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Report

Largescale hydrogen production in Norway - possible transition pathways towards 2050

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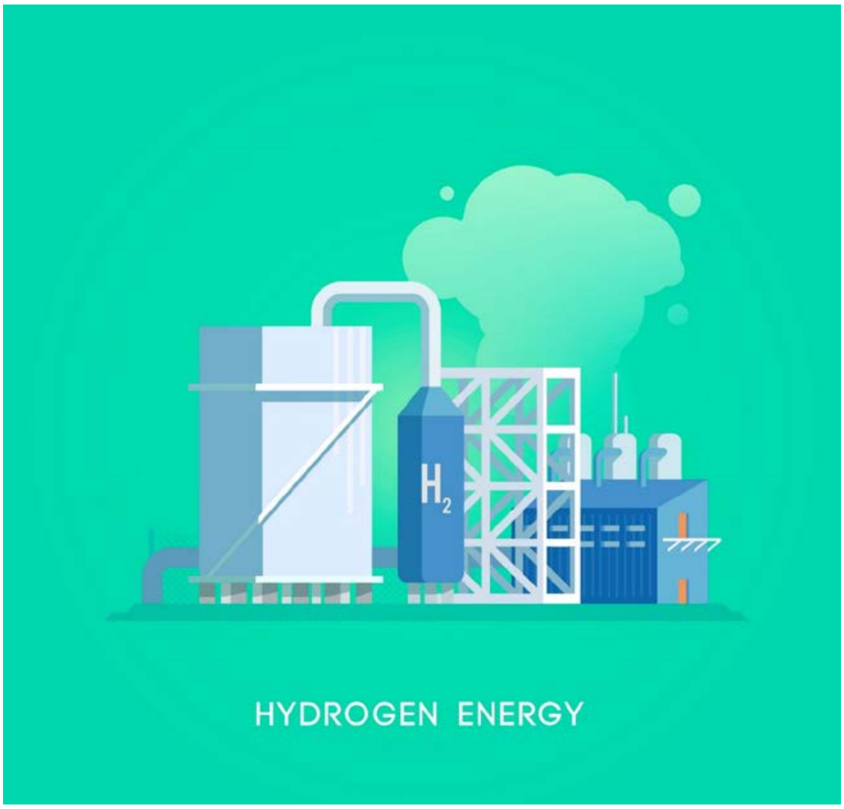

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ABSTRACT

The report presents a case study where qualitative research framed within transition studies and the multi-level perspective (MLP) is used to discuss the role Norwegian hydrogen production may play in sustainable energy transition towards 2050. Ongoing initiatives and stakeholder perspectives on drivers and barriers are discussed. The focus is on the interaction between wider socio-political and market trends and national regime developments, and how this influences the scope for hydrogen production and deployment. The qualitative results are held up against the findings from model-based assessment of two transition scenarios.

Our main finding is that hydrogen may be a key to reach the national climate targets. While hydrogen from natural gas with CCS has been associated with the largest potential, the shift towards a renewable and more distributed energy system is opening new opportunities and roles for hydrogen from electrolysis. The hydrogen industry is growing, but still fragmented, and calls for national coordination. Whereas economic and technological barriers have received most attention, the social acceptance of hydrogen as a sustainable zero-emission solution is a critical factor. The transition is currently at a critical tipping point. Systems thinking and increased focus on sociotechnical interactions are required to unleash the market.

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1. REMES model assumptions

Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
AE	Alkaline Electrolysis
AEM	Anion exchange membrane
ATR	Autothermal reforming
BEV	Battery Electric Vehicle
BIPV	Building Integrated PhotoVoltaics
CCS	Carbon Capture and Storage
CEER	Council of European Energy Regulators
CHP	Combined Heat and Power plant
CLIMIT	Norwegian national funding programme for CCS
DOE	Department of Energy (United States)
ETC	Energy Transition Commission
ETS	EU Emission Trading System
FCEV	Fuel Cell Electric Vehicle
FCH-JU	Fuel Cell Hydrogen Joint Undertaking (EU)
GDP	Gross Domestic Product
GoO	Guarantee of Origin
HAEOLUS	Hydrogen-Aeolic Energy with Optimised eLectrolysers Upstream of Substation
HRS	Hydrogen Refueling Station
Hy2GEN	German company, aiming to produce hydrogen globally
HYBRIT	Hydrogen Breakthrough Iron-making Technology (Swedish initiative)
HyNOR	Hydrogen highway Norway project, 2003-2012
Hyop	Norwegian hydrogen distributor, shut down 2018
IEA	International Energy Agency
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MLP	Multi-Level Perspective
LNG	Liquid Natural Gas
LULUCF	Land, Land-Use Change and Forestry
MLP	Multi-Level Perspective
MoZEES	Mobility Zero Emission Energy Systems
NCEC	Norwegian Clean Energy Cluster
NEL	Norsk Elektrolyse (provider of electrolysers)
NETP	Nordic Energy Technology Perspectives
NIP	National Innovation Program for Hydrogen and Fuel Cell Technologies (Germany)
NIS	Norwegian International Ship Register
NOR	Norsk Ordinært Skipsregister (Norwegian domestic ship register)
NOU	Norges Offentlige Utredninger (Official Norwegian Reports)
NOW	National Organisation for Hydrogen and Fuel Cell Technology, Germany

NVE	Norwegian Energy and Water Resources Directorate
NTP	National Transport Plan
OECD	Organisation for Economic Co-operation and Development
PEM	Proton Exchange Membrane
PEMFC	Polymer electrolyte membrane fuel cell
POX	Partial Oxydation
R&D	Research and development
RCN	Research Council of Norway
REC	Renewable Energy Corporation, shut down 2012
REFHYNE	Clean Refinery Hydrogen for Europe (FCH-JU project)
SME	Small and/or Medium Sized Enterprise/s
SMR	Steam Methane Reforming
SOE	Solid oxide electrolysis
SOFC	Solid oxide fuel cell
TRL	Technology readiness level
TTI	TiZir Titanium & Iron ilmenite plant
WBCSD	World Business Council for Sustainable Development

1 Introduction

The report discusses the findings from a case study under *Norwegian Energy Roadmap 2050*, a competence project financed by the Research Council of Norway. The main objective of the project is to strengthen the knowledge base on how transitioning to a low-emission society will influence the energy, power and transmission systems, map economic ripple effects, and provide recommendations as to how relevant measures may be realized and implemented in Norway. The core activity is quantitative modelling. The present case study is mainly based on qualitative research, to elaborate on the role hydrogen production in Norway may play in energy transition towards 2050.

Hydrogen is associated with a considerable green transition potential. At the same time, it is surrounded with great uncertainty, given the range of possible production methods, energy sources and coupling with other technologies. In the Norwegian context, hydrogen as an energy carrier was up to recently considered relevant mainly for the transport sector. A range of studies has been carried out for specific applications and user cases. There are also feasibility studies and research and development projects in other areas, such as power-to-gas and replacing fossil fuel in industry. However, most of this is technical or technoeconomic. Until DNV GL's synthesis report (DNV GL, 2019), limited attention had been paid to hydrogen production. Few, if any studies, have taken a transition studies approach to the multitude of technical, economic, and socio-political barriers to value chain development in Norway.

Our study fills this gap. A socio-technical system perspective is employed to cast light on the transition potential associated with hydrogen production as part of an emerging value chain for more sustainable energy solutions, as illustrated below (Figure 1).

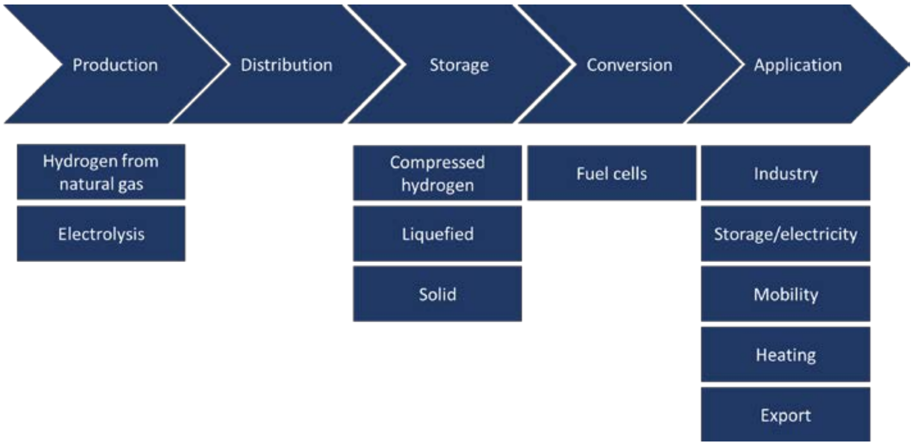

Figure 1: Hydrogen energy value chain.

Large-scale deployment will require large-scale production of hydrogen. At the same time, there is an uncertainty about the demand, which creates a "chicken or the egg" dilemma. This study therefore takes current initiatives to establish large-scale hydrogen production as its empirical point of departure. By large-scale we mean facilities aiming for a capacity of 5 MW or more.

The report has a conventional structure. Chapter 2 outlines the background for the study. It begins with the current climate goals and energy policy in Norway and an overview of perspectives on the energy system towards 2050, before presenting technical aspects, capabilities, and prevailing projections for hydrogen as an energy carrier. Chapter 3 describes the analytical perspective and methods applied. In chapter 4 we take a closer look at six ongoing and recent initiatives to establish large-scale hydrogen production in Norway, discussing their ambitions, resources and challenges. Chapter 5 provides more detail on the opportunities and barriers in the different parts of the value chain, as presented in reviewed literature and discussed in stakeholder interviews and workshops. In chapter 6 we analyse the findings in a multi-level perspective. We discuss trends and specific events in wider society, developments in the national energy regime, and processes in the emerging niche for hydrogen solutions, with a focus on how they interact and influence the transition potential of hydrogen. In chapter 7, we discuss the role hydrogen may play in the Norwegian energy system towards 2050, in terms of three different transition pathways. Chapter 8 is a concluding chapter where we summarize the findings and discuss their implications.

2 Background

2.1 Climate goals and energy policy in Norway

The national Climate Act *(Lov om klimamål (Klimaloven), LOV-2017-06-16-60)* defines legally binding targets for reduction of climate gas emissions by 2030 and 2050. It states that Norway's climate gas emissions shall be reduced by 40% by 2030, as compared to emissions in 1990. Towards becoming a low-emission society by 2050, Norway shall actively pursue the objectives and policy schemes specified in the Paris agreement of 2015, implying that emissions must be reduced by 85-90% by 2050.

