshore wind power (industrial development and use of domestic resources);
- Use of domestic resources to provide grid balancing services to the European market;
- CCS technology to safeguard the future economic value of Norwegian gas resources;
- Flexible energy systems: smart grid operation and the integration of renewable sources;
- Technology for the use of waste heat and conversion of low-grade heat to electricity.

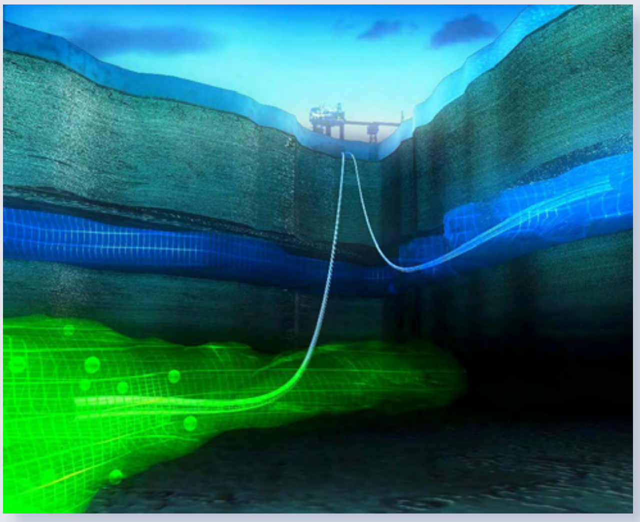
Energy research and development has been taking place within a highly structured framework in the form of the RENERGI 'Clean Energy for the Future' programme, which runs from 2004 to 2013. It is financed through the Research Council of Norway (Forskningsrådet), the government body responsible for stimulating innovation through research. Its objectives dovetail with the aims of the Energi21 strategy but its scope includes transportation[17]. The successor programme, ENERGIX, will run for a ten-year period from 2013.

2.2.5 Carbon Capture and Storage

The Norwegian government intends for Norway to take a pioneering role in the development of workable CCS[18]. This would act as long-term insurance of its fossil fuel assets against a future where emissions penalties could render their use uneconomical[19]. Since Norway is the only net fossil fuel exporter in Europe, CCS would contribute towards safeguarding European energy security.

Public funding of RD&D in carbon capture from power plants and industrial sources takes place through the CLIMIT Programme for Power Generation with Carbon Capture and Storage. It is jointly managed by the state enterprise for CCS, Gassnova SF, established in 2005, and the Research Council of Norway. The focus for CLIMIT is on co-funding prototype and demonstration projects with clear commercial potential on the 2020 horizon[20]. The Norwegian government has committed a sizeable amount to large-scale CCS demonstration projects: $1.3 billion, out of a global public funding total of $25 billion (as of 2010). Only a small handful of (more populous) countries have put forward more.

Minimising CO_2 from Norway's Natural Gas



Domestic emissions

The use of natural gas in domestic electricity generation has been a bone of considerable political contention in Norway and only a small handful of gas-fired power plants have been constructed[a]. Much hinges on what gas-fired capacity replaces: in a country with coal-fired power plants, gas can be seen as a low-carbon alternative, but this is not the case in Norway. The use of gas in the country has thus been closely tied to the discussion of carbon capture and storage (CCS). The 420 MW gas-fired power plant at Kårstø, Norway's first, was commissioned in 2007 on the back of plans for full-scale carbon capture to deal with approximately 1.2 million tonnes of carbon dioxide generated annually by the plant at full capacity. These plans were shelved, however, with the plant's operational intermittency cited as a major obstacle[b,c].

Testing carbon capture

The future for post-combustion CO_2 capture in Norway is looking brighter. In May 2012, a CO_2 capture pilot facility was commissioned at the gas-fuelled combined heat and power (CHP) plant at Mongstad refinery. Known as the Technology Centre Mongstad (TCM), it is the world's largest facility for testing and optimising carbon capture technology, designed to capture 100,000 tonnes of CO_2 per year. It is co-owned by the Norwegian government, Statoil, Shell, and South African petrochemical company Sasol. TCM is aiming to identify and accelerate viable vendor technology that can minimise both the cost of CO_2 capture and the parasitic load it imposes on a power station[d].

Cleaner production

Separation and storage of CO_2 extracted from natural gas during upgrading is already being practised in Norway. The Sleipner gas field in the North Sea has a high concentration of CO_2 and since 1996 Statoil has been extracting a million tonnes of CO_2 a year during upgrading of the gas on an offshore platform and injecting it into a vast pocket below the sea bed[e]. A similar practice has started at the Søhvit field in the Barents Sea to the north of the country[f].

This is not CO_2 from combustion of the gas, but it highlights the potential for carbon sequestration beneath the ocean floor of Norway's continental shelf. This may be considerable: the North Sea seabed is considered favourable for CO_2 storage due to its geology and the availability of depleted oil and gas reservoirs and saline aquifers. In 2006, Statoil stated that there could be sufficient capacity for the CO_2 produced by all Europe's fossil fuel power plants for hundreds of years, if this can be technologically and economically achieved[g]. However, care would need to be taken to ensure this storage is secure and stable, and will not leak CO_2[h].

A low-carbon alternative

Most of the emissions from Norway's gas are of course generated outside of Norway; it supplies around 20% of the natural gas used in Europe and also exports liquefied natural gas (LNG) to the USA, Japan and South Korea[i]. In these countries, unlike in Norway, the use of natural gas is increasingly viewed as a means to reduce emissions – with nuclear generation falling out of favour in Germany, for instance, and plans for more coal-fired power plants on the cards, gas-fired capacity is certainly the lesser of two evils[j]. But by minimising CO_2 released during extraction, providing funding towards the commercialisation of CO_2 capture technology and hosting CO_2 storage reservoirs, Norway can make further contributions to emissions reduction.

Beyond that, natural gas, if it is to be used at all, should be used in the most efficient way possible. CHP generation is one way to do this and fuel cells are another. In the long run, if Norway's expertise can be applied and adapted to producing hydrogen from natural gas with integrated CO_2 capture and storage at source, it will deliver the ultimate prize.

2.2.6 Energy Fund

State-owned body Enova administers the government's energy fund, tasked with funding measures for enterprises to increase energy efficiency and implement renewables.

Energy provision to buildings carries a comparatively low emissions burden in Norway because of the use of hydroelectricity and wood for residential heating. However, Norway needs to cut emissions where it can and improving the energy efficiency of buildings is a policy focus area. In April 2012, the government stated its intention to tighten energy use requirements in building regulations to passive house standard by 2015, and to a nearly zero-energy standard by 2020[21]. Owners of existing commercial, public or residential buildings can apply to Enova for grants to carry out energy efficiency measures and receive a payment per kilowatt-hour of saved or renewable energy.

Enova also aims to stimulate diversification in the sources of heating, including the introduction of wood pellets. Historically low electricity prices have led to a high proportion of electricity being used for space heating and hot water[3], but oil is also used for heating and displacing it with renewables is desirable. The government is specifically targeting the phasing out of oil-fired boilers and generators[21,22]. New buildings must comply with technical requirements for renewables in heating.

The availability of cheap energy resources has supported the growth of energy-intensive industry in Norway. In the industrial sector, Enova's primary focus has been to stimulate better energy management for easy wins in energy efficiency, but support for projects implementing more complex energy efficiency measures is also available. Grants are available to industry for projects leading to energy savings of more than 0.1 GWh through optimisation, waste heat recovery or the use of renewable sources. Industrial heating systems delivering up to 5 GWh annually qualify for funding where the heat source is renewable or waste heat recovery. The implementation of new energy technology in industry is receiving increasing attention, as shown by the creation of the new climate and energy fund under Enova[21].

2.2.7 Vehicles and Fuel

Road transportation offers the most scope for emissions reduction outside of industry. The government is investing in improved public transport and other measures to combat growing numbers of passenger vehicles on urban roads[21], but the bulk of emissions must be addressed by fuel substitution and more efficient drivetrains. The integration of the stationary and transportation sectors would allow for more efficient use of clean energy but, despite this, the focus of the Norwegian Energy Strategy (Energi21) is on stationary energy production and use, and does not include transportation.

Initiatives to switch to alternative fuels and more efficient forms of transportation are implemented by the state through Transnova, which has a similar function to Enova and supports a number of pilot and demonstration projects. The budget for Transnova, however, is relatively low at around NOK 10 million per annum (a factor of 20 lower than that of Enova) and this is hampering the introduction of alternative fuels.

There is policy support on the purchase side: biofuels, biogas, CNG and hydrogen are all subject to lower, or exempt from, fuel and CO_2 taxes[23]. Incentives for electric vehicles (EV) are generous, in line with the government ambition to have 50,000 zero-emission vehicles on the road by 2018. All-electric cars, including fuel cell electric vehicles (FCEV), are exempt from purchase tax and VAT, receive a 90% discount on annual road tax, pay no toll or municipal parking fees, qualify for free ferry passage, and have access to bus lanes and thousands of public charging points[24]. (There is also a grant available for establishing private charging points.)

Norway has one of the highest vehicle purchase tax levels in the world, rendering the cost of a family car around twice as expensive as in countries like Sweden or Germany. The fact that this tax is not applied to EV and FCEV is a major driver for the introduction of these vehicles[25].

2.2.8 Electricity Generation Subsidy

Norway has no feed-in tariffs per se, but electricity generated from renewable sources may receive a higher price through the common Norwegian–Swedish Green Certificate market, which came into force at the start of 2012 and will run through 2035. Certificates are issued to producers that add renewable generation capacity and consumers are obliged to buy a number of certificates when purchasing electricity, as a form of subsidy for producers and a tax on consumers (although certain sectors are exempt). The incentive is expected to add 26.4 TWh of annual renewable energy generation between 2012 and 2020[26]. This capacity, which may not be equally distributed between the two countries, would derive particularly from wind power but also from hydropower and biomass. The next section discusses these resources in more detail.

2.3 Adding Low-Carbon Capacity

2.3.1 Hydropower

Norway is well-equipped for hydropower: it is the most mountainous country in northern Europe and has high levels of precipitation; it also benefits from a long coastline and the effects of glaciation that created many steep-sided fjords.

The Norwegian Water Resources and Energy Directorate (NVE) puts the mean annual production of hydroelectricity at about 124 TWh, with annual variation of ±20% dependent on precipitation. Installed capacity at the end of 2011 was 29.6 GW in 1,250 hydropower plants. The country's reservoir capacity is a massive 83.4 TWh, and can be used to level out seasonal and annual variation[27]. This has relevance beyond Norway's borders; see the feature on page 12.

The total hydropower potential in the country is 206 TWh, of which 45 TWh is in protected areas and cannot be developed. The development of the remainder is subject to licensing which may be delayed for long periods or withheld. There is very limited scope for growth in large-scale hydropower with reservoirs but somewhat more scope in small hydroelectric projects[27]. Renovation of old plants with more efficient technology will also add some capacity.

2.3.2 Wind Power

Given its geographical position and long coastline Norway's theoretical potential for wind energy is high – over 1,000 TWh per year[28], but of course much of this is not practically exploitable. Wind power currently contributes about 1% of the electricity supply[29].

In November 2011, the NVE had received applications for new wind power plants amounting to a total of 60 TWh of additional annual capacity, and it had granted licences for 10 TWh with another

4 TWh under appeal[27]. The Norwegian Wind Energy Association estimates that installed capacity in 2020 will be between 3,000 MW and 3,500 MW, with annual production at around 8 TWh. State-owned electricity enterprise Statkraft installs wind farms in Norway, as well as in Sweden and UK; its stated goal is to install 1,100 MW of land-based and 150 MW of offshore wind energy by 2015[30]. Technology development for offshore wind farms reaps the benefit of the knowledge and experience of Norway's offshore oil and gas industry.

2.3.3 Biomass and Biogas

In 2010 bioenergy took a 6% share of the TPES, ~17 TWh. Current sources are mostly wood for heating in individual homes and waste in district heating, plus wood waste and black liquor used by forestry and other industries[31]. The use of wood/agricultural and solid waste biomass for electricity generation or cogenerated heat and power outside of the forestry industry is minimal. Around half a terawatt-hour of digester and landfill biogas is produced in Norway; some of this is flared but an estimated 0.3 TWh is harnessed as electricity and heat[32].

Norway makes relatively little use of its biomass for energy compared to Sweden and Finland as it has had less need to exploit this resource. The Norwegian government target for bioenergy in heat and electricity production is relatively modest: an additional 14 TWh over the 2009 level by 2020[31], equating to 28 TWh in total. Within that, potential energy from agricultural and food waste and landfill gas is estimated at 6 TWh; the government is aiming for 30% of livestock manure and 600,000 tons of food waste annually to be treated in biogas plants by 2020 and is legislating waste management accordingly[32].

The need for bioenergy is much greater in the transportation sector and it is probable that much of the biogas generated from waste will find its way into transportation. Biogas is currently the preferred fuel for buses in cities. The infrastructure for refuelling of cars with biogas is also under construction, but it is likely that buses and large public utility vehicles will take the greatest share of the supply.

2.3.4 Other Sources of Electricity

A small amount of solar power capacity is installed in Norway, around 8 MW, most of which is grid-connected, and capacity is expected to remain low until 2020[33]. Over the last two to three decades, a substantial number of small photovoltaic panels have been installed in numerous remote mountain cottages, most of which are not grid-connected.

Public funding is supporting the development and demonstration of technology for wave, tidal and osmotic power (collectively ocean energy); a number of small-scale and full-scale prototypes and demonstrations are in progress and there are plans for permanent capacity in all three energy sources[34]. These are only expected to make a significant contribution to the TPES by about 2050 and the current Norwegian–Swedish Green Certificate Scheme does not provide certificates for ocean energy[35].

Norway: A Green Battery for Europe?

Storing clean energy

Half of Europe's total hydroelectric reservoir capacity is located in Norway, meaning the country has the potential to store a very substantial amount of energy through pumped storage and as reserves. It is this potential that has led to assessments of Norway as a possible clean energy store for Europe[k,m].

The stimulus for this is the rapid growth in variable renewable sources in the European energy mix. Undoubtedly a positive development, it however poses significant challenges in practice: wind is an intermittent, highly variable and occasionally unpredictable source of energy, while solar power obviously depends on daylight. This makes it difficult to keep an electricity grid that incorporates a large proportion of intermittent renewable power in balance, i.e. matching supply to demand and smoothing out what may be very sharp peaks and deep troughs in the supply. In addition, sudden peaks in demand require that the grid has supplies of energy in reserve that can be accessed quickly. A greater degree of predictability and flexibility is needed than is offered by just the direct integration of variable renewables.

The 'green battery' concept proposes a system to meet these challenges in a completely renewable way, using Norwegian hydropower plants and infrastructure. Primarily this would be through pumped storage: during periods of excess supply, energy is used to pump water from low-lying reservoirs to reservoirs at higher altitudes; this energy is held in reserve and available for quick release in the form of hydroelectricity when demand outstrips supply.

Energy exchange

This would allow excess wind energy from Denmark or Germany, for example, to be converted and stored as potential energy in Norway, via the electricity grid. In a fully integrated grid with sufficient connectivity, it doesn't matter where the wind (or solar) and hydropower capacity is located and it is theoretically possible to create a system that covers much of Europe, although transmission losses and logistical complexity increase with distance. In practice, implementation is likely to encompass countries bordering the North Sea.

Limited energy exchange already takes place between Norway, Denmark, Sweden and the Netherlands and has facilitated new renewable capacity in those countries. Denmark, for instance, exports excess wind power to Norway when hydro output drops, while during periods of high rainfall Norway exports hydroelectricity.

To what extent the full green battery concept will be realised depends on a number of factors, not least the laying of new subsea cables from Norway to northern Europe and the United Kingdom, for which plans are in place, plus investment in national grids and other infrastructure. There is genuine interest in the concept but political engagement is needed as cooperative agreements would have to be reached by the participating countries. Should all this occur, it is considered feasible to put the system into commission well before 2020.

Green battery vs power-to-gas

There is a pressing need for large-scale energy storage to help countries meet challenging renewables targets. Germany has lately been prominent in exploring another storage option: power-to-gas, in which excess wind energy is used to electrolyse water to produce hydrogen that is then stored in the gas grid (the energy storage capacity of the German gas grid is substantial). Power-to-gas and the green battery should be viewed as complementary concepts: each has its limitations, in terms of capacity and where it can be sensibly deployed, and it is likely both will find wide application within Europe as renewable capacity grows.

2.3.5 Other Sources of Heat

Norway has a rapidly growing proportion of geothermal energy in the form of ground source heat pumps (borehole thermal energy storage is also used). Penetration of heat pumps generally is high in Norway, where the market has been growing rapidly since 2001; over 600,000 households now have a heat pump of one type or another[36]. Solar heating is also used: a number of Norwegian companies have developed active and passive solar heating systems for energy-efficient buildings, which are finding application in the domestic market (the Norwegian Solar Energy Association estimates up to 4 TWh of building heat is generated by passive solar heating annually[37]).

Energy consumption from district heating (DH) more than tripled from 2000 to 2010, when it supplied 4.3 TWh (1.5% of the TPES), but is still a full order of magnitude below Sweden, Denmark and Finland. However it continues to grow very rapidly and recent years have seen record investment in DH. About two-thirds of DH in Norway is from low-carbon sources, including waste, waste heat, heat pumps, biomass and hydroelectricity[38,39,40].

There has been limited use of combined heat and power (CHP) generation in Norway, as one would expect for a country that has not had to rely on fuel combustion for electricity, but this is also on the increase. Some heat generated in DH plants is being used for electricity production, while new gas- and biomass-fired power plants are being operated in CHP mode[41,42]. There is potential for energy efficiency gains in the use of fuel resources by implementing CHP at various scales.

2.3.6 Energy for Transportation

Adding renewable capacity in transportation can be accomplished two ways: either by implementing renewable fuels directly, as is the case with biofuel, or using energy carriers that are generated by renewable means, such as hydroelectricity. In Norway, energy consumption for all forms of transportation is presently about 1.2% from electricity and 2.3% from biofuel, with the remainder fossil fuels[3].

Sales of liquid biofuels (biodiesel and bioethanol) are increasing rapidly, in line with government targets. Only second-generation biofuels are likely to receive policy support in the future, but availability is limited: the practical maximum for transportation energy sourced from second-generation biofuel is estimated at about 10%[43].

Currently around 2.5% of new cars sold in Norway every month are electric, benefiting from the generous incentives for these vehicles. The Transnova-backed ‘Grønn Bil’ (Green Car) project reports that at the end of September 2012, 9,162 rechargeable cars (including some plug-in hybrids) were on the road in Norway[44]. Because the electricity supply is largely carbon-free, these cars are essentially using renewable energy. However, as in any other country, there are practical limits to how much of the Norwegian fleet can be powered using grid electricity to charge batteries directly, due to the population distribution and driving patterns.

2.4 Implications for Hydrogen and Fuel Cells

2.4.1 The Domestic Opportunity

As Norway's electricity supply is already largely decarbonised, the transportation sector must supply a substantial proportion of emissions cuts. Emissions targets apply to the total primary energy supply, so meeting these targets from just one sector will mean that sweeping measures are necessary within that. As the previous section has indicated, biofuels and clean electricity will not be sufficient for the changes needed in the transportation sector.

As a result, hydrogen is being considered as part of a three-pronged approach, with electricity and biofuel, to help decarbonise Norwegian transportation – primarily road transportation, but its application in ferries and ships is also being studied. Like electricity, hydrogen is an energy carrier rather than a fuel in the conventional sense, and can be generated by energy-efficient or renewable means to act as a low-carbon or carbon-free source of energy for vehicles.

Although hydrogen can be combusted in specialised internal combustion engines, when used in fuel cell vehicles it offers the most benefits in terms of energy efficiency, local air quality and other factors such as driving experience. The introduction of FCEV as a substantial proportion of the domestic fleet is thus integral to the implementation of hydrogen in transportation in Norway.

No country is better suited than Norway to implementing hydrogen as a transportation fuel. It has the political will to cut carbon emissions and has committed to challenging targets. It is backing this up with investment in energy efficiency and new sources of energy. Further, it has recognised the role of innovation in helping to meet energy challenges and there is an appetite for the adoption of new technologies.