Furthermore, the Climate Act specifies five priority areas for climate action, based on the strategy established in the *New emission commitment for Norway for 2030 – towards joint fulfilment with the EU (Meld.St-13, 2014-2015)*. These include:

- Reducing emissions from the transport sector
- Low-emission technologies for the industry
- Carbon Capture and Storage (CCS)
- Strengthening Norway's role as supplier of renewable energy
- Environment-friendly shipping

In October 2019, Norway and Iceland formally agreed, under the European Economic Area (EEA) Agreement, to apply the EU *Effort Sharing Regulation* and the *Regulation on Land, Land-Use Change and Forestry (LULUCF)* with the same obligations and flexibilities as EU Member States.[1]

A technical committee led by the Norwegian Environment Agency has been set up to assess measures and monitor the national progress towards the stated targets. Furthermore, the present government has agreed to increase the national emission reductions to 90-95% by 2050 while cutting 45% of the emissions falling outside the European emission trading scheme (ETS) and strengthening the cooperation to reduce emissions abroad through initiatives such as Rainforest Foundation Norway.[2] In February 2020, Norway announced its climate commitments under the Paris Agreement for 2020, where the climate targets have been tightened to a 50% and possibly up towards 55% reduction of greenhouse gas emissions by 2030.[3]

While the national progress report shows that progress has been made, there is still a substantial gap between the target and the emission budget anticipated for Norway as part of the joint commitment with the EU, implying the need for additional measures amounting to 18.8 $MtCO_2e$ (Norwegian Environment Agency,

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[1] https://ec.europa.eu/clima/sites/clima/files/news/20191025.pdf

[2] "Granavolden-plattformen" – Political platform for the present government, of January 2019: https://www.regjeringen.no/contentassets/7b0b7f0fcf0f4d93bb6705838248749b/plattform.pdf

[3] https://www.regjeringen.no/no/aktuelt/norge-forsterker-klimamalet-for-2030-til-minst-50-prosent-og-opp-mot-55-prosent/id2689679/

2018). Figure 2 shows historical emissions, projections and trajectories for emissions falling outside of the ETS.

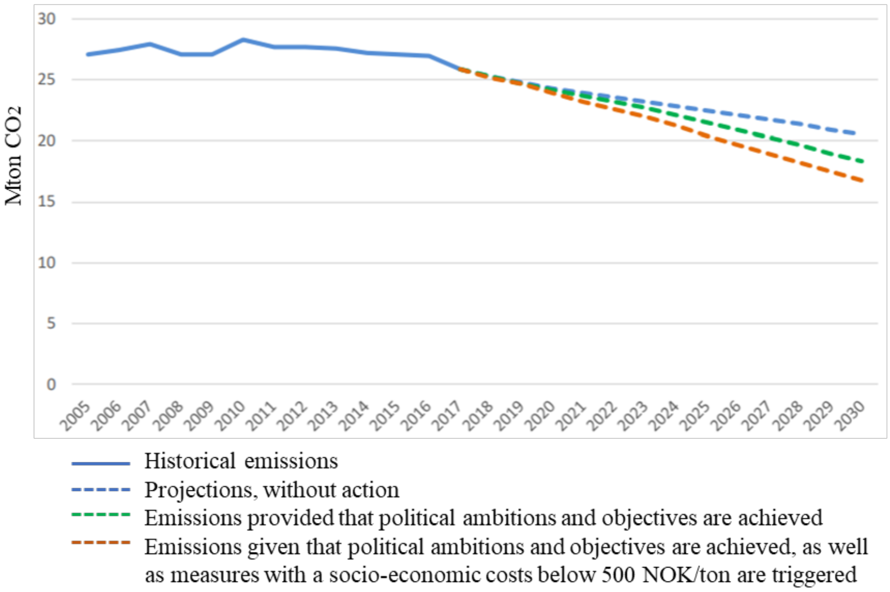

Figure 2: **Historical emissions, projections and trajectories for the non-ETS sector (Norwegian Environment Agency, technical documentation of measures in the Climate Act monitoring report 2018).**

As the diagram indicates, the gap will remain even if current political ambitions are achieved, and even if they are supplemented with new measures at a cost below 500 NOK/tCO_2e. This suggests the need for stronger policies, better tools, and/or new solutions. In January 2020, the Norwegian Environment Agency launched Climate Cure 2030 – a broad-based assessment of possible measures indicating that a 50% emission reduction by 2030 could be realised, if current policy is strengthened rapidly to enable largescale behaviour change and uptake of new technologies, as well as implementation of new instruments (Norwegian Environment Agency, 2020).

The 2016 White Paper on Energy *(Kraft til endring – Energipolitikken mot 2030 (Meld. St. 25 (2015–2016))* has four focus areas:

- Ensuring a reliable supply of electricity
- Market-based development of renewable energy
- More efficient and climate friendly use of energy
- Industrial development and value creation based on efficient exploitation of profitable renewable resources

Hydrogen is discussed as a possible energy carrier for the future, both in transport and for stationary applications. Emphasis is placed on research and development within production and storage, as well as use of hydrogen. The need for further demonstration and eventual market introduction of solutions for road transport is mentioned, and support for hydrogen refuelling stations is explicitly defined as part of the mandate for Enova, as a government-owned funding agency for new energy and climate solutions.

Although the white paper discussed a hydrogen strategy, it was criticized for not sufficiently addressing the connections between energy, climate, and industrial development, as well as lacking a more specific strategy for hydrogen.[4] Such a strategy had already been called for by the parliamentary committee on energy and environment *(Innst. 147 S (2014–2015)* and repeated by the committee for enterprise development (*Innst. 374 S (2016–2017*). It has also long been called for by a wide range of other stakeholders. In April 2018, the parliament requested that the government explore the opportunities for a joint Nordic hydrogen strategy *(Innst. 253 S (2017–2018)*. The work to prepare an integrated Norwegian hydrogen strategy is currently ongoing. A national dialogue meeting was held on February 11, 2019. The mentioned techno-economic study by DNV GL (2019) forms an important part of the knowledge base but there is the need for more perspectives.

2.2 Perspectives on the energy system towards 2050

Regardless of whether the target is climate neutrality or the 2-degree Celsius limit, greenhouse gas emissions need to decrease significantly. The EU target is a 95% reduction in climate gas emissions by 2050, compared to the 1990-levels. There are various proposed pathways to get there. Global studies (ETC, 2018; IRENA, 2018; Gielen et al., 2019; Ram et al., 2019), European analyses (European Commission, 2018; Kanelloupolos and Blanco, 2019), as well as Nordic research reports (NETP, 2016) all highlight the importance of energy efficiency measures and the need to increase the renewable share in energy generation.

The discussed transition pathways are largely dependent on electrification, which implies large investments in power generation and grid capacity. The estimates for the share of wind and solar power generation vary from 46 % (Gielen et al., 2019) to 90 % (ETC, 2018), dependent on the assumptions for CCS and availability of biomass resources, the volume of nuclear power generation and the potential for energy efficiency entered into the model analyses. At the global scale, the current share of wind and solar power aggregated is 2 %. Decarbonising the transport sector is mentioned as a crucial factor in the NETP (2016).

The projections in Hansen et al. (2018) show that it is not possible to reach a 100 % renewable energy system within 2050 in Germany without exceeding the limit for sustainable utilization of biomass resources. Additionally, a strong resistance to onshore wind power development is evolving in several countries (Skonhoft 2019). This may be a driver for hydrogen decarbonizing the transport sector, and for the implementation of CCS, to enable a continuation of thermal power generation. The Energy Transition Commission (ETC) upholds the implementation of CCS as a crucial factor to reach the 2-degree target (ETC, 2018). The implementation of CCS will enable the utilization of natural gas for hydrogen production. Additionally, the increasing use of variable energy sources for electricity generation may provide an interesting business case for the utilization of surplus power for hydrogen production. This could be profitable in island communities and remote areas with limited electricity grid capacity, as well as contribute to energy flexibility.

The transition that is required is radical and will demand large investments in infrastructure for transmission grid and fuel stations, coupling of the household, industry and energy sectors, as well as political stimulus. Hydrogen may play several important roles (cf. Hydrogen Council, 2017; IRENA, 2018): Enabling large-scale renewables integration, distributing energy across sectors and regions, and acting as a buffer to increase system resilience, as well as decarbonizing end use, and as renewable industry feedstock. While decarbonisation of specific sectors has received most attention up to now, the potential in terms of sector coupling and buffering is increasingly in focus.

2.3 Hydrogen as energy carrier

Hydrogen is abundant in nature and suited as an energy carrier because it can be produced and converted into power at relatively high efficiencies. The product of utilization is pure water, it can be stored in several forms

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[4] See for example the opinion by Marius Holm, ZERO: https://sysla.no/meninger/slik-kan-stortinget-redde-energimeldingen/

and transported over long distances. It can also be converted into other forms of energy in more ways and more efficiently than any other fuel, and it is environmentally friendly (Veziroglu and Barbir, 2005).

Hydrogen production can be based on multiple energy resources, such as natural gas, oil and coal, hydropower, wind and solar energy, algae from sunlight, and biomass (Arnold, 2017). Currently, natural gas reforming is the dominant method. Reforming is the conversion of hydrocarbons and alcohols by chemical processes into hydrogen, with water (vapour), carbon monoxide and carbon dioxide as by-products (EERE 2019). In addition to the raw material, reforming requires an oxidant, which supplies the necessary oxygen. Based on the oxidant, three basic methods can be identified:

- **Steam methane reforming (SMR):** Pure water vapour is used as oxidant. The reaction requires the introduction of heat ("endothermic").
- **Partial oxidation (POX):** Oxygen or air is used as oxidant. The process releases heat ("exothermic").
- **Autothermal reforming (ATR):** A combination of SMR and POX. The ratio of the two oxidants is adjusted so that no heat needs to be introduced or discharged ("isothermal").

Figure 3 provides a schematic overview of how steam methane reforming can be combined with carbon capture to produce blue hydrogen:

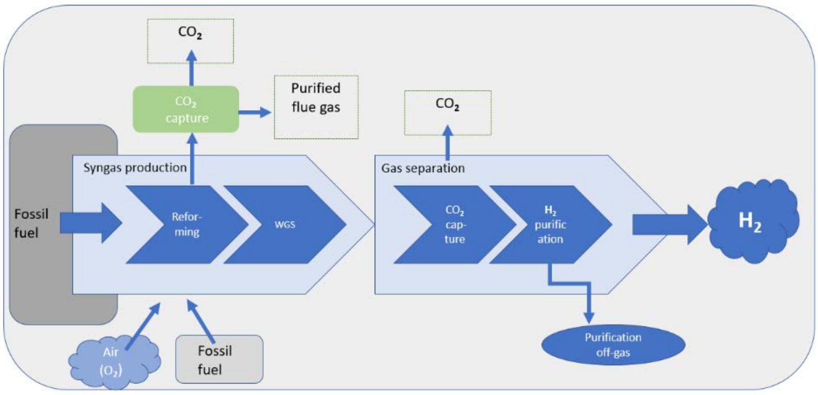

Figure 3: SMR with carbon capture, figure based on Vormsund et al. (2016).