2.4.2 Feasibility

In 2005, Statkraft, Norsk Hydro and Statoil commissioned the NorWays study to assess the introduction of hydrogen as a transportation fuel in Norway. The resuts were published in 2009 (more information on the study can be found on page 16). The use of hydrogen in FCEV was found to be a "prerequisite" for Norway to reach longer-term (post-2020) targets for clean transportation, when available bioenergy is not sufficient and hybrid vehicles do not allow for sufficiently deep emissions cuts.

It was concluded that hydrogen fuel can become competitive at around 5% market penetration; this could be achieved by 2025 with sufficient policy support and innovation. According to this assessment, by 2050 the hydrogen supply base in Norway would most likely be a mixture of on-site electrolysis, natural gas and by-product hydrogen, plus some gasified biomass (the share of each strongly dependent on technological developments). The overall investment required was assessed at €1.5 billion (in 2005 terms) until 2050.

2.4.3 Resources

Part of the appeal of hydrogen for Norway is that it can be sourced from abundant domestic resources, all of them preferable to gasoline or diesel. As the NorWays study concluded, a combination of these can be used in practice to yield a range of benefits:

A. By using electricity to drive water electrolysis (splitting water into hydrogen and oxygen):
   - Grid electricity is already 95% carbon-free so this would be an immediately exploitable source of renewable hydrogen;

- Addition of wind power capacity to the grid will add variability and the production of hydrogen from excess wind energy will help to stabilise the grid, will store the energy in a usable form, and will add value to wind energy as a source of vehicle fuel;
- The use of electrolytic hydrogen to store energy will thus facilitate the addition of renewable generation capacity in Norway and, potentially, Europe.

B. From natural gas:

- Energy efficiency gains versus conventional transport solutions are possible by using the hydrogen in FCEV, even without applying CCS technologies;
- Moving the production of carbon emissions from the tailpipe to a point source allows for the implementation of carbon capture when viable technology is available;
- Likely to be comparatively low-cost, depending on technology used.

C. From gasified biomass such as wood, or from biogas:

- May maximise the value of these underexploited resources where they are not needed for heat or electricity;
- Most likely to be used for distributed, smaller-scale production at source;
- Later application of CCS is also possible.

D. As a by-product of some industrial processes:

- Extracts value from what would otherwise be a waste product;
- Low cost but limited availability.

But there are other, less tangible, resources in Norway that are useful in this regard. These include decades of relevant experience in the production of hydrogen from renewable and fossil sources and its industrial use, and a solid research base to build upon in an environment that promotes energy innovation.

2.4.4 The Strategic Opportunity

As Norwegian agencies develop the means to effectively introduce hydrogen in transportation they will build up significant expertise. This will cover technology for producing hydrogen from the above-mentioned sources; economic storage and distribution of hydrogen; hydrogen refuelling of vehicles; and the effective exploitation of hydrogen through fuel cell technology. This is expertise that can be exported, and to a great extent is applicable in the stationary power sector as much as in transportation. Because Norway's energy resources are abundant and far outstrip its domestic needs, this opportunity may also encompass the export of hydrogen itself.

These considerations have led to Norwegian strategic interest in hydrogen: it is pursuing the use of hydrogen to decarbonise its own transportation sector while recognising the economic opportunity offered by a global hydrogen economy. This strategy will be discussed in more depth in Section 3. Section 4 examines some of the hydrogen production technology development currently taking place in Norway and Section 5 looks at progress so far in implementing hydrogen and fuel cell vehicles.

The NorWays Study

Creating a roadmap

The NorWays project sought to inform policymakers about the introduction of hydrogen in transportation and how this could be achieved. It was coordinated by SINTEF and carried out in association with the EU HyWays project and involved, among others, the research institute IFE, the Norwegian University of Science and Technology (NTNU), Statkraft, Hexagon and Statoil/Hydro. The project was financed by the Research Council of Norway and the industrial partners. In May 2009 it culminated in a set of recommendations to the Norwegian government.

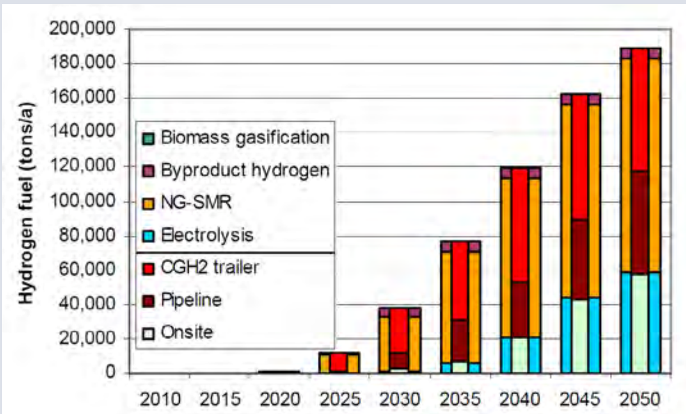
The study developed a number of scenarios for the adoption of hydrogen, with the focus on early markets. Regional models were used to analyse the use of hydrogen in competition with other alternative energy sources such as natural gas, biofuels and grid electricity.

Best use of energy

The study recommended that due to the limited quantities of biofuel likely to be available this is best reserved for heavy-duty vehicles. BEV could cover ~25% of passenger kilometres and PHEV a further ~25%, but the use of hydrogen in FCEV was found to be the best solution for at least 50% of passenger transportation. Using renewable electricity directly in BEV is about twice as efficient on a well-to-wheels basis; however, hydrogen offers the benefits of faster refuelling and longer range. The latter is important in a large country with low population density and means that for a considerable proportion of the domestic fleet electromobility can only be accomplished using FCEV.

Sources of hydrogen

According to NorWays, due to Norway's population distribution the use of distributed hydrogen production technologies, particularly electrolysis, will play a crucial role in establishing a supply infrastructure. Conventional centralised steam methane reforming with carbon capture was not found to be economically competitive with distributed generation by electrolysis, primarily due to the high cost of hydrogen distribution and the assumption of a CO_2-quota price of €25 per tonne. The projected supply mix for the base case scenario is shown alongside.



Core message

The study concluded that 'substantial intervention from government is required' to effect a transition to a sustainable form of transport – but in addition to the benefits for the environment, economic benefits would accrue to Norway by making sustainable use of its resources and by becoming a pioneer in hydrogen technologies. This has become the core message of the Norwegian hydrogen initiative.

For further information see:

a) www.ntnu.no/norways

b) NorWays: *Core Message and Executive Summary*, Coordinated by SINTEF Materials and Chemistry, Dr S. Møller-Holst, May 2009

c) Stiller et al., *International Journal of Hydrogen Energy*, **35** (2010), 2597–2601

3. The Norwegian Hydrogen Strategy

3.1 State Initiative

In 2003, the Norwegian government appointed a committee to develop a national hydrogen programme, with support from the Ministry of Petroleum and Energy and the Ministry of Transport and Communication. The committee received input from industry and academia on production of hydrogen and its use in stationary power generation, and on the use of hydrogen as a transportation fuel. This resulted in Official Norwegian Report NOU 2004:11 on 'Hydrogen as the Energy Carrier of the Future'[45].

It assessed Norwegian competence and resources, the characteristics of hydrogen as an energy carrier, the level of international effort in hydrogen and fuel cells, and the advantage to Norway of investing in hydrogen. It then laid out a detailed vision for Norwegian activity in hydrogen and emphasised the need for robust funding support.

The committee set four overarching goals:

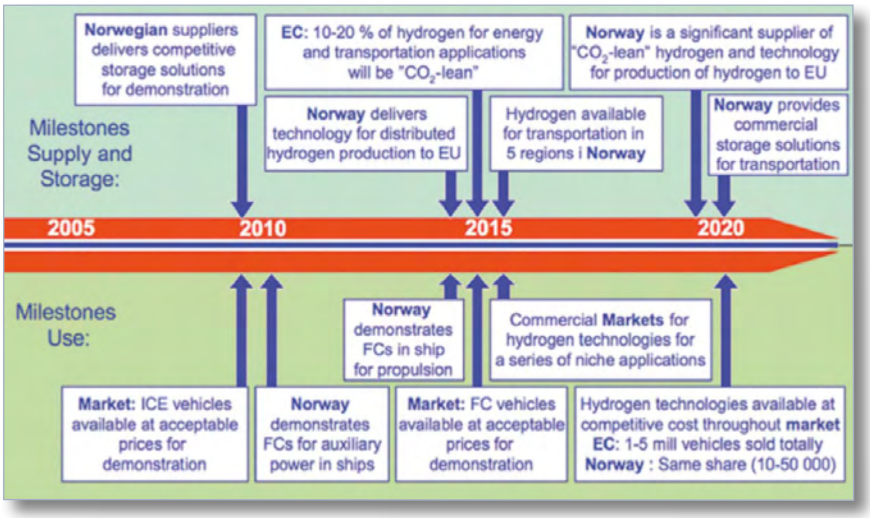
1. Production of hydrogen from natural gas with carbon capture, at a cost that is competitive with petrol or diesel, for use in Europe;
2. Early introduction of hydrogen vehicles in Norway;
3. Development of internationally-leading competence in hydrogen storage, with competitive products and services;
4. Development of a 'hydrogen technology industry', comprising: participation of Norwegian companies in international supply chains for hydrogen technology; the supply of hydrogen refuelling stations using electrolysis; competence in the use of fuel cells on ships; and R&D of an international standard in fields related to hydrogen.

This report was followed up by the Ministries of Petroleum and Energy and of Transport and Communication in 2005 when they jointly formulated a national hydrogen strategy. The intention of the strategy, for which international activity in hydrogen energy is regarded as a prerequisite, is to position Norway to profit from a global hydrogen economy that would create demand for Norwegian resources, expertise and technology[19].

The strategy resulted in the creation of the Norwegian Hydrogen Platform, with the Secretariat based at The Research Council of Norway, and the appointment of the Norwegian Hydrogen Council (NHC) to act as liaison and advisor to the Ministries and formulate action plans.

3.2 First Action Plan 2007–2010

The first Action Plan from the Norwegian Hydrogen Council was published in December 2006 and covered the period 2007 to 2010, with milestones for the overall strategy as shown in the figure on the next page[46]. Outcomes of the first Action Plan include FCEV receiving equal treatment with other electric vehicles in incentive schemes and the establishment of Transnova (in which the environmental foundation ZERO also played a key role by lobbying politicians). This has led to increased public support for alternative fuels and for more efficient vehicle technology.



Progress towards meeting all these targets has been good. For example, the demonstration of fuel cell APU in a marine vessel was successfully concluded in 2010, as described in the feature on page 34[47], and demonstration of fuel cell vehicles is well underway in Norway (see Section 5), with Norwegian technology for distributed hydrogen production also being trialled (see Section 4).

3.3 Second Action Plan 2012–2015

The second Action Plan from the Norwegian Hydrogen Council was published in May 2012[48]. A full English translation is now available and it is recommended reading, as it sets out a comprehensive and ambitious vision for Norway's role in an international hydrogen market (download it at www.hydrogen.no).

The document presents an updated plan for the Hydrogen Initiative, taking into account the recent withdrawal of Statoil from hydrogen (see page 28), political processes and trends within Norway, the forthcoming commercialisation of FCEV, and new applications such as using hydrogen for grid balancing. The aim of its recommendations is for Norway to be one of the global leaders in hydrogen and benefit from value creation.

The recommendations are grouped as follows:

> '**Business Development for Increased Value Creation**', including measures to involve Norwegian SMEs in the emerging hydrogen technology market;
>
> '**Research and Development, Network and Infrastructure**', including extending and focusing R&D in hydrogen production, storage, distribution and use, as well as the creation of a national network of test laboratories;
>
> '**National Facilitation**', involving: the strengthening of Transnova to reflect the challenges it is handling, funded through an gradual increase in the fuel tax; the creation of a national plan for fuel supply for future vehicles, including incentives and support for hydrogen refuelling stations; and the investigation of the potential for large-scale export of sustainable hydrogen from Norway based on Norwegian energy resources;
>
> '**Effective Tools for Early Introduction of Hydrogen Vehicles**', including incentives for zero-emission vehicles, with a required proportion of these vehicles in public fleets, subsidies for hydrogen cars until they are competitive, and coordinated procurement of FCEV with a focus on hydrogen in urban transport or fleet vehicles.

The Action Plan also recommends national lighthouse projects focusing on four particular areas; these are summarised in the box below. The total cost for implementation of all the recommendations is estimated by the NHC at around NOK 1.6 billion (~€ 218 million) over the four years from 2012 to 2015.

The document urges political backing to allow Norway to capitalise on its investments in hydrogen over more than two decades, to use its natural resources and fully benefit from the emerging hydrogen economy.

NHC Recommendations for National Lighthouse Projects

A pilot project for hydrogen production at power plants with CCS:

Co-location of hydrogen production with gas-fired power plants would take advantage of shared infrastructure for both natural gas supply and CO_2 handling, reducing investment costs. This could work, to a different extent, with both post- and pre-combustion carbon capture. When projects to scale-up hydrogen production technology are proposed, this sort of co-location should be considered, for example at the Technology Centre Mongstad (see page 8).

A national project to demonstrate fuel cells in ship propulsion:

This would build on the first phase of the FellowSHIP project (see page 34). The use of fuel cells in industrial vessels and the numerous car ferries operating along the Norwegian coast could address this significant source of emissions.

Demonstration of 'green harbours':

Norway has heavy shipping traffic and a number of harbours. When docked, ships tend to switch to diesel generators to keep auxiliary systems powered; the Action Plan quotes a figure of 3,000 litres of diesel consumed per hour for an average cruise ship. A reduction in emissions could thus be achieved by allowing the ships to connect to shore power, but this may require investment to upgrade the local power grid. Hydrogen-based solutions can be a viable alternative, and the Action Plan recommends that a feasibility study is launched to investigate this, to be followed by a demonstration project. Other advantages would result from the use of hydrogen in the harbour, as it could also be used to fuel land-side vehicles such as cargo handling equipment.

Demonstration of grid balancing with hydrogen and fuel cells:

With the integration of an increasing proportion of variable renewable energy sources into the electricity grid, technology for energy storage is needed to keep the grid supply and demand in balance. Although Norway has abundant hydropower capacity that can be used in this regard (see Page 12), in some regions this is not feasible. Here, hydrogen production by electrolysis can be used; fuel cells could be used to return electricity to the grid or the hydrogen could also be used as vehicle fuel. The Action Plan recommends the initiation of a project to demonstrate the feasibility of this concept for local grid balancing.

The Norwegian Hydrogen Forum

Established in 1996 as a non-profit organisation, the Norwegian Hydrogen Forum (NHF) acts as a coordinating body for hydrogen activities in Norway. Members are drawn from industry, universities, research institutes, and other organisations and people.

Its activities encompass:

- Promoting the advantages of hydrogen as an energy carrier;
- Information dissemination;
- Supporting research and innovation in hydrogen technology;
- Securing increased political awareness in close association with the Norwegian Hydrogen Council;
- Constructively partnering public authorities and other bodies in the development of policy;
- Stimulating start-ups and involving SMEs in the emerging hydrogen industry;
- Active membership of the European Hydrogen Association.

The NHF compiles 'The Norwegian Hydrogen Guide'. This is a useful overview of all the Norwegian companies and organisations involved in hydrogen for energy – the 2012 edition is available in English on the NHF website.

The website also hosts the outreach material from the Norwegian Hydrogen Council, including its mandate and action plans, with English translations available for downloading. The NHF website can be found at: www.hydrogen.no

Utsira: Demonstrating Wind to Hydrogen

The earliest practical use of water electrolysis in an energy application in Norway was in the Utsira Wind Power and Hydrogen Plant, on the small island of Utsira, just off the south-west coast of Norway. This landmark project was one of the first in the world to demonstrate the concept of wind-to-hydrogen production at full scale, under real-life conditions. An integrated renewable energy system was constructed on Utsira to demonstrate reliable power provision to local households, which have a weak grid connection to the mainland. Excess electricity generated by the wind turbine was used in the electrolyser to produce hydrogen. This was compressed and stored, and fed through a generator or fuel cell when electricity was required and wind power was not sufficient.

Over four years of operation, from 2004 to 2008, the concept was successfully proven as energy for ten households was exclusively supplied by the pilot plant. However, several challenges were identified, not least low energy efficiency, and it was concluded that "further technical improvements and cost reductions" were needed for commercial viability.

Utsira wind and hydrogen plant components:

- 600 kW wind turbine
- 10 Nm^3/h, 48 kW alkaline electrolyser (12 bar), supplied by Hydro
- 11 Nm^3/h hydrogen compressor (200 bar)
- 2,400 Nm^3 hydrogen gas storage (200 bar)
- 55 kW hydrogen genset (rebuilt diesel engine)
- 10 kW PEM fuel cell system, from IRD

Reading:

Ulleberg et al., *Int. J. of Hydrogen Energy*, 2010, 35, 1841-1852

Hydro Oil & Energy, 'Utsira Wind Power and Hydrogen Plant: Inauguration', 1 July 2004

4. New Technology for Hydrogen Production

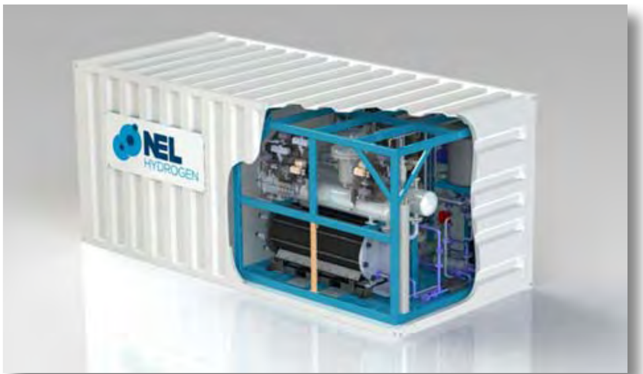
4.1 Electrolysis and Renewables

Electrolysis has a long industrial history in Norway. The early use of the technology for fertiliser production dates back to the founding of Norsk Hydro in 1905, and can be directly attributed to the availability of abundant hydropower. In 1927 Norsk Hydro started to convert its original fertilizer production method to the Haber–Bosch process, for which pure hydrogen is required[49]. This marked the beginning of the manufacture and use of water electrolysers in Norway, producing large quantities of hydrogen for industrial use.

The use of electrolysers to produce hydrogen is therefore nothing new, but interest in the technology as a means to renewably produce hydrogen as an energy carrier has gathered momentum over the last decade. Energy applications fall into four broad areas, with much overlap between them: renewable energy storage; grid demand-side management; remote/off-grid energy systems; and production of fuel for FCEV. These have specific requirements that differ from the requirements of industrial use, and innovations in electrolyser technology are needed for it to be efficient, effective and economic in energy applications.

4.1.1 Alkaline Electrolyser Development

Norsk Hydro's water electrolyser arm ultimately evolved into NEL Hydrogen, which continues to supply electrolysers for industrial hydrogen production and is now exploring opportunities in hydrogen for energy applications. Its strong industrial base puts it in a good position to do so, as it is profitable with growing annual turnover.



For industry, NEL Hydrogen has supplied hundreds of large alkaline electrolysers that work at atmospheric pressure, producing from 10 to 500 Nm^3H_2/h. It is adapting the technology for use in large-scale renewable energy installations, and has recently released a pressurised electrolyser specifically designed for energy applications such as hydrogen refuelling stations. (NEL Hydrogen supplied the electrolyser for the first commercial hydrogen station, which opened in Iceland in 2003.)

NEL Hydrogen sees opportunities in transportation, grid energy storage, isolated energy systems and energy independence. To realise these opportunities, electrolysers must have flexible load operation with ultra-fast response time. After extensive testing of a 3.4 Nm^3H_2/h prototype at the Energy Park test facility in Porsgrunn, it has been verified that NEL Hydrogen's new 60 Nm^3H_2/h electrolyser (*above left*) can start up immediately from standby, has a response time of <1 s and an operational range of 10–100%[50,51].

An alternative approach to alkaline electrolyser design is being taken by start-up RotoBoost, which has patented a rotating stack electrolyser technology, the RotoLyzer. The rotation facilitates gas and liquid separation by centrifugal force, allowing for increased efficiency in a more compact unit. The company says capital costs may be halved by using this design. It will be engaged in development through 2013 and 2014 and is looking for investment or partnership to commercialise beyond that. This timeframe would allow it to target the emerging hydrogen refuelling market[52].