The energy input in the form of natural gas in large-scale hydrogen production is typically 22 to 28 kWh/kg H_2, with an efficiency of 70-80% (Møller-Holst et al., 2016). POX and ATR are mainly for heavy hydrocarbons (oil and coal).

The most prominent alternative to gas reforming is water electrolysis, which involves splitting water into hydrogen and oxygen by passing electricity through an electrolyte (Fig. 4). The electrolyser consists of a DC source and two noble metal-coated electrodes, which are separated by an electrolyte. Electrolysers are differentiated by their electrolyte materials and operating temperature.

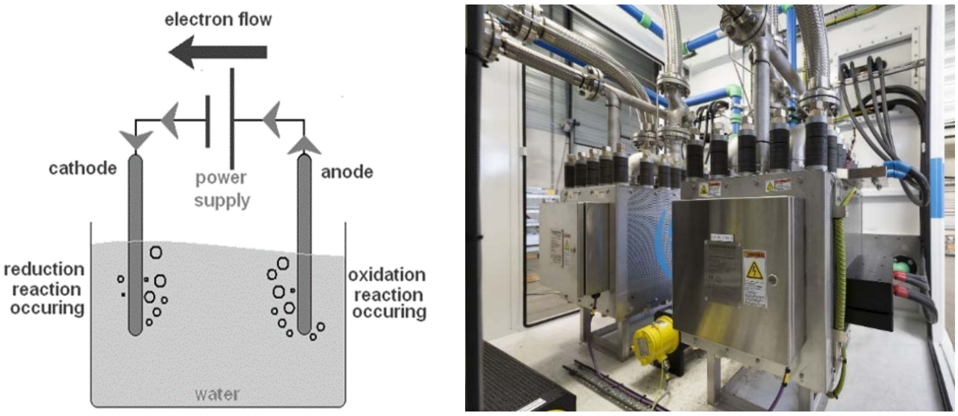

Figure 4: Left: Basic process, water electrolysis (Source: Open Energy Information, Wikipedia) Right: An electrolyser (Source: Hydrogenics/Varanger KraftHydrogen AS).

Alkaline electrolysis (AE) is a mature technology based on a liquid caustic electrolyte and relatively cheap metal coating. The hydrogen produced will typically have a purity of 99,8 %, which may be further increased by removing water and oxygen. Normal operating temperature is 60-80 °C, and energy efficiency 65-82% (Adolf et al., 2017). AE is currently the clear market leader among electrolysers.

Proton Exchange Membrane (PEM) electrolysis uses a polymer, as electrolyte, and works at similar temperature and with similar efficiency and purity as AE. The use of PEM has increased in recent years because it works at high current density, which may reduce operating costs, especially when dynamic sources such as wind or solar energy are used. It requires less space and largescale facilities will have a significantly smaller footprint than with AE. With PEM, it is also easier to compress the hydrogen, which may reduce transport and storage costs. While PEM is a younger and more expensive technology, some studies suggest the long-term (5-10 year) efficiency is slightly higher. The cost is expected to drop rapidly in the next 5-10 years and the long-term cost is already more or less the same as for AE (Blue Move, 2018).

Anion exchange membrane (AEM) electrolysis has only just appeared on the market. There is also high-temperature electrolysis, including **solid oxide electrolysis (SOE)**, which still is at an advanced R&D stage (Arnold, 2018). The expected advantages of the latter are increased conversion efficiency and the possibility of producing a synthesis gas directly from steam and CO_2, for use in synthetic liquid fuels.

The different electrolysis technologies are all modular, allowing for flexible production and gradual investment/upscaling. According to the ETC, the current investment costs for electrolysers is US$1000/kW, and it is expected to decrease to US$250 by 2050. The estimations for investment costs for water electrolysis in 2030 (in 2017 prices) varies from 397 to 955 (PEM) and 787 to 906 euro/kW (AE) (ETC, 2018).

The carbon footprint of hydrogen from natural gas reforming is around 10-14 $kgCO_2e/kgH_2$. Hydrogen from electrolysis has a footprint of around 0,8 $kgCO_2e/kgH_2$ when the emission declaration for power in Norway is taken into account (NVE, 2018b), and less than 0,2 $kgCO_2e/kgH_2$ when based directly on Norwegian hydropower. This means that whereas production by electrolysis is a (close to) zero emission alternative, there is considerable potential for reducing the climate gas emissions from natural gas reforming. One way to do this is by adding carbon capture and storage (CSS). It is estimated that hydrogen produced by SMR based on offshore gas with CCS may achieve a footprint as low as 0.5 $kgCO_2e/kgH_2$ (H21, 2018).

Hydrogen based on natural gas reforming with CCS is popularly termed "blue hydrogen", as opposed to "grey hydrogen" based on conventional fossil methods, and "green hydrogen" based on renewable energy. Through the EU CertifHY-project, the threshold for low-carbon hydrogen has been set at about 4.36 kg/CO_2eq per kilo of hydrogen, which is 60% below a set benchmark of the best available technology for gas reformation (Fig. 5). When the renewable source is on-site or has purchased GoOs, the scheme automatically sets the CO_2-level to 0. If the CertifHY scheme of origins is implemented as standard, the threshold for low carbon H_2 demands CCS when the source is non-renewable (CertifHY, 2016).

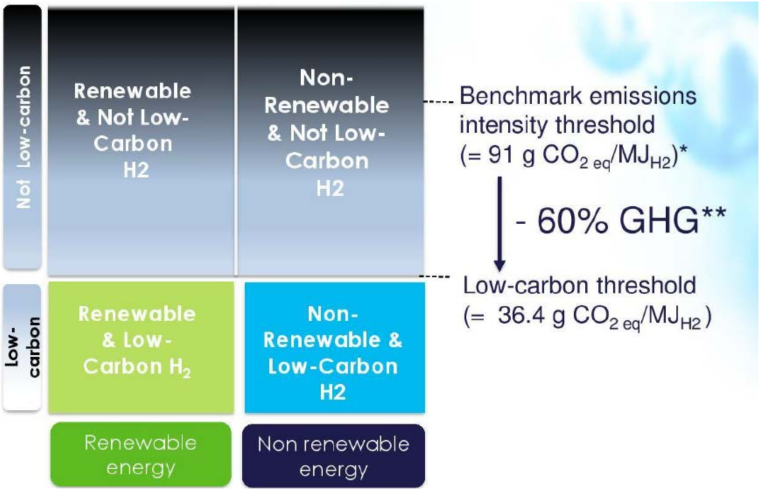

Figure 5: **Hydrogen is categorised according to energy input and GHG (greenhouse gas) emissions (CertifHY, 2016).**

The development of hydrogen as energy carrier is closely linked to that of fuel cells, which convert hydrogen into electrical and heat energy. Fuel cells may reach efficiencies of over 80%, but due to voltage losses current achieved efficiencies are lower (Eichlseder and Klell, 2012). There are presently five fuel cell types, differentiated by electrolyte type and temperature. The market is dominated by the low-temperature polymer electrolyte membrane fuel cell (PEMFC), which is associated with high power density, flexibility and cost reduction potential, and well suited for mobility. However, the solid oxide fuel cell (SOFC) is also gaining importance, as a high-temperature fuel cell for stationary applications (Adolf et al., 2017).

2.4 Development scenarios for hydrogen towards 2050

Globally, DNV GL (2018) expects a low uptake of hydrogen up to 2050, summing up to 0.5% of the energy mix in 2050. This is explained by high storage costs and low efficiency of conversion. It is argued that hydrogen still is at an early stage of development and will require technology learning and scale-up to gain market shares. The uptake is expected to increase from the mid-century due to a market pull towards the use of more environment friendly fuels. DNV GL assumes that hydrogen generation will be by electrolysis. Also, Shell Sky (2018) expect a growth in hydrogen deployment mainly from 2050 and onwards. They expect a market share of 2% of total final consumption globally, but 18% in Europe in 2050.

The most optimistic estimate is by the Hydrogen Council, which estimates a 20% hydrogen share of total global energy consumption in 2050 (Hydrogen Council, 2017). The development of the hydrogen sector is highly dependent on policy incentives, the development of CCS technology, and the development of competing technologies, such as batteries.

Except for heavy-duty transport, only a small share of the transport sector is expected to convert to hydrogen. To decarbonize the industrial sector, the hydrogen share is expected to increase. Hydrogen is already used as feedstock in industry, and this sector is difficult to electrify and decarbonize. Hydrogen is also expected to play a significant role in decarbonising the heating sector and provide flexibility to the future energy system with a high share of variable electricity generation.

Figure 6 shows different projections for hydrogen development in 2050. The projections are largely dependent on the applied model assumptions. Some studies deal with pathways towards energy neutrality, other studies investigate emission reductions according to specific goals, for example, according to the 2-degree goal, while some study pathways to a 100% renewable energy system. In addition, assumptions must be made about available biomass resources and alternative uses, carbon prices, weather scenarios regarding wind power generation, costs for CCS and costs of grid capacity expansion.

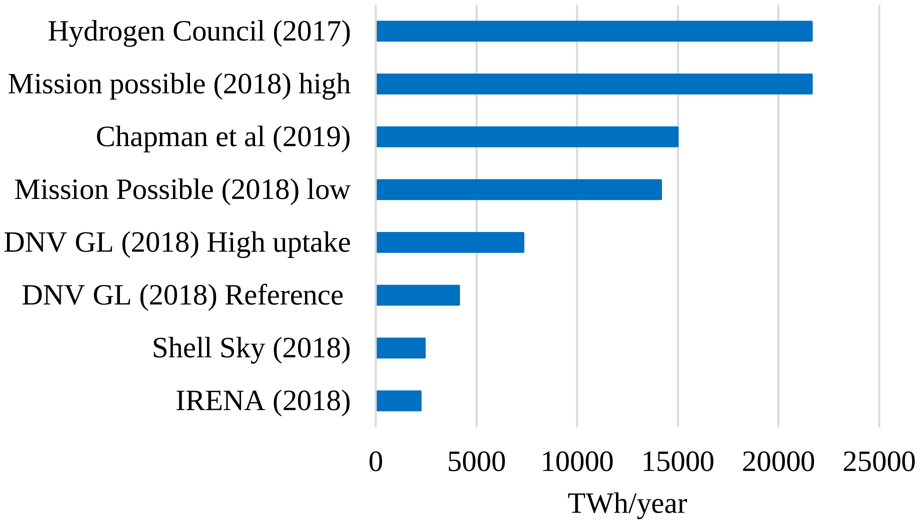

Figure 6: Projections for hydrogen consumption in the global energy system in 2050.

3 Analytical approach

This chapter makes a brief presentation of the perspective and methods applied for the study. Following a general introduction to socio-technical transition studies, we present core analytical concepts and discuss the methods selected for data collection.

3.1 Sustainability transition studies

Climate change involves complex environmental, economic, technological, and social challenges that cut across all sectors. These require comprehensive system changes and may be perceived as shifts towards new kinds of socio-technical systems, or “sustainability transitions” (Elzen et al., 2004).

Sustainability transition studies (Köhler et al., 2019) take a long-term system perspective, aiming to shed light on different policy options and what their impacts and implications could be. Where model-based scenarios assess specific strategies based on economic rationality and a set of pre-specified premises, transition studies tend to focus on the interaction between actors, institutions, and technologies, emphasizing co-evolution and multi-dimensionality. Transitions involve many kinds of agency (e.g. sense-making, strategic calculation, learning, making investments, conflict, alliance building, power struggles), and the timing and direction in technology development is difficult to foresee. Transitions research addresses the drivers, barriers and opportunities arising from these processes and aims to understand patterns and possible pathways towards increased sustainability.

The multi-level perspective (MLP) is a middle-range theory that conceptualizes overall dynamic patterns in socio-technical transitions (Geels, 2011; Markard, 2012). The MLP views transitions as non-linear processes resulting from the interplay of developments at three analytical levels: niches (the locus for radical innovations), socio-technical regimes (established practices and rules that stabilize existing systems), and an exogenous socio-technical landscape (Rip and Kemp, 1998; Geels, 2002; Geels 2011).

Each level refers to a heterogeneous configuration of elements, and ‘higher’ levels are more stable than ‘lower’. The regime level is of primary interest, because transitions are defined as shifts from one regime to another (Geels, 2011). The socio-technical regime refers to the semi-coherent set of rules that orient the activities of the social groups and form the "deep structure" of an existing socio-technical system (Geels, 2004). Because existing regimes are characterized by lock-in, innovation tends to occur incrementally, with small adjustments accumulating into stable trajectories. These trajectories occur not only in technology, but also in cultural, political, scientific, market and industrial dimensions, which co-evolve and interpenetrate each other (Geels, 2011).

Niches are "protected spaces" with actors (such as entrepreneurs, start-ups, spinoffs) working on radical innovations. Niches gain momentum if expectations become more precise and more broadly accepted, if the alignment of various learning processes results in a stable configuration (‘dominant design’), and if networks become larger. The wider socio-technical landscape includes the established technical and material backdrop that sustains society, as well as demographical trends, political ideologies, societal values, and macro-economic patterns. Although the MLP sometimes is summarized as ‘micro-meso-macro’, the levels refer to different degrees of structuration of local practices and are not necessarily hierarchical (Geels, 2011).

Each transition is unique, but the general dynamic may be illustrated as in Figure 7: (a) niche-innovations build up internal momentum, (b) changes at the landscape level create pressure on the regime, and (c) destabilisation of the regime creates windows of opportunity for niche innovations.

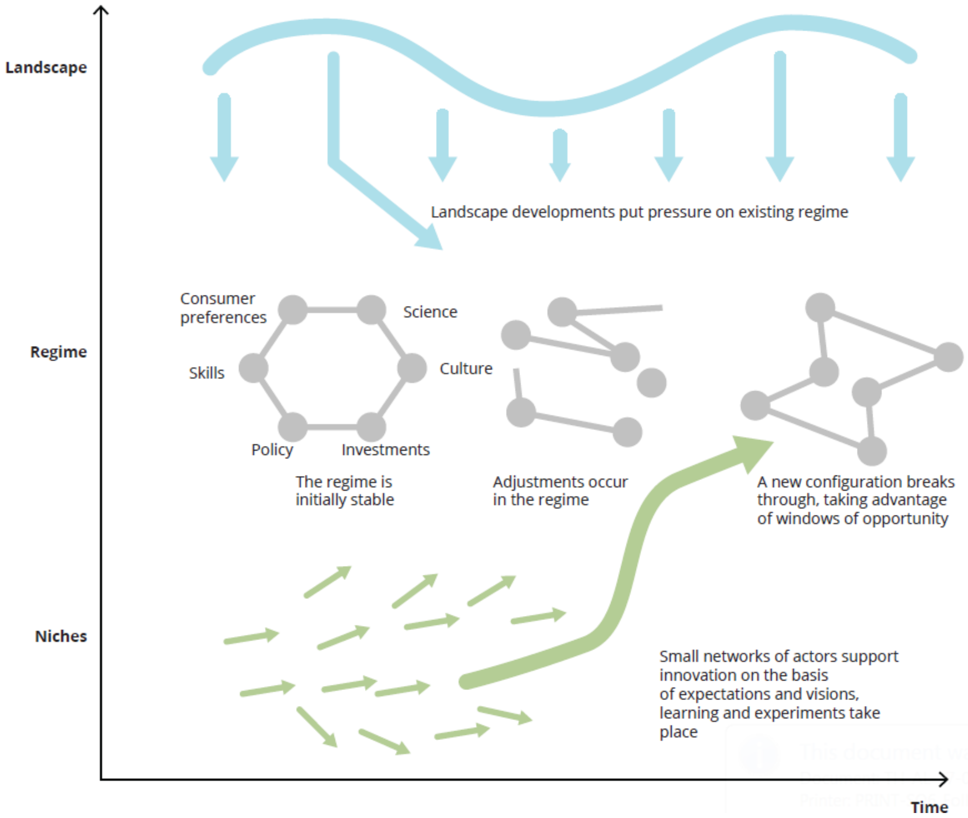

Figure 7: Multi-level perspective on transitions (EEA, 2017, Geels, 2011:28).

The notion of transition pathways refers to different trajectories or forms these processes may take. Several different typologies have been developed (e.g. Geels and Schot 2007, Haan and Rotmans, 2011). We find the concepts useful in discussing the emergence of hydrogen as energy carrier in Norway and how the potential may be realised in different ways, depending on the development of the energy system and wider economy.

Another central concept is that of lock-in (Klitkou et al., 2015). Lock-ins can be defined as positive feedbacks or increasing returns to the adoption of a selected technology. Due to such mechanisms, incumbent technologies have a distinct advantage over new entrants. A stable incumbent regime is the outcome of various lock-in processes and favours incremental innovation. As different regimes are characterised by different lock-ins, increased attention to such mechanisms may increase our knowledge of transition processes as an *"interplay of path dependence, path creation and path destruction"* (Martin and Sunley, 2006:408). Klitkou et al. (2015) identify nine types of lock-in mechanisms, summarised in Table 1:

Table 1: Lock-in effects (based on Klitkou et al., 2015).

Learning effects	Cumulative production leads to improved knowledge, skills and organisation, facilitating higher quality outputs, lower costs and better alignment with user needs and expectations.
Economies of scale	Sunk costs from earlier investments in production capacity are spread over an increasing production volume.
Economies of scope	Cost advantages are induced by the production and use of a variety of products rather than specialization and dependence on only one product.
Network externalities	Advantages due to compatibility with existing infrastructure and standards.
Informational increasing returns	The adoption of a technology means it receives greater attention, which in turn stimulates other users to adopt it.
Technological interrelatedness	The adoption of a technology favours development of complementary technologies, decreasing technological uncertainty and leading to increased user acceptance.
Collective action	Emergence and subsequent reproduction of societal norms, customs, consumption patterns and formal regulations, based on coalition-building in associated networks.
Institutional learning effects	Learning effects related to increased adoption of institutions linked to the new technology, which make them rather complex and difficult to change.
Differentiation of power and institutions	Asymmetries of power, institutional complementarity and symbiotic relations may lead to imposition of rules, mutual obligations and reciprocal action that contribute to institutional lock-in.

We do not apply this list exhaustively but find the concepts useful for discussing drivers and barriers to different forms of hydrogen production and their prospects within different energy scenarios for Norway.

3.2 Methods

The study is based on a combination of methods, including document studies, interviews, and participant observation in workshops and conferences where the challenges, opportunities, and the transition potential associated with hydrogen were discussed between key stakeholders.

A desk top study was carried out to assess relevant documents enabling a better understanding of energy perspectives and hydrogen strategies among core market actors, regulatory authorities and other relevant stakeholders. The study covered both peer reviewed articles on different aspects of hydrogen, white papers presenting scenario analyses for the future energy system globally, for Europe, the Nordic region and for Norway, and reports from various non-governmental organizations, consultancies and key actors in the energy market on their assessments and projections for hydrogen as energy carrier.

Six production initiatives in Norway were selected as starting points for the empirical data collection. The selection of cases was discussed with the Norwegian Hydrogen Association. They were among the most mature at larger scale in Norway in the second half of 2018, and are dispersed along the Norwegian coast, as illustrated below (Figure 8).

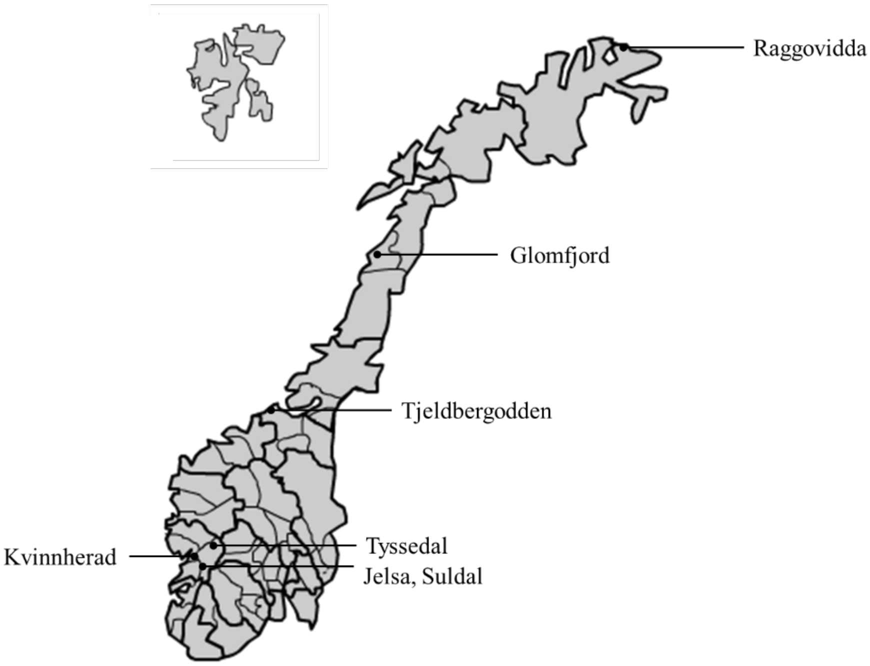

Figure 8: Location of production initiatives in focus in the case study.

Key stakeholders in each case were consulted, and the initiatives were assessed in terms of actor perspectives, activities, plans, technological approaches, planned capacity, goals/ambitions, market opportunities, available resources and collaborative partnerships. In the next step we interviewed a wider set of stakeholders, on drivers and barriers to the development of hydrogen value chains in Norway.