4.1.2 PEM Electrolyser Development

Proton exchange membrane (PEM) water electrolyser development in Norway was initiated in 1997 and had its origin in the PEM fuel cell research at the Norwegian University of Science and Technology (NTNU) that commenced in 1990. Since 2001, however, the Norwegian Institute for Scientific and Industrial Research (SINTEF) has grown to take the leading role in R&D in this area; NTNU is still active in fundamental R&D.

A €3.4 million EU project coordinated by SINTEF has the objective of developing an efficient PEM electrolyser for sustainable hydrogen production. The two-year NEXPEL project started in January 2010 with the aim of improving electrolyser efficiency and lifetime while reducing cost; the targets are 75% efficiency (LHV), hydrogen production cost of around €5,000 per Nm^3/h (system) or €2,500 per Nm^3/h (stack), and lifetime of 40,000 hours[53].

The approach has seen the electrolyser essentially redesigned from the ground up. The project has involved development of new catalyst and membrane materials, component redevelopment with cost-effective materials, and new stack and system design with advanced construction methods. Significant progress has been made: using the NEXPEL design, cost per stack at a production volume of ten stacks has been reduced by over a third compared to the conventional design. The target of €2,500 per Nm^3/h (stack) is reached at a production volume of 100 units, and economies of scale are more pronounced for the new design[54].

The electrolyser is intended for use with wind or solar power: it can sustain intermittent operation and has a power range of 10–200%. It produces >99.99% purity hydrogen, suitable for fuelling fuel cell vehicles. The final stage of NEXPEL is integration into the renewable energy system at Porsgrunn Energy Park (which includes two 6 kW wind turbines, two 2.1 kW solar panels, and a hydrogen refuelling station, *above*), testing these capabilities from late 2012.

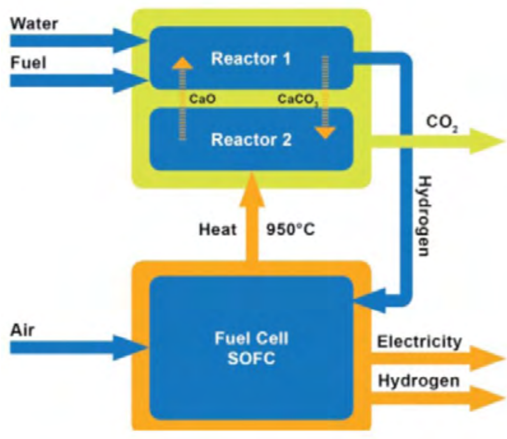
The successor to NEXPEL is the four-year NOVEL project, which started in late 2012. This will continue materials development and system optimisation; extensive durability studies on the newly-developed stacks will also be conducted. This project is specifically intended to develop a cost-effective, small-scale PEM electrolyser for home or community use (around 1 kWe) with overall system efficiency of over 70% (LHV)[55].

4.2 Sorption-Enhanced Steam Methane Reforming

4.2.1 The ZEG Process

One of the challenges facing implementation of carbon capture is the significant parasitic load it usually places on the plant, but a novel approach could solve this problem and actually increase the efficiency of power production with integrated carbon dioxide capture. The zero-emission gas (ZEG) process was collaboratively developed by the Institute for Energy Technology (IFE) and Christian Michelsen Research (CMR). ZEG Power was established as a joint spin-off company to commercialise the technology, which has been patented[56].

In the ZEG process, methane is reformed using novel sorption-enhanced steam methane reforming (SE-SMR) technology. The process uses a circulating solid sorbent to remove the carbon dioxide from the gas mixture in Reactor 1 as soon as it is formed, allowing the reforming and water-gas shift reactions to proceed simultaneously and driving the equilibrium further towards hydrogen production[57]. The sorbent is regenerated in Reactor 2, releasing a pure CO_2 stream ideal for storage or further industrial use. The heat required for this process is provided by an integrated solid oxide fuel cell (SOFC), which uses the hydrogen produced by the SE-SMR reactor to generate electricity. Excess hydrogen can be recovered and used elsewhere, for example in a refuelling station for FCEV.



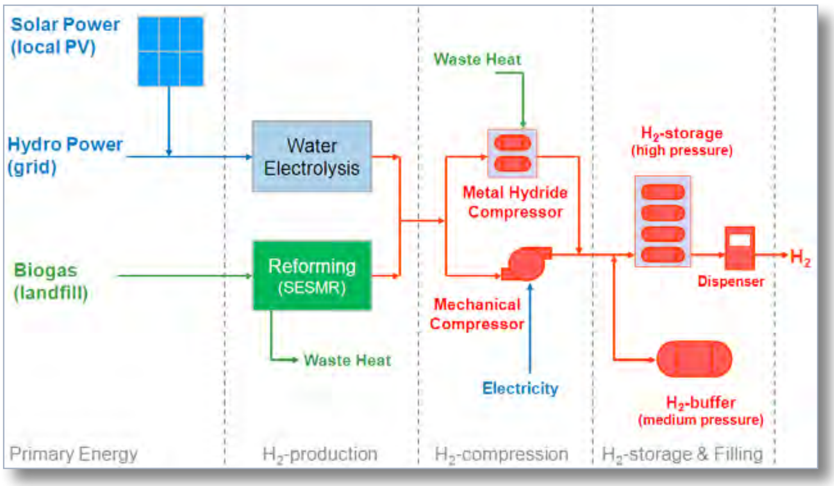
According to ZEG Power, this relatively simple and elegant process has a potential energy efficiency of over 80%, and almost 100% carbon capture can be accomplished at low cost. The developers are targeting a hydrogen yield of over 95%. Any gaseous hydrocarbon fuel can be used, and the proportions of electricity, hydrogen and heat generated are flexible. The process is being developed to be scalable from kilowatt up to megawatt-level output.

ZEG Power has verified the technology in a 1 kWe + 1 kW_{H2} unit. It is now working on a demonstration in a 20 kWe + 30 kW_{H2} plant; this is being done as part of the HyNor Lillestrøm project at Akershus Energy Park (see below). The next step is a 400 kW scale pilot plant; the possibility of testing the technology at the Technology Centre Mongstad is under discussion.

The ultimate objective is to market the technology for large-scale power plants[58]. To do this ZEG Power needs commercial partners, and it has invited interest from industry and investors.

4.2.2 Testing at HyNor Lillestrøm

HyNor Lillestrøm is both a company and a project; the company was founded in 2009 and is owned by Akershus Energi AS, IFE Venture, Lillestrøm Centre of Expertise (Kunnskapsbyen), Kjeller Innovasjon AS and Skedsmo municipality. At Akershus Energy Park near Oslo it is demonstrating Norwegian competence in integrated hydrogen energy systems.



The project incorporates hydrogen production from two different renewable energy sources (solar PV and landfill gas), hydrogen compression and storage driven by renewable thermal energy, and hydrogen vehicle refuelling. Phase 1 of the project is illustrated below.

Hydrogen is generated both by water electrolysis driven by renewable electricity and by methane reforming. For the latter, biogas is piped in from the Berger landfill site in Skedsmo municipality and is cleaned and upgraded before being fed to the reformer. The fluidised bed SE-SMR technology was developed by the Institute for Energy Technology (IFE): it is a one-step process that produces hydrogen at a relatively low temperature (625°C) and with high yield. Production capacity of the unit is 12.5 Nm^3/h.

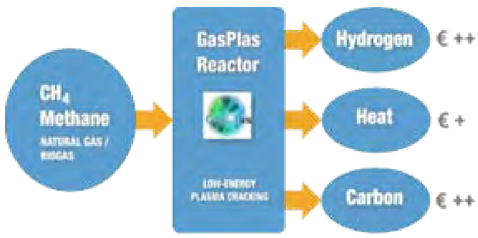
In the second phase of HyNor Lillestrøm, starting in 2013, the ZEG process will be demonstrated; i.e. an SOFC will be thermally integrated with SE-SMR, generating electricity, hydrogen and a pure CO_2 waste stream ideal for CO_2 storage or industrial use. As the process will be using biomethane from upgraded landfill gas, it has been dubbed the 'BioZEG concept'.

Waste heat from the reforming process is used to compress hydrogen in an innovative metal hydride system from HYSTORSYS (also a spin-off from IFE). It compresses hydrogen from 10 to 200 bar using two different metal hydride alloys at two pressure levels. This solid-state storage method has a number of advantages compared to a mechanical compressor: no moving parts, no detrimental effect on hydrogen purity, and a high volumetric density of hydrogen storage can be achieved at moderate pressure and temperature. Further compression to 850 bar takes place in the hydrogen refuelling station provided by Denmark's H2 Logic (see Section 5.5)[59,60].

HyNor Lillestrøm is intended as a showcase, test-bed and training facility for Norwegian hydrogen technology that can be capitalised on by the local economy. Technical visits to Akershus Energy Park are welcomed.

4.3 Microwave Plasma Method

GasPlas AS may have another solution for producing emission-free hydrogen. The company uses novel microwave plasma technology to convert methane directly to hydrogen and carbon powder, a valuable commodity in its own right, producing only usable heat as a by-product. Microwave plasmas are not new to science, but GasPlas says its proprietary technology has for the first time allowed scale-up and implementation at an industrially useful level. It delivered its first reactor to the SINTEF Materials and Chemistry laboratory in Oslo in March 2012.



The GasPlas reactor is scalable and can form the basis for a distributed hydrogen generation system, producing fuel for transportation from fossil methane or biomethane. It has called this the Hydrogen2U (H2U) concept, and is looking to address the market through commercial partners to which it will license the technology.

According to GasPlas, the capital cost of such a system is "low" and operating costs would be comparable to decentralised reforming, while carbon capture is accomplished without a sacrifice in system efficiency. Production of one kilogram of hydrogen with this technology requires 24 kWh of electricity (much lower than electrolysis but a supply of renewable electricity would still be a benefit) and has a cracking efficiency of about 85%. Production of 1 kg hydrogen by efficient, centralised SMR requires just 3 kWh energy input – but this creates 9 kg CO_2 which must be captured and stored in some way, while the GasPlas process instead leaves you with high-quality dry carbon[61].

5. Implementing Hydrogen in Road Transport

5.1 The HyNor Project

Recognising the strength of Norway's position, a national project called HyNor was started in 2003 to introduce hydrogen in transportation, with support from industrial, academic and regional government partners. The secretariat is run by the Zero Emission Resource Organization (ZERO). HyNor's initial purpose was to create sufficient hydrogen refuelling infrastructure for market testing of hydrogen as vehicle fuel. In the first phase, this was intended to take the form of a hydrogen corridor between Oslo and Stavanger; in the second phase from 2009, the focus has been on building a cluster of hydrogen refuelling stations in and around Oslo[62].

HyNor facilitates cooperation on both the creation of hydrogen refuelling infrastructure and the acquisition of cars and buses for the project. It is highly proactive: to begin with it acquired hydrogen internal combustion engine cars to allow early testing of hydrogen mobility to begin (these were fifteen specially modified Toyota Prius acquired early in 2007 and four Mazda RX-8 Hydrogen RE acquired in 2009 under a collaboration with Mazda, *left*). FCEV have been added to the project from 2011 onwards (*below*; see Section 5.5).

As for the creation of hydrogen refuelling stations (HRS), HyNor has been very successful: at the time of writing Norway has six operational HRS, five established under HyNor's aegis and the sixth under the H2 Moves Scandinavia project in which HyNor is a partner. This is sufficient to mark the country out as an important early market for FCEV – which in turn has attracted the interest of global automakers looking to commercially launch FCEV from ~2015 onwards. In order for this commercial introduction to succeed, a dense and stable refuelling network in the Oslo region is thus the main priority for HyNor for the period to 2015, rather than the full realisation of the hydrogen corridor between Oslo and Stavanger.

The project's scope has grown to encompass the provision of carbon-dioxide-neutral hydrogen to its stations through renewably-powered electrolysis, use of steam methane- and plasma-reforming of biogas (also incorporating carbon capture), and the use of industrial by-product hydrogen. The aim is to foster collaboration on the development and implementation of hydrogen production technologies to grow Norwegian competence in this area[63]. Working towards 2015, HyNor is also collaborating on the creation of 'hydrogen links' with Denmark and Sweden under the Scandinavian Hydrogen Highway Project (SHHP).

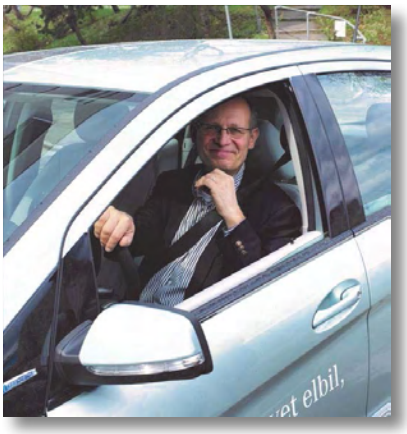
5.2 Key Initiatives in Scandinavia

5.2.1 The Scandinavian Hydrogen Highway Partnership

The SHHP has existed since 2006 and comprises the three bodies which coordinate hydrogen in transportation activities within their respective countries: Hydrogen Sweden, Hydrogen Link (Denmark), and HyNor (Norway). Its aim is to ensure that Scandinavia will be one of the first regions in the world where FCEV are commercially deployed.

The partnership emphasises that the introduction of FCEV requires some level of infrastructure to be in place well ahead of 2015. It is working to achieve this in Scandinavia through a number of demonstration projects, with a few smaller stations interconnecting these. The SHHP also aims to get overt government backing to support hydrogen infrastructure until it becomes self-sustaining, in order to create a 'predictable' environment for early deployments by the various vehicle OEMs[64].

5.2.2 H2moves Scandinavia



The H2moves Scandinavia project was a lighthouse project under the EU Fuel Cells and Hydrogen Joint Undertaking (FCH JU), and ran for three years from 2010 to 2012. The principal aim of the project is to gain customer acceptance for FCEV in Scandinavia.

Its main activities have been: deploying and demonstrating nineteen FCEV; building one new HRS in Oslo (at Gaustad); designing, assembling and demonstrating a mobile hydrogen refueller; and conducting a European Hydrogen Road Tour, which took place from 13 September to 10 October 2012. The Norwegian component of this project, co-funded by Transnova, has overseen the establishment of the new HRS and its commercial operation (see Section 5.4.5).

5.2.3 Next Move

The Next Move project runs for three years from April 2011 and is EU funded by the Interreg IVA Öresund–Kattegat–Skagerrak programme; the Öresund–Kattegat–Skagerrak (OKS) region incorporates parts of Norway, Denmark and Sweden, as shown alongside[65].

This cross-border partnership aims to facilitate the acquisition of FCEV by certain municipalities and communities within this region which share an ambition to introduce zero-emission vehicles. The partners will collaborate on purchase, servicing and competence building; and will establish one new HRS and deploy tens of FCEV[66].

The Norwegian partners in Next Move are Akershus Energi, Hynor Lillestrøm, Lillestrøm Kunnskapsbyen (Centre of Expertise), Skedsmo Municipality in Akershus County, Ruter AS, the Council for Drammen Region and ZERO. Akershus County has for some years been actively pursuing hydrogen in transportation and is in the process of launching a hydrogen strategy for 2013 to 2025[67]; see the feature on the next page.

Further information and news from all these Scandinavian initiatives can be found on the SHHP website at: www.scandinavianhydrogen.org.

Hydrogen in Akershus and Oslo: a Regional Approach

Cutting emissions in half:

Akershus County Council has an ambitious target: to reduce GHG emissions in Akershus to half of 1990 levels by 2030. Its neighbour, the City of Oslo, has the same ambition and the two are collaborating on strategies and initiatives to implement clean and efficient transportation.

Increasing use of public transportation is an important target, which would have emissions benefits in itself, but the two councils also intend to completely eliminate fossil fuels in public transportation by 2020. This will be significant for Norway as a whole: the Oslo-Akershus Metropolitan Area has 1.2 million inhabitants (around a quarter of Norway's population), is among the fastest growing metropolitan regions in Europe and has a substantial proportion of the country's public transportation, and overall road traffic.

The region is already successful in implementing battery electric vehicles: BEV now make up 5 % of new car sales in the region and almost a thousand charging points have been installed. Biogas and biofuel have made significant inroads into public transportation: public transport authority Ruter AS, jointly owned by Oslo Municipality and Akershus County Council, has more than a quarter of its buses running on these fuels. Ruter AS is operating the CHIC-Oslo project with five fuel cell buses in regular operation and a 350 bar hydrogen refuelling station for these buses.

Launching a hydrogen strategy:

In 2012, Akerhus County Council began working on a regional hydrogen strategy, to be launched in 2013 for the period until 2025, and will encompass the deployment of hydrogen infrastructure as well as fuel cell electric vehicles and buses in the greater Oslo-Akershus region. Establishing a viable infrastructure in the region is important for attracting commercial FCEV deployments. Further, an early introduction of FCEV will be of vital importance for Norway as a whole.

A project group of 25 people from interested parties have been working on formulating the strategy. The group includes participants from IFE, Hynor Lillestrøm, the Norwegian Hydrogen Forum, Akershus Energi, HYOP, The Institute for Transport Economics, Ruter, Mercedes Benz and Toyota among others.

The project group has proposed three phases for the strategy: the pre-commercial phase with small-scale infrastructure, lasting until the commercial rollout of FCEV starts around 2015; the early commercial phase from 2015 to 2020, with more cars and stations available; and the maturing market beyond 2020 when the market will gradually become self-regulating. The process has been divided into three working groups which focus on: (1) hydrogen production, distribution, and refuelling; (2) public and private finance mechanisms and incentives; and (3) communication, publicity and knowledge creation.

Challenges remain, especially related to the current high cost of hydrogen production and distribution. There is also still ambivalence as to whether hydrogen is the 'right solution' – not just among the public but also at national government level – and highly visible political commitment in Oslo and Akershus will be important.

The commitment is there: Akershus County Council has decided to take a lead role in supporting hydrogen research, development and demonstration to ensure the success of its strategy, and both the council and the City of Oslo are making funds available while working to secure further EU funding and private investment. The region is likely to become increasingly prominent in driving forward hydrogen development and deployment[n,o,p].

5.3 From Demonstration to Commercialisation

5.3.1 HYOP: Operating Hydrogen Stations

State oil and gas company Statoil was prominently involved in the early establishment and operation of hydrogen refuelling stations in Norway, working closely with HyNor, but the company withdrew from these activities during 2011 and in early 2012 announced that it would end its involvement in hydrogen vehicle fuelling. This is primarily due to a change in Statoil's business model: the company has pulled back from downstream activities to focus on upstream oil and gas extraction, its core business. This included divesting its stake in Statoil Fuel & Retail, selling it to Canadian company Alimentation Couche-Tard in June 2012.

The move could have derailed Norwegian demonstration activities, had the H2moves Scandinavia project not been rescued by a number of stakeholders and had a new company not stepped in for the Statoil hydrogen stations. The company, HYOP AS, was established by Kjeller Innovasjon on behalf of the interested parties in the Lillestrøm region, including Akershus Energi, IFE, and the Lillestrøm Kunnskapsbyen, with the intention of maintaining progress in establishing hydrogen infrastructure.

On 8th May 2012, HYOP acquired Statoil's hydrogen stations at Porsgrunn, Drammen and Oslo Økern. It is also discussing the possibility of assuming responsibility for operating the HyNor Lillestrøm station and the H2moves station in Oslo, should these fit with its business model. The Drammen and Økern stations are on ex-Statoil forecourts and HYOP has an agreement for the continued use of these; they are open to the public and operate automatically around the clock with high uptime. The Porsgrunn station will be converted to 700 bar operation by the end of January 2013, with the intention for this to be the standard for all stations[68,69,70].

Having become familiar with operating hydrogen stations, HYOP CEO Ulf Hafseld says the company next aims to gain an understanding of the characteristics of commercial stations serving two to three hundred cars a day. It should be possible to establish larger commercial stations from around 2014 – if enough hydrogen cars are available. HYOP has regular dialogue with automotive OEMs to ensure that Norway remains under consideration as one of the early markets for the commercial rollout of FCEV.

5.3.2 Business Model

With the certainty provided by increasing numbers of these cars on Norwegian roads, HYOP will begin to attract private investment. For the moment, it is mainly funded by national and local government and this will continue to be the case for the next few years. Despite the disappointment of national bodies such as Statoil and Statkraft drawing back from hydrogen, HYOP says there is still sufficient government commitment to implementing hydrogen in transportation to drive progress forward during this intermediate phase.