A total of 26 semi-structured interviews were conducted, with informants representing different parts of the value chain and other stakeholders. Their distribution across categories is presented below (Table 2).

Table 2: Stakeholders interviewed for the case study.

Stakeholder category	Number of stakeholders interviewed
Established energy companies	4
New actors, focused on H2 production	3
Technology providers	3
Distributor	1
Potential users	3
Researchers and consultants	2
Municipalities with H2 initiatives	3
County Councils	2
Public agencies, national level	3
NGOs, energy and climate	2

Some of the interviews were conducted face-to-face, while others were carried out via video or phone. Each interview lasted between 60 to 90 minutes and covered topics as expectations for the future, views on the role of the authorities and questions aimed for mapping the current state.

Data were also collected by systematic observations at seven workshops, at regional, national and international level (Table 3). Put together, this provided insight into the current plans, perspectives and concerns among a wide range of stakeholders.

Table 3: List of workshops and seminars were additional data were collected.

Event	Type	Date	Organizer	Researcher's role
Hydrogen in Rogaland	Dialogue conference, regional/national	07.03.2019	Rogaland County	Participant
Unleashing the H2 market	Workshop (central industry actors, national)	21.11.2018	SINTEF	Participant
Legal-administrative barriers to hydrogen in Norway	National workshop /breakfast meeting	11.10.2018	Hydrogenforum, SINTEF	Organizer, presenter
Scandria2Act	Workshop, Nordic	05.12.2018	Akershus County, (Interreg project)	Participant
Hydrogen – grunnlag for ny industri og arbeidsplasser i Norge (Hydrogen as basis for new industry and employment in Norway)	Seminar, national/regional	24.10.2018	Tjeldbergodden Utvikling	Participant
H2FC 2018	International conference	14-15.05 2018	NTNU, SINTEF	Participant, poster presentation
Input meeting – national, integrated hydrogen strategy	National input meeting	11.02.2019	Ministry for Petroleum and Energy, Ministry for Climate and Environment	Audience, observer
HyLAW EU Workshop	International workshop, around 100 participants	06.12.2018	Hydrogen Europe, Brussels	Presenter, participant

Towards the end of the report, the qualitative findings and analysis are discussed in relation to preliminary quantitative results from the project. These stem from two different models:

TIMES-Norway, a bottom-up optimization model of the Norwegian energy system that addresses cost-minimized long-term development of the Norwegian energy system, capturing the relationship between several energy carriers, energy generation technologies, energy transformation options and end-use technologies. The model is divided into 400 groups of end-users within the industry, building and transport sectors. The spatial resolution is according to the five elspot bidding areas of NordPool in Norway and the time resolution is 260 time units per computed year. One of the endogenous variables in the model is CO_2 emissions (Rosenberg et al., 2013).

REMES, a multi-regional computable general equilibrium model that represents the Norwegian economy with a focus on the energy system. The model is flexible both in terms of industry and spatial resolution, and the level of aggregation in this study was five regions, 36 industries and 32 products or services. The products and services can be used as end products, as input factors or investment goods for other industries within or outside the region or exported abroad. In Norwegian Energy Roadmap 2050 a dynamic version with an annual resolution was developed.[5]

4 Hydrogen production in Norway

The chapter provides an overview of the historical backdrop of hydrogen as a low-emission solution in Norway, before presenting and discussing the production initiatives that were used as empirical starting points for this study.

4.1 Historical backdrop

Norsk Hydro/Yara started hydrogen production based on electrolysis for ammonia and fertilizer production at Notodden as early as in 1927. Their plant at Glomfjord had the world's largest production in 1947, and was later bypassed by a third plant, at Rjukan, which by 1953 had a capacity exceeding 30.000 Nm3/hour.[6] When natural gas production in Norway started, gas reforming became more viable, economically speaking, and the last electrolysis plant shut down in 1993.

Norwegian institutions were active in collaborative programs on hydrogen and fuel cell research under the International Energy Agency (IEA) and European framework programs since their inception. From the 1980s SINTEF took a leading position, and in 1996 the Norwegian Hydrogen Association was established. One of the first prestige projects in industry was a feasibility study by Shell and Aker Kværner in 2002-2003, for a demonstration plant at Kollsnes, outside Bergen. The concept was to apply solid oxide fuel cell (SOFC) technology, using natural gas as primary energy source. The project was considered a success, but the follow-up would cost around 150 mill NOK (OECD, 2006) and the plans for a 6MW Kollsnes II plant were not realized.

The Utsira project, which combined windmills with fuel cells for power generation, was set up in 2004. The demonstration received a lot of attention. As the world's first 'hydrogen society', the island community would be self-sufficient and independent from the national grid. The plant was established by Norsk Hydro in collaboration with Enercon. The system efficiency for hydrogen production was 53% (Ulleberg et al., 2010). However, wind utilization was low and the fuel cell would have to be improved to make the project commercially viable.

The most visible project nationally in this early phase was HyNor, where Statoil and Norsk Hydro joined efforts with national support to carry out a market-realistic demonstration of hydrogen refueling stations and vehicles. The first station opened in 2006 near Stavanger, the second in Porsgrunn (Grenland) in 2007, and two stations were opened in Oslo and Lier, near Drammen, in 2009 (Fig. 9).

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[5] EMPS, a stochastic optimization model that minimizes the operational costs of a power system under the assumption of perfect competition is also applied in Norwegian Energy Roadmap 2050, but the results from the analyses using EMPS are not applied in the present case study.

[6] https://nelhydrogen.com/about/#timeline

Figure 9: Hydrogen road open. Source: Hynion

Two more hydrogen stations were planned (Lyngdal and Bergen) but did not materialize. The sale of battery electric vehicles (BEVs) in Norway took off from 2010-2011, and the international producers prioritized other markets for introduction of fuel cell electric vehicles (FCEVs). Experiments in other countries also indicated a limited maturity level. The financial crisis from 2008 led to a dramatic fall in oil prices and enthusiasm about the new technology had to compete with increasing scepticism, epitomized in the influential book; *"The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate"* (Romm, 2004).

Statoil and Norsk Hydro put their efforts on hold in 2009. Around the same time, the first *Climate accord* in the Parliament (*St. Meld. nr. 24 (2006-2007))* led to the establishment of Transnova, a state program to facilitate environment-friendly transport solutions. While Transnova supported a broad range of solutions, including hydrogen refuelling stations (HRS), the market for electrical vehicles was more mature. In the years that followed, the success and benefits of electrification gained further prominence in the discourse on energy transition. Statoil decided to close their hydrogen refuelling stations in 2011 and the stations were repossessed by Hyop from 2012.

Some of the developed technology lived on in smaller niche companies, such as NEL Hydrogen and Hexagon Composites. Initially, these lacked the financial muscles to expand internationally.[7] In the period 2000-2010, NEL lost around 37 million euro. Profiled investor Øystein Stray Spetalen entered in 2011, and generated renewed interest in hydrogen in 2014 when he seized the whole company, motivated by the falling price of solar energy in the EU. Hyundai brought the first FCEVs to Norway in 2014, and by 2015, NEL went on to buy the Danish hydrogen fuel station producer H_2 Logic. Meanwhile the maturity of hydrogen technologies kept increasing, both nationally and internationally.

The Parliament voted for creating a new National Hydrogen Strategy, reflecting new prospects for the role of hydrogen as a vector in a renewable energy system. Toyota started selling FCEVs in Norway from 2016, and as we have seen, the white paper on energy defined support for hydrogen refuelling stations as part of Enova's mandate. Since then, Norwegian technology providers have had increasing international success. The piloting and deployment of hydrogen solutions have increased slowly but steadily, though the enthusiasm in some quarters diminished when Hyop shut down in late 2018. A new blow came in June 2019 when one of the remaining refuelling stations had a serious explosion. It is too early to say what impact this will have on the uptake of hydrogen solutions.

Figure 10 provides an overview of the historical trajectory of hydrogen in Norway.

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[7] https://www.aftenbladet.no/meninger/i/5yMyz/Hydrogen-den-neste-oljen

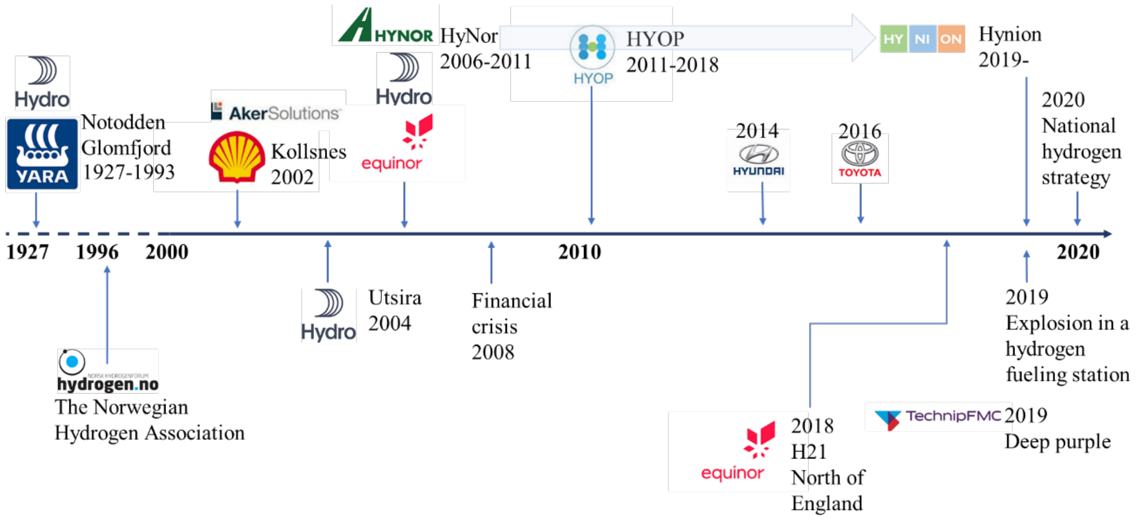

Figure 10: Timeline, emergence of hydrogen as energy carrier in Norway.

4.2 Initiatives to establish largescale hydrogen production

Yara and Equinor currently produce around 180,000 tons of hydrogen annually and the total annual production in Norway is 225 000 tons, mainly for industrial use (DNV GL, 2019). Two companies, Nippon Gases (formerly Praxair) and Ineos, produce and distribute green hydrogen for transport. In addition, there are several projects, plans and studies aiming to establish large scale production of hydrogen for use as energy carrier. The six initiatives we focus on in this study are at different stages of maturity. They are also varying in terms of energy source, technology, resources, planned capacity and potential end users.