But ultimately, HYOP must survive as a commercial entity. In order to make money, its operations will have to integrate the production of hydrogen with supply to consumers; production will be by on-site electrolysis to begin with, moving to some centralised electrolytic production at a later phase. The provision of renewable electricity is key, playing to Norway's strengths in this area and opening the way for utility companies to become involved in the enterprise.

Hydrogen stations could be a valuable market for their electricity – especially if the Green Certificate scheme leads to a surplus of renewable electricity, which may well be the case. HYOP has calculated that to supply renewable hydrogen to the entire Norwegian fleet will require no more than about 10% of the annual consumption of electricity.

Its pricing model will set the price of hydrogen so that it costs the consumer the same to travel 100 km on hydrogen as it would on petroleum. For a station designed for 200 to 300 cars per day and at current prices of grid electricity and petroleum, this would allow a profit to be turned at about 60 to 70% capacity.

However, it is very important that the customer won't have to compromise in other ways – for example, by having limited range. HYOP intends to facilitate a driving experience that is as 'normal' as possible. For this, more hydrogen stations will be needed so the pace and location of further infrastructure rollout will be carefully planned, with a good balance to be struck between a cluster (focused on Oslo) and corridors to facilitate longer trips. From there, a network can be rolled out nationally[71].

5.4 Existing Hydrogen Refuelling Stations

5.4.1 HyNor Stavanger

Norway's first HRS was opened in August 2006 in Stavanger, the nerve centre of the Norwegian oil and gas industry. An initiative to use hydrogen as vehicle fuel had been running in Stavanger since 2003, a result of what was Statoil's interest in the application at the time. The Stavanger station has been dismantled and moved to Risavika Harbour, where hydrogen will be produced locally from natural gas and five fuel cell forklifts will operate in the port area. It is not currently operational[62,72].

5.4.2 HyNor Porsgrunn

Statoil has a test centre in Porsgrunn, in the Grenland region, and a hydrogen station was opened at this facility in June 2007. The station has access to a high-capacity hydrogen pipeline, carrying industrial by-product hydrogen, that could potentially serve thousands of cars. The station supply can also be supplemented with hydrogen from an on-site electrolyser test unit integrated with renewable energy. Originally serving a fleet of nine converted Priuses for five years, these have now been taken out of service and the station is being upgraded with a 700 bar line to serve fuel cell vehicles[71].

5.4.3 HyNor Oslo Økern

The HRS at Økern (*shown top of page 28*), Oslo's first, was opened in May 2009. Ex-Statoil, this station is now owned and operated by HYOP. It uses packaged hydrogen, produced by centralised electrolysis[62,72], and is open to the public.

5.4.4 HyNor Drammen

The HRS (*shown top of page 29*) is the product of a collaborative effort to develop and demonstrate the production of carbon-neutral hydrogen to fuel a local fleet. Also opened in May 2009 and also ex-Statoil, the station is now owned and operated by HYOP. It is identical to the Økern station, and is currently supplied with packaged hydrogen from renewable sources (produced by alkaline electrolysis), but a project is underway to produce hydrogen locally by reforming biogas generated from waste[62,72].

5.4.5 H2moves Scandinavia / HyNor Oslo Gaustad

Norway's first HRS to use hydrogen exclusively generated by on-site electrolysis opened in November 2011, at Gaustad, on the premises of SINTEF's research centre in Oslo[73]. The station is part of the H2moves Scandinavia project and was manufactured in Denmark and established under the aegis of SINTEF by Danish company H2 Logic, which continues to own and operate it. The station currently serves seventeen FCEV in the Oslo area[62] and the mobile refueller has been used for outreach activities at various events[74].

The Gaustad station has been included in the HyNor network and has also been used to develop tools for the optimal operation and use of HRS (see the feature on the next page).

5.4.6 HyNor Oslo Buss

Part of HyNor, the Oslo Buss project falls under the FCH JU CHIC project. Project partners are the regional transport authority Ruter, ZERO, Oslo City Council and Akershus County Council. Air Liquide supplied the refuelling station, which is located at Ruter's Rosenholm bus depot and was commissioned at the end of May 2012; the company will continue to operate the station for five years. Hydrogen is generated on-site using two Hydrogenics electrolysers and renewable grid electricity[75,76]

5.4.7 HyNor Lillestrøm

The Lillestrøm test and demonstration facility's hydrogen station was delivered by H2 Logic in April 2012 and formally opened on 13 June[77]. The station is owned by HyNor Lillestrøm AS and it is refuelling Think city H2EV, Daimler B-Class F-CELL, and Hyundai ix35 FCEV cars.

The hydrogen supply is currently only from renewably-driven electrolysis (using solar PV panels on the roof of the facility), but reforming of landfill gas will begin early in 2013, making it the world's first refuelling station to be supplied by hydrogen generated this way[62,72]. The demonstration of second-generation carbon capture technology will commence at the facility later in 2013; for more information see Section 4.2.

R&D at the Oslo Gaustad Hydrogen Station

Next-generation hydrogen refuelling stations:

As part of the H2moves Scandinavia project, three research and development programmes have been carried out with the aim of facilitating the further development of hydrogen refuelling station (HRS) technology and increasing customer acceptance.

The activities are geared at providing high-quality hydrogen at the lowest possible cost and meeting vehicle drivers' everyday needs by assisting them in finding the nearest HRS.

Hydrogen quality assurance at lower cost

Hydrogen is produced from various sources by utilising different technologies. However, irrespective of production method, the hydrogen must be very pure — nearly 100% — for use in fuel cell electric vehicles (FCEV). Even ultra-low levels of impurities in hydrogen fuel can damage fuel cells severely, and must therefore be reliably identified and removed.

SINTEF has measured hydrogen quality at three HRS in the Oslo area, and the data have been used as input for developing new, more efficient strategies to predict and mitigate impurities.

Hydrogen supply at lower cost by optimisation

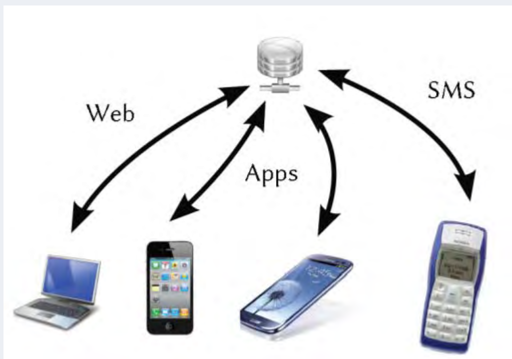
SINTEF Energi AS has developed concepts and models for using HRS as grid-balancing units. Various power conversion system topologies have been assessed and simulations have revealed how HRS system control may facilitate frequency, fault and voltage support for the grid.

Such systems for HRS in Germany, the Nordic Countries and in Norway require different optimised designs due to the nature of the price variations in the specific regions.

Hydrogen refuelling station availability for FCEV drivers

In the early phases of FCEV deployment the number of available HRS will be limited, and the distance between them may be inconveniently long. Stations will also periodically undergo maintenance. Ensuring the availability of hydrogen for drivers is an issue that is key to gaining customer acceptance.

SINTEF has developed a common server solution and user-friendly applications for the internet, both iPhone and Android platforms, as well as SMS. The user can select their personal preference and will receive GPS directions to the nearest HRS.



Information and images courtesy of ***Steffen Møller-Holst, Norwegian Hydrogen Council***

5.5 Fuel Cell Vehicle Deployments

5.5.1 *Van Hool Buses*

Ruter, the public transport authority for Oslo and Akershus, handles over 200 million passenger journeys per year. It aims to have climate-neutral operation by 2020 and already has buses running on second-generation biofuel and biogas. It is using the Oslo Buss project to trial hydrogen fuel cell buses for its fleet[78]. In this FCH JU funded CHIC project, five Van Hool fuel cell buses started operating at the beginning of June 2012[79]. They run on route 81A, from outside Oslo to the city centre, as part of Ruter's regular fleet. The buses are fitted with Ballard HD6 Velocity fuel cell modules[80].

5.5.2 *Think H2 Logic Retrofit*

Battery electric Think City Cars were equipped with fuel cell range extenders by H2 Logic and five were deployed in Oslo in 2011 under the H2moves Scandinavia project. These are equipped to take 700 bar hydrogen and have a 250 km range so can be tested on a par with other FCEV. These cars are intended only for demonstration and test purposes and will not be commercially deployed[59].

5.5.3 *Daimler*

Daimler, which was part of the original H2moves Scandinavia project consortium, supplied ten Mercedes-Benz B-Class F-CELLs for deployment in the Oslo area in 2011. The leasing of these vehicles to customers is managed by the local Mercedes-Benz dealer Bertel O. Steen. Daimler chose Norway for demonstration of its FCEV due to the attractive incentives for EV and the high share of renewables in the energy mix[74]; although it is a relatively small market, Daimler sees Norway as an important pilot for much larger markets in the USA and Germany[81].

5.5.4 *Hyundai*

In early 2011, Hyundai signed a memorandum of understanding (MoU) with representatives from Norway, Denmark, Sweden and Iceland under which Hyundai would provide FCEV for demonstration and the countries would continue to develop the necessary refuelling infrastructure[82]. In May 2011, Hyundai test-drove its ix35 FCEV in Oslo, among other cities.Then, at the opening of the H2moves hydrogen station in Oslo in November 2011, Hyundai officially confirmed that it was joining the H2moves Scandinavia project and supplied two ix35 FCEV SUVs for deployment in Oslo, as well as two for Copenhagen[83].

ZERO Rally

The Zero Emissions Resource Organisation (ZERO) describes itself as a "Norway-based independent not-for-profit foundation working for zero emission solutions to the global climate challenge". It is funded by industry and business partnerships (80%) and government grants (20%) and it directs these funds towards projects that it believes will be beneficial in achieving emissions reduction, among them the introduction of hydrogen in transportation.

ZERO organises an annual rally for zero- or low emissions cars, including FCEV. The 2012 rally, which took place from the 14th to 16th of June, crossed country borders for the first time and ran along the 'Green Highway' between Östersund in Sweden and Trondheim in Norway, a long EV highway that is being established through Scandinavia.

This was the fourth event in the series, which has the aim of demonstrating that practical transportation is possible without fossil fuels. Anyone with a driver's licence and a zero- or low-emission car can participate. Over 50 teams took part in the 2012 rally, among them three teams driving Daimler B-Class FCELLs, two driving Hyundai ix35 FCEV and one driving a Toyota FCHV-adv.

More information can be found at www.zerorally.com and www.zero.no

5.5.5 *Future Deployments*

In May 2012, in a significant development, Hyundai signed an MoU with HYOP, to coordinate the supply of its fuel cell vehicles to Norway. The MoU is intended to support an Oslo-based pilot project to provide FCEV for public agencies, commercial fleets and taxi firms. At the signing, HYOP indicated that it plans to build additional hydrogen stations in accordance with the rollout of vehicles[84].

Hyundai was joined by Toyota, Nissan, and Honda on the 9th October 2012 when the automakers gathered in Copenhagen to sign an agreement with representatives from Norway (HyNor), Denmark (Hydrogen Link), Hydrogen Sweden and Iceland on the market introduction of fuel cell vehicles in the Nordic countries.

Specifically, the partners agreed to cooperate on:

- FCEV introduction and hydrogen refuelling infrastructure development from 2014 through to 2017;
- Advocating public financing and support measures for FCEV and hydrogen infrastructure;
- Engaging key national car dealerships;
- Engaging key national energy and infrastructure companies.

Under the terms of the MoU, the automakers will work towards a market launch of FCEV in 2015 or later, while the infrastructure collaborators will endeavour to introduce sufficient refuelling facilities; in both cases, the efforts are subject to the creation of sufficient public financing and support mechanisms[85].

Fuel Cells in Shipping

In 2010, road traffic in Norway generated 10.1 million $MtCO_2e$ (metric tonnes carbon dioxide equivalent) of greenhouse gas emissions. Statistics Norway reports[q] that, in the same year, international ocean transport in Norwegian territory generated 10.5 million $MtCO_2e$. Domestic coastal traffic and fishing vessels made a further contribution on top of that. Shipping is thus a significant target for the reduction of GHG emissions.

Air pollution is no less of an issue, as ships emit large quantities of sulphur dioxide (SOx), particulate matter, and nitrogen oxides (NOx), greatly affecting the quality of coastal air. However, international regulatory limits on these emissions from shipping are becoming tighter[r], with certain Emissions Control Areas such as the North and Baltic Seas deemed especially sensitive and subject to a higher level of protection[s].

Against this backdrop, the Norwegian hydrogen strategy has from early on included the use of fuel cells in ships. The first action plan (published at the end of 2006) envisaged fuel cells demonstrated as maritime APU by 2010, and fuel cell technology in ship propulsion demonstrated by 2014 (see page 18). So what progress has there been in implementing fuel cells in ships?

In 2002, work began on an EU scoping study called FCSHIP looking at fuel cells for both propulsion and as APU; this was headed by the Norwegian Shipowners' Association and had several Norwegian partners in the consortium[t]. Among them was Det Norske Veritas (DNV), a standards-setting organisation and provider of risk-management services, aiming to take a leading role in facilitating the "safe and reliable" introduction of fuel cells into maritime vessels[u].

DNV subsequently took part in two EU projects. METHAPU assessed the use of fuel cell APU running on methanol on a car transporter, the MV *Undine*, owned and operated by Swedish company Wallenius Wilhelmsen Logistics. The 20 kW solid oxide fuel cell (from Finland-based Wärtsilä) operated successfully, proving the concept during a year-long trial that concluded in 2010. Importantly, the project showed that the use of fuel cell technology with an alternative fuel poses no more of a risk to a commercial vessel than conventional equipment and fuel, laying the foundation for further deployment[v].

The second project is FellowSHIP, managed by DNV and co-funded by the Norwegian Research Council and Innovation Norway, demonstrating the use of a fuel cell as a supplementary part of the propulsion system of a merchant vessel[w]. Norwegian company Eidesvik Offshore ASA is a specialised fleet operator working in supply, subsea operations, seismic surveying and cable installation; it has a progressive environmental policy and introduced the first gas-fuelled supply ship in 2003[x]. There are now several LNG-fuelled ships in its fleet[y], among them the *Viking Lady* (photo, top). The gas–electric propulsion system of the *Viking Lady* facilitated the installation, in September 2009, of a 330 kW molten carbonate fuel cell from MTU Onsite Energy, which can use natural gas without pre-reforming. During the trial, the fuel cell logged 18,500 successful operating hours, providing supplementary power to the ship at an electrical efficiency of over 52% at full load.

While cost, weight and footprint of the fuel cell system would need to come down for commercial implementation (and is expected to do so), this first phase of the project demonstrated the feasibility of using a fuel cell power pack in a merchant ship – well in advance of the 2014 target. The next phase of FellowSHIP will continue this world-leading demonstration, and the installation of a battery pack for energy storage to create a true hybrid propulsion system for the *Viking Lady* is now underway[z].

6. Concluding Remarks

Norway's development of hydrogen refuelling infrastructure, motivated by its unique energy profile and its need to decarbonise transportation, has been an important factor in attracting the automakers' interest and involvement. With a commitment from these companies to provide fuel cell electric vehicles to the Nordic countries as an important early market, investment in further infrastructure can now take place with the assurance that there will be vehicles available to use it.

However, continuing political support is needed for hydrogen to play its pivotal role in reaching the country's ambitious emissions reduction targets. The strategic efforts and recommendations of the Norwegian Hydrogen Council should prompt government action. Further progress of Norwegian demonstration projects, facilitated by hydrogen refuelling station operators, must be assured in order for Norway to maintain a leading role in implementing hydrogen technologies. Certainly, the members of the Norwegian Hydrogen Forum are anxious to see technologies given the opportunity to mature and become widespread.

It is also clear that Norway is equipped to play a leading role in sustainable hydrogen production, both by capitalising on its own resources to produce the gas, for domestic use and for export, and through the development and export of innovative hydrogen technology. This will require some far-sighted investment, but if this is forthcoming Norway stands to benefit from the commercialisation of fuel cells and hydrogen in Europe and the rest of the world. Equally, export markets would reap substantial benefits from Norwegian innovation – not least if it allows environmentally benign use of Norwegian natural gas and efficient use of renewable energy sources.

Norwegian Engagement in R&D Projects Under the FCH JU

Norwegian stakeholders were active in the establishment of the European Fuel Cells and Hydrogen Joint Undertaking (FCH JU), initially with Statoil as a member of the Industry Grouping (www.new-ig.eu) and SINTEF as a member of the Executive Board of the Research Grouping (www.nerghy.eu).

The Norwegian Institute of Science and Technology (NTNU) and the Institute of Energy Technology (IFE) have since become members of N.ERGHY, whereas Statoil has withdrawn from the Industrial Grouping.

In addition to the demonstration projects, H2moves Scandinavia (Section 5.2.2 and 5.4.5) and CHIC (Sections 5.4.6 and 5.5.1), SINTEF is engaged in the LBST-coordinated HyLift DEMO project, in which fuel cells are incorporated in forklifts and tow tractors. But the majority of the Norwegian effort is devoted to R&D, the Norwegian activity totalling to close to €10 million. The funding level of the FCH JU programmes is supplemented by top-up funding (up to 75%) from the Research Council of Norway. This is a prerequisite for the participation of Norwegian R&D institutes in the FCH JU programme.

Norwegian stakeholders are involved in the following collaborative R&D projects:

Project name (coordinator, country)	Start date	Focus area	Norwegian partners
NEXPEL (SINTEF, Norway)	1/1/2010	PEM water electrolysers	NEL Hydrogen, SINTEF
KeePEMalive (SINTEF, Norway)	1/1/2010	Degradation of stationary PEMFC for CHP applications	SINTEF
STAYERS (Nedstack, the Netherlands)	1/1/2011	Degradation of PEMFC for stationary applications	SINTEF
RAMSES (CEA, France)	1/1/2011	Solid oxide fuel cells	SINTEF
SSH2S (University of Torino, Italy)	1/2/2011	Fuel cells and solid-state hydrogen storage	IFE
IdealHy (Shell, the Netherlands)	1/11/2011	Efficient liquefaction of hydrogen	SINTEF Energi AS
RE4CELL (Tecnalia, Spain)	1/2/2012	Advanced multi-fuel reformer for fuel cell CHP systems	SINTEF
BOR4STORE (Helmholtz ZG, Germany)	1/4/2012	Boron-hydride-based solid-state hydrogen storage	IFE
STAMP’EM (SINTEF, Norway)	1/6/2012	Bipolar plates for PEMFC	SINTEF
NOVEL (SINTEF, Norway)	1/9/2012	Materials, design and life-time of PEM electrolysers	SINTEF
Sapphire (SINTEF, Norway)	1/2/2013	Intelligent control for increased lifetime of PEMFC	SINTEF
SmartCat (CEA, France)	1/5/2013	New catalysts for automotive PEMFC	SINTEF

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Acronyms

APU	auxiliary power unit
BEV	battery electric vehicle
CCS	carbon capture and storage
CHP	combined heat and power
CNG	compressed natural gas
DH	district heating
EEA	European Economic Area
EU	European Union
EV	electric vehicle
FCEV	fuel cell electric vehicle
FCH JU	Fuel Cell and Hydrogen Joint Undertaking
GDP	gross domestic product
GHG	greenhouse gas
HRS	hydrogen refuelling station
IEA	International Energy Association
LHV	lower heating value
LNG	liquefied natural gas
MoU	memorandum of understanding
NG	natural gas
NHC	Norwegian Hydrogen Council
NHF	Norwegian Hydrogen Forum
NOK	Norwegian Krone
NOU	Official Norwegian Report
NVE	Norwegian Water Resources and Energy Directorate
OECD	Organisation for Economic Co-operation and Development
OEM	original equipment manufacturer
OKS	Öresund-Kattegat-Skagerrak region
PEM	polymer electrolyte membrane / proton exchange membrane
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic
R&D	research and development
RD&D	research, development and demonstration
SE-SMR	sorption-enhanced steam methane reforming
SHHP	Scandinavian Hydrogen Highway Partnership
SME	small and medium enterprises
SMR	steam methane reforming
SOFC	solid oxide fuel cell
SUV	sports utility vehicle
TCM	Technology Centre Mongstad
TPES	total primary energy supply
VAT	value-added tax

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