Since the study commenced other initiatives have also been launched. Møre and Romsdal county has commissioned a feasibility study regarding hydrogen production at Smøla which is followed up by Norsk Vindenergi Senter and suggests the potential for a production of 1 ton per day in connection with the existing windfarm on the island (Endrava, 2019). Further down the coast, at Kollsnes outside Bergen, ZEG Power and Coast Center Base have launched plans for a gas reforming plant including CCS, where the first module will be ready by 2021 and a full-scale 20 MW plant shall be in place by 2023.[8]

4.2.1 VarangerKraft Hydrogen

Raggovidda wind farm is located in the Varanger peninsula, the extreme North of Norway. It entered into operation in 2014 and has a concession for 200 MW. However, only 45 MW of the installed load capacity has been realized due to limited grid capacities in the region. The owner, Varanger Kraft, therefore sought new opportunities. A particular individual at Varanger Kraft was named in the interviews, as a driving force and originator of the idea. In close dialogue with the municipality of Båtsfjord the company developed a pre-study with SINTEF, which has been followed by a large research and innovation project funded by the EU called HAEOLUS (Hydrogen-Aeolic Energy with Optimised eLectrolysers Upstream of Substation). The aims to develop a new-generation electrolyser plant integrated within a wind farm in a remote area with a weak power

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[8] https://sysla.no/gronn/varsler-storsatsing-pa-hydrogenproduksjon-pa-kollsnes/

grid.[9] HAEOLUS has a budget of 6.9 million euro and includes partners from Spain, France and Italy, including electrolyser manufacturer Hydrogenics.[10]

A subsidiary called VarangerKraft Hydrogen was established in January 2019 and plans to initiate production by the start of 2020, using a prototype 2.5 MW PEM electrolyser. The pilot will be realized in Berlevåg and is actively supported by the municipality which provided a feasible site. According to the manager of VarangerKraft Hydrogen, the capacity of the equipment is 1080 kg per day, hence the expectation is a production of a little more than 390 tons per year.[11]

Figure 11: Left: Raggovidda wind farm (photo: Bjarne Riesto/Varanger KraftVind AS).

Right: Pilot plant site at Berlevåg (photo: Berlevåg Municipality).

Based on the experiences with the pilot, the possibility of for upscaling and setting up green hydrogen production in proximity to other wind farms in the region is also considered. This could open opportunities for export of hydrogen to replace coal-fired power in Svalbard.

4.2.2 TiZir, Tyssedal

TiZir Titanium & Iron ilmenite plant (TTI) is in an industrial area with a long history due to cheap hydropower, year-round shipping, and thereby easy access to world-wide customers. TTI commenced operations in 1986 and uses a process of pre-reduction, metallisation and smelting to upgrade ilmenite into high-quality titanium products and high-purity pig iron. By replacing current use of coke with hydrogen, TiZir can reduce its CO_2 emissions by 90 percent and energy consumption by up to 40 percent. In a full-scale plant, the need for hydrogen will be up to 30 tons per day (50 MW).[12]

Enova provided 122 mill NOK for phase 1 to transform the production process of TTI. As originally planned, this would be the start of a 10-year process with a total investment of 6 billion NOK. When completed, it will result in a reduction of around 121 000 tons CO_2e per year.[13] According to the consultancy Greenstat, which is centrally involved, power grid capacity and the cost of hydrogen are the main barriers currently, but this

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[9] Further info at: https://www.fch.europa.eu/

[10] Further info at: http://www.haeolus.eu/

[11] https://enerwe.no/nar-strommen-kommer-fra-vind-er-det-sa-gront-som-du-kan-fa-det/168622

[12] https://greenstat.no/hydrogen/erstatte-kull-med-hydrogen-for-tizir/

[13] http://www.hardanger.com/Dokument/Hardangerr%C3%A5det/Innkalling%20og%20m%C3%B8teb%C3%B8ker/Innkalling%20med%20saker%20og%20vedlegg%20HR%2015_12_2016%20i%20Odda.pdf

may change in future. An additional core reference is the carbon price and whether industrial units like TTI will be subject to stricter climate policy measures in future, to enable fulfilment of the 2030 climate policy goals. The electricity required for a full-scale hydrogen facility will be 600 GWh per year and electricity may constitute around 90% of the operation costs.[14] TiZir, together with the energy company Sunnhordland Kraftlag and Greenstat have carried out a study into the possibilities for large-scale production of green hydrogen just outside the factory gate. Greenstat has developed a specific concept, with a plant owned by Greenstat and electricity supplied by Sunnhordland Kraftlag (Fig. 12).

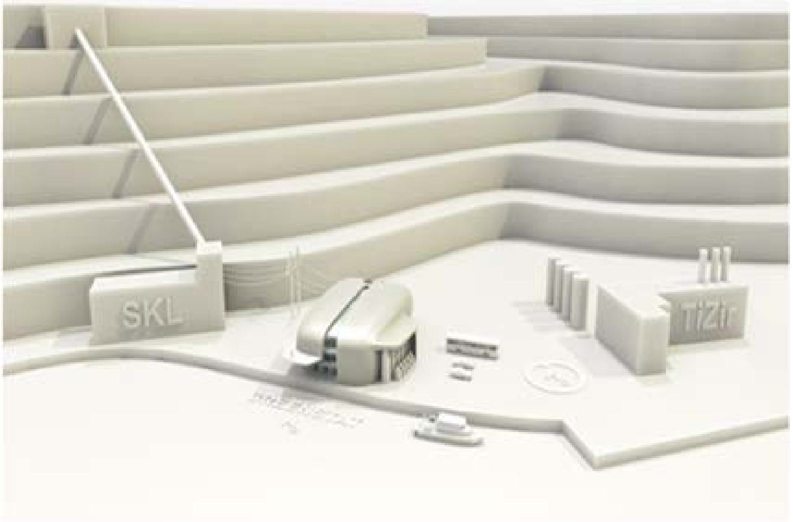

Figure 12: **Greenstat concept, value chain including power from Sunnhordland Kraftlag to Greenstat production plant, TiZir and customers in maritime and land-based transport. (illustration: Greenstat).**

Another potential supplier is Statkraft, which owns the nearest power plant and has long-established relations with the industry. They have carried out a separate feasibility study for Tyssedal, as well as one for Mo industrial park, where they looked at a 20 MW electrolyser plant. If green hydrogen is not available, TiZir may consider using blue hydrogen, but their stated preference is for green alternatives.[15] The pioneering effort is associated with considerable risk and TiZir representatives emphasize that public support is necessary to motivate the shift from a fully functioning process plant to a completely new process based on hydrogen. TiZir originally planned to build a demonstration plant in the period 2017-19 (Scale 1/100) and full-scale pilot plants from approx. 2020, but this has been postponed. A full-scale pilot is within the company's current 5-year plan and expected to cost between 100 and 200 million NOK.[16]

The next step would be a total reconstruction of the plant, to reduce CO_2 emissions with 300 000 CO_2e annually. This involves an investment up to 7 billion NOK. With these dimensions, a relatively small increase in production can be enough to fuel the demand of the local transport sector. Therefore, Tyssedal and the neighboring municipalities are in dialogue about turning a regional highway (E134) into a new "hydrogen highway" across the mountain separating the southeastern and southwestern parts of Norway.

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[14] https://sysla.no/gronn/i-denne-fabrikken-vil-de-erstatte-kull-med-hydrogen/ (2017)

[15] Personal communication at workshop "Unleashing the H2 Market"

[16] https://sysla.no/gronn/klimaversting-skal-bli-klassens-beste/

4.2.3 Norsk H_2, Suldal

Norsk H_2 at Jelsa in Suldal, Rogaland county was considered as a promising initiative at the time this study commenced. However, in July 2019, the company went into bankruptcy. There are rumors that the initiative will be continued under different ownership,[17] but at the time of writing we have no firm knowledge about this. Norsk H_2 was established in 2017, following the encounter between a local entrepreneur and a group of German tourists with an interest in green hydrogen production. Suldal has 46 hydropower plants, including the Kvilldal plant, which has an annual production of 3611 GWh. Thus, Suldal is the municipality with most hydropower plants in Norway. Since Suldal is a small municipality it was easy to bring in the mayor for informal discussions and also involve Innovation Norway. The locals insisted that Norsk H_2 would have to be a Norwegian company, and the local entrepreneur started building it from scratch, based on his individual experience from establishing and managing industry companies in Norway. However, the investors came from different parts of the EU, and Norsk H2 was established as the subsidiary of a German company called Hy2gen AG, which was set up simultaneously.

The projected plant at Jelsa would have the same capacity as the world's largest facility for hydrogen production based on electrolysis, which is being established for Shell under the REFHYNE project and will operate in Köln from 2020.[18] A 6000 m^2 industrial facility previously used for production of plastic barrels (Figure 13) would be repurposed for production. PEM electrolysers from ITM Power would be applied, with a planned capacity for the first phase at 10 MW. The original target was to start initial production in 2019 and increase gradually to over 100 tons per month by the end of 2020. From there, the plan was to increase to as much as 1,500 tons per month. Norsk H_2 claimed to already have a customer base ensuring relevant capacity utilization. The aim was to deliver both nationally and internationally, targeting both transportation and industry. The facility has its own deep-water berth. Thus, the location is ideal for sea transport and possible export of green hydrogen, and strategic in relation to the world's first hydrogen ferry, which will serve the nearby Hjelmeland-Nesvik-Skipavik route from 2021.

Figure 13: Ferry port across the municipal border, where hydrogen ferry will land from 2021 (photo: Andreas Askildsen/Stavanger Aftenblad).

According to a public interview by Norsk H_2 in 2018, the first stage would be associated with a 200 mill NOK investment.[19] The core investors have relevant competence from Mercedes, Fina and HyEnTEC, and close ties with the University of München. For its commitment to CO_2-free production and sale of green hydrogen, Hy2Gen AG and Norsk H_2 AS received the 2018 f-cell award from NOW GmbH (National Organisation

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[17] https://sysla.no/gronn/hydrogenselskap-konkurs-med-6-millioner-gjeld/

[18] https://www.tu.no/artikler/en-av-verdens-storste-fabrikker-for-gronn-hydrogen-etableres-i-norge/430122?key=NzLqzjbx

[19] https://www.aftenbladet.no/aenergi/i/gPAr0q/Ny-hydrogenfabrikk-kan-skape-et-industrieventyr-i-Suldal

Hydrogen and Fuel Cell Technology) in Germany. Norsk H_2 was a member of the Norwegian Hydrogen Association and tried to establish collaboration with University of Stavanger.

4.2.4 Kvinnherad

In Kvinnherad, the municipality, the local power producer (Sunnhordaland Kraftlag) and the gas producer Gasnor signed a collaboration agreement January 2019 (Fgigure 14). The goal of the collaboration is to achieve large-scale production of liquid hydrogen from power-to-gas.

Figure 14: Kvinnherad municipality (photo: Lislerud).

The background for the agreement is a report on possible sites for green hydrogen production in Kvinnherad, launched by Greensight in January 2019 (Hirth et al., 2019), and the contract signing for the Hjelmeland-Skipavik ferry in 2019, which is for a ship running on liquid, rather than gaseous hydrogen. According to Greensight, which is a subsidiary of Greenstat, it is possible within a few years to achieve a production of hydrogen with an installed capacity of 30-60 MW and a production of liquid10-20 tons per day. With this capacity Greensight calculated that the hydrogen price will be competing with fossil fuels for land transport. With a 20% higher operating cost for the speed ferry, requirements in the public procurement system is prerequisite to come up to this volume. The production facility will be scalable and located by the hydro power plant.

The high-speed passenger vessel between Bergen and Rosendal is another major potential consumer of hydrogen, with a new tender for the connection at the earliest in 2023. According to Greensight, a hydrogen fuel cell vessel for this route would have an average weekly demand of 512 kg hydrogen (600 kg per weekday). Furthermore, the large power resources and access to deep-sea vessels make it possible to scale up the production for exports. Gasnor, which is owned by Shell, will have the role as a distributor. A pilot project is currently running as a follow-up of the report. The pilot project will look for solutions in terms of framework conditions, financing and ownership and customers. To increase the volume of demand, a fleet project with Notodden, Odda and Ullensvang municipalities is being developed. The plan is to order up to 20 hydrogen electric vehicles in all three municipalities to provide courier and home care services by 2020.

4.2.5 Tjeldbergodden

At Tjeldbergodden, in Møre og Romsdal county, Reinertsen New Energy has done test production of hydrogen from synthesis gas since 2017 to assess a new palladium membrane technology that can remove CO_2 from the gas effectively and at the same time produce high-purity hydrogen (fig. 13).

Figure 15: Tjeldbergodden methanol plant (photo: Øyvind Hagen/Equinor)

The capacity of the test facility is 5-10 kg of hydrogen per hour. The cost of approximately 100 mill NOK is covered via support from the Norwegian state enterprise and main funding programme for CCS, Gassnova/CLIMIT (70 mill NOK) and Reinertsen itself (30 mill NOK). The testing is carried out in liaison with Equinor and Conoco Phillips who are running Europe's largest methanol plant at Tjeldbergodden. The plant has a yearly production of over 900 000 tons of methanol. As noted by DNV GL (2019), the plant produces around 112 500 tons of hydrogen per year, as input to the methanol production.

Currently, around 15 tons of the produced hydrogen is recirculated and used for firing the plant (together with natural gas). This hydrogen may well be taken out of the process and, especially with Reinertsen's new technology, be of a purity suited for other applications, such as maritime transport. Tjeldbergodden is on the shipping lane between Trondheim and Kristiansund. This is a good location due to the growing ocean-based industry in the mid-region of Norway, especially within aquaculture and the petroleum activity in the Norwegian Sea. Hydrogen production at Tjeldbergodden has the advantage that it may be upscaled stepwise, as the demand for hydrogen develops.

The methanol plant receives natural gas from the Heidrun field through the Halten pipe, which currently has 2/3 free transport capacity. This is presented as an opportunity for further research and development towards CO_2-free hydrogen production from natural gas. Equinor is currently considering a technology study on how excess oxygen and 10% of the natural gas stream for the methanol production may be used for production of hydrogen with auto-thermic reforming and CO_2 capture.[20]

Reinertsen New Energy AS and the daughter company Hydrogen Mem-Tech AS emerged out of one of Norway's leading engineering companies which closed down in 2017. Reinertsen New Energy's core ambition is to contribute to reduced climate gas emissions from the production and use of oil and gas. Hydrogen Mem-

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[20] https://www.regjeringen.no/contentassets/0762c0682ad04e6abd66a9555e7468df/tjeldbergodden-utvikling-as---innspill--til-strategi.pdf

Tech was established in 2016 to continue the development of palladium membranes for hydrogen separation from a project in Reinertsen AS. The project was based on a close collaboration with SINTEF, which continues today. Hydrogen Mem-tech is the entity operating the pilot plant at Tjeldbergodden. The budget for the pilot plant estimates an annual turnover of 1,5 billion NOK and an annual profit before taxation of approximately 0,5 billion NOK.[21]

Equinor is interested in hydrogen as a means of developing its core business model more sustainably. The focus is on hydrogen from natural gas, and hydrogen production in itself is not necessarily an aim. Equinor does not have specific goals for hydrogen. Hydrogen solutions do, however, fall in under other goals in the corporation's Climate Roadmap, which also states that 15-20% of Equinor's investments in the coming years shall be in renewable energy (Equinor, 2018). The market for hydrogen, in their perspective, is in principle, international and as vast as the current market for natural gas. To ensure a long-term future for its natural gas, Equinor is engaged in several projects with large energy actors in the EU, such as Northern Gas Networks in the UK, Gasunie in the Netherlands, and Open Grid Europe, with German partners. The focus of these initiatives is on the possibilities for converting coal or gas-fired powerplants into blue hydrogen production, with Equinor's role being mainly in gas reforming and CCS.

Equinor's renewed engagement is generating increasing interest in hydrogen as a solution for transitioning the petroleum-based economy and not merely as an alternative fuel. The plans and opportunities associated with the pilot at Tjeldbergodden receive wide attention and support, both at local, regional, and national level.

4.2.6 Glomfjord

In recent years, there has been a push to re-establish large scale hydrogen production in Glomfjord. The small town has an industrial park which is the largest in the region (Figure 16). Yara is the largest unit, with around 180 employees, but there are also another 8 companies in the park that might benefit from new energy solutions.

REC (Renewable Energy Corporation) was also present with a plant of 200 employees until 2012 when the company had to shut down. Following the demise of REC, Meløy municipality began searching for new industries that could benefit from the abundant supply of renewable energy. In 2016, Meløy Energi AS, Meløy Næringsutvikling AS, NEL ASA, and Greenstat AS established a joint venture called Glomfjord Hydrogen AS. The aim of Glomfjord Hydrogen is to use the nearby hydropower, the low grid fees, empty factory buildings from REC, and local hydrogen competence to build a hydrogen plant with electrolysers inside the existing industry park (Figure 16). This was Greenstat's first activity towards actual production of hydrogen, and Greenstat has been the primary force behind the initiative.

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[21] https://www.nettavisen.no/na24/tror-pa-gull-i-hydrogen/3423274188.html

Figure 16: Glomfjord industrial park and location of initial hydrogen plant (source: Edmund Ulsnæs, Ny Næring AS).

The production plans involve instalment of NEL's largest electrolyser (model A485) with production capacity of 300-385 Nm3/hr (~2 MW). The set-up is scalable so that more electrolysers can be added when needed. The scheduled plant will produce up to 6 tons of hydrogen per day, or 2190 tons per year.[22] The location near the Svartisen glacier provides the necessary hydropower. The local power plant has a combined capacity of 700 MW. The local electricity grid is owned by Yara and the grid fee is 6 øre/kWh. At the time of the interview in October 2018, there were talks about a computer company, KryptoVault, establishing a crypto currency mining factory inside the industrial park. It was hoped that such a development would bring the grid fee down to about 2 øre/kWh. The Norwegian government has since retracted on its policy of subsidizing data centres with low grid fees.

Despite a number of potential users, including fleet vehicles, the Nordlandsbanen railway, local ferry, buses, heavy duty vehicles and industry (Glomfjord as well as Mo industrial park) that are identified, lack of customers has been the main obstacle up to now. However, the planned relocation of Bodø airport opens up a new area for city development, branded as a zero-emission neighbourhood. According to a presentation by Meløy Utvikling in April 2019, Bodø Municipality is now working to realise a hydrogen refuelling station.[23] Glomfjord Hydrogen has entered an agreement that if Bodø builds a refuelling station, then Glomfjord Hydrogen will provide the hydrogen.

4.3 Comparative assessment

This section discusses the studied initiatives in terms of five dimensions which are considered important in governance for innovation uptake (Bressers, 2009): Geographical scales and involvement with different administrative levels;actors and networks; resources and responsibilities; motivation, goals and ambitions; and use of available support mechanisms.

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[22] NEL ASA: Announces reestablishment of large-scale hydrogen production in Glomfjord, Press release (2016) http://mb.cision.com/Public/115/9959737/b39176b16b4112f1.pdf

[23] https://www.google.no/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&ved=2ahUKEwi_zZvhs4LkAhVqyaYKHVJKDegQFjADegQIBBAC&url=https%3A%2F%2Fwww.meloynf.no%2F%3Fdfi%3DForedragFinnNordmo-Melyseminaret2019.pdf&usg=AOvVaw3pZFuqBpjRA18Y0M4vwrwd

Levels and scales

The spatial distribution of initiatives reflects the distribution of natural resources and wider economic geography of Norway. When it comes to geographical focus area, the initiative at Raggovidda was associated with a vision of export since its early beginning, see Table 4 below. However, the noted prospects for shipping to Svalbard and the potential for deployment in transport and industry has also been emphasized. It is still uncertain how the recent decision to build a 420kV power line to Varangerbotn will play out, but as noted by Statnett, it opens up for more wind power and industrial activity in the region, including largescale production of hydrogen and ammonia.[24]

Norsk H_2 was also looking towards an international market, first and foremost on the European continent, as well as national and regional users. The initiative centered on Tjeldbergodden is likewise associated with wide-ranging ambitions. Hydrogen Mem-Tech's current clients are national, but the prospect of largescale export is repeatedly invoked by both Reinertsen and Equinor, who are investing substantially in research and development on transport options and future markets in Europe. The focus in Kvinnherad is more national, with a focus on maritime transport. However, the possibilities for upscaling and export are also alluded to in Greensight's report (Hirth et al., 2019). The initiative in Glomfjord has primarily focused on potential customers in northern Norway. Greenstat's in Tyssedal is also more regional, in that TiZir and transport in Southwestern Norway is in focus. A similar perspective seems to be behind Statkraft's studies. However, they are also considering hydrogen production at other locations and generally have a global outlook.

The initiatives also vary in terms of involvement with different levels of the public administration. In Glomfjord, the municipality is a part-owner and driving force. There has also been an active dialogue with Nordland county and major towns in the region, but limited involvement from the national level. In Kvinnherad, too, the municipality is central. This initiative may also be related to the increasing focus on hydrogen in the collaboration between counties in Western Norway (Vestlandsrådet).[25] Norsk H_2 at Jelsa was mainly a private initiative. As noted, there was dialogue with the municipality and county council, but to our knowledge limited engagement from the national level. The initiative in Tyssedal has received more attention from the national authorities, as a pilot project for industry deployment. Statkraft is in a different position, as an incumbent with established relations to the industry and national authorities. They have been less active in the media and do not disclose much information about their dialogue with customers and public stakeholders.

At Raggovidda, the establishment of the windfarm involved national decision-makers, whereas the municipality has been an important facilitator when it comes to hydrogen.[26] With the investigation of the potential for shipping to Svalbard, national stakeholders such as Statkraft, Statnett and NVE, as well as the Ministry for petroleum and energy, have become more engaged. The plans and prospects surrounding Tjeldbergodden, likewise, are a focus of national interest. The Norwegian State owns altogether 70.5% of Equinor. Substantial amounts of national funding have been allocated to the research and development projects, and the dialogue cuts across all levels.

Actors, networks

The respective scopes discussed above indicate that the actors and networks involved in the hydrogen production initiatives vary significantly. In this section, we take a closer look at the different partnerships. Table 4 provides an overview of main actors and stakeholders. It is not exhaustive – Norway is a small country

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[24] https://www.tu.no/artikler/statnett-bygger-likevel-420-kv-linje-til-varangerbotn/461635?utm_source=newsletter-tudaily&utm_medium=email&utm_campaign=newsletter-2019-03-29
[25] http://www.vestlandsraadet.no/
[26] http://naturpress.no/2018/11/19/berlevag-kommune-haper-pa-vindbasert-hydrogeneventyr/

and most actors in the hydrogen business know each other to some extent. The idea here is to provide an overview of the kind of actors and relations that are involved in each case.

Table 4: Overview of main actors and networks behind the studied initiatives.

Initiative	Main actor/operator/lead partner	Main collaborators	Broader network
Raggovidda	VarangerKraftHydrogen	VarangerKraft, Berlevåg Municipality, Båtsfjord Municipality, SINTEF, Hydrogenics	European: EU Project partners, Kawasaki Industries
Tyssedal	Greenstat	Potential user: TiZir (owned by global Eramet). Power supply: Sunnhordaland Kraftlag NEL	Largely national: County admin., national actors.
	Statkraft	Potential user: TiZir	Global: Hydrogen Council, etc.
Jelsa	Norsk H_2	HY2GEN, ITM Power	European: University of München
Kvinnherad	Kvinnherad Municipality	Gasnor, Sunnhordland Kraftlag, Kvinnherad Energi, BKK, Greensight	Regional: County admin., Greenstat
Tjeldbergodden	Hydrogen Mem-tech	Reinertsen New Energy, Equinor, SINTEF, Conoco Phillips. Tjeldbergodden Utvikling (TBU).	Global: FMC Technip, Gassco, Shell, Total, Hydrogen Council.
Glomfjord	Glomfjord Hydrogen	NEL, Meløy Municipality, Meløy Energi, Meløy Enterprise Development, Greenstat	Regional, with potential international links: Yara

Two of the initiatives (Glomfjord and Kvinnherad) have for a large part been driven by municipalities. Municipalities and county administrations have also played a role as facilitators in the other cases. Two of the initiatives emerge from energy companies (Raggovidda and the second initiative associated with Tyssedal), and two are owned by private business interests (Tjeldbergodden and Jelsa). Greenstat is involved in as many as three of the cases (Glomfjord, Kvinnherad and Tyssedal), while SINTEF, not as a business actor but as research partner, is involved at Raggovidda as well as Tjeldbergodden. For two of the cases we also find that specific individuals have been crucial. Furthermore, three of the initiatives are linked to international networks; in research and development at Raggovidda, foreign investors at Jelsa, and a broad international industry network at Tjeldbergodden where not all are involved in the specific pilot but engaged in related projects to do with largescale production and possible export of blue hydrogen.

Resources and responsibilities

The actors associated with Tjeldbergodden have the financial muscles to drive huge, ambitious projects. Equinor alone states in their climate strategy that new energy solutions will potentially represent around 15-20% of capital expenditure by 2030. By 2020 the corporation will spend up to 25% of its research funds on new energy solutions. They will also invest USD 200 million through their new energy ventures fund, and partner in the USD 1 billion OGCI Climate Investments (Equinor, 2018). The current focus is on offshore wind, but other solutions are also important. Furthermore, they possess a unique competence base and position in Norwegian industry. The social capital of Equinor is seen to impact on the level of interest among decision-makers, the media, and the public. The unique position also places high expectations and a special responsibility on Equinor. The climate strategy for Equinor includes specific targets, reduce the carbon intensity of their upstream oil and gas portfolio to 8 kg CO_2/boe and achieve annual CO_2 emission reductions of 3 million tons by 2030, as compared to 2017.

Statkraft, one of Europe's largest energy companies, also has the financial capital required to invest in large-scale production. Although the department handling new business opportunities and hydrogen is small, the overall capacity is high. Statkraft's standing in Norwegian society is also very high and as electricity provider the company has long-established relations with many potential industry users. At Raggovidda, funding has been attracted through the EU and high-competence actors are involved. At Jelsa, capital would be raised through a network of European investors as well as targeted efforts in Norway, but this did apparently not succeed. The relations to potential users and core competence in Norway did also seem less developed. There were some sceptic commentaries in the media regarding the strong involvement of German actors and the decision to use foreign rather than Norwegian electrolysers. Greenstat is a spin-off from the cluster of knowledge institutions in Bergen which also includes CMR Prototech. So far, Greenstat is mainly a consultancy. The initiatives are based on feasibility studies with interested local parties and are more dependent on public funding. In all the three cases where Greenstat is involved, NEL is also on board as a supplier of equipment.

Motivation, goals, ambitions

As noted above, the goals and ambitions behind the initiatives vary. For Equinor, the main motivation is to green its core business and ensure that Norwegian gas will remain valuable in a decarbonised 2050 perspective. For Reinertsen New Energy, the core business is technological innovation for reforming natural gas. Statkraft wants to strengthen its position as an international provider of renewable energy. It is currently expanding in six strategic directions, including European flexible generation and new business development in Norway. The interest is in plant sizes from 0.5 to 100 tons (1-200 MW) per day and their main target areas are metallurgical industry, biofuels, e-fuels, and green chemicals, as well as maritime and heavy-duty transport.

In the case of Raggovidda, Varanger Kraft's initial motivation is to utilize the full capacity of the windfarm. There is also a concern, especially for the municipality, to contribute to enterprise development in northern Norway. For SINTEF, research and development is the aim, while Hydrogenics wants to promote and further develop their solutions. In Glomfjord, the main motivation is local enterprise development. The motivation in Kvinnherad is to utilize regional power surplus, support maritime industry, and generate local business. For the local partners, the initiative in Jelsa was also about using excess hydropower to generate local business, and for the owners green business development seems to have been the main motivation.

There are marked differences between the initiatives in terms of perspective, motivation, and resources. At the same time, some actors, most notably NEL and Greenstat, but also SINTEF, are involved in several cases. While public stakeholders are important in most cases, the industry drive is strong at Tjeldbergodden and was at Jelsa. When discussing future supply, most of the other stakeholders interviewed saw Tjeldbergodden and Raggovidda as the most important initiatives. Given their different motivations and resources, the impact of political measures and instruments will vary across cases, and their chances of success and wider impact in sustainable energy transition will be different in different energy scenarios.

Use of public support mechanisms

As noted above, the piloting of the HAEOLUS concept is enabled through EU project funding, as well as cash and in-kind contributions from industry partners, and VarangerKraft Hydrogen was established in this context.

Greenstat's initiative in Tyssedal is linked to TiZir's project to transform its production process. TiZir already received grant support from the Norwegian state, through Enova, of more than 12 million euro for phase 1 of this project, and states that a full-scale conversion will require further grant support. Reinertsen New Energy received grant support of 70 million NOK, or around 7 million euro, also from state funding programs.

In Glomfjord, the municipality was defined as a transition zone (*omstillingskommune*) following the shutdown of REC Solar, and a total of 100 million NOK was dedicated to joint efforts to facilitate industrial transition; 50 million from the state, 25 million from the county and 25 million from the municipality itself. The local development company and hydrogen initiative have grown out of this. As regards hydrogen, support under an EU program for hydrogen buses was targeted, but the deadline came too soon. It is anticipated that support for an initial hydrogen refuelling station will be available, when committed users are in place. To our knowledge, Norsk H2 received only limited public support, by way of local support from Innovation Norway. The recent initiative in Kvinnherad emerged following a feasibility study financed by the county of Hordaland and is motivated by green public procurement enabling introduction of local ferries that will need supply of liquid hydrogen. Thus, public support programs have played a crucial role. As we shall see below, most of the consulted stakeholders emphasized that this, as well as active use of other instruments, is necessary to realize the full potential for largescale production of hydrogen in Norway.

5 Opportunities and barriers

In this chapter we take a look at the opportunities and barriers to large-scale hydrogen production and deployment in the different parts of the value chain. The discussion cites some of the major assessments, overviews, and facts that the actors themselves often refer to, and relates this to stakeholder perspectives expressed in the interviews and attended workshops.

5.1 Production

The studied production initiatives address many of the same deployment opportunities and face common challenges. In addition, there are barriers and opportunities that are more specific to the respective production methods.

Blue hydrogen – big business and CCS uncertainties

We have linked the ongoing efforts to promote blue hydrogen to the pilot at Tjeldbergodden, but once a business case develops, large-scale production of blue hydrogen could take place in several locations with established gas and CCS infrastructure, such as the ports in Bergen and Ålesund, or the gas terminals in Kårstø or Melkøya. The potential for production of blue hydrogen was emphasized by several of the consulted stakeholders, as well as at the attended workshops. The main arguments for hydrogen produced from natural gas relate to costs and volume, in that current methods for grey hydrogen production (without CCS) are profitable and well suited for larger scales. DNV GL (2019) finds that in a 10-year perspective, natural gas reforming with CCS will be cheaper than large-scale electrolysis. However, they also note that large-scale blue hydrogen production will be limited to certain locations.

As we have seen, the renewed interest in blue hydrogen in Norway is closely linked to the need to decarbonize the oil and gas industry and maintain a market for natural gas. The need for large volumes of alternative fuels to cut emissions from maritime transport and process industry are emphasized. There is also a close dialogue and collaboration with maritime industry. For example, Equinor collaborates with Moss Maritime, Wilhelmsen shipping and DNV GL on ship design for onboard transport of hydrogen, with a view to decarbonization of long-distance shipping.[27] At the local and regional level, the prospect of a demand from hydrogen ferries and passenger vessels realized through innovative green public procurement is an important driver.

In 2017, Norway exported 117.4 bcm (1250 TWh) of natural gas (Gassco, 2018). Transforming this volume into blue hydrogen, with an assumed efficiency of 75%, would give around 22.5 million tons of hydrogen (THEMA 2019). This would be more than enough to serve the current European industrial and refining market demand (Shell, 2017). In 2018, the export of gas was about 120 billion Sm^3.[28] Increased deployment of hydrogen as an energy carrier may increase the demand further. According to DNV GL (2018b), the market for hydrogen in the transport sector will primarily be for green hydrogen. However, the market in heating may be dominated by blue hydrogen. This is due to blue hydrogen's lower production costs, that parts of the existing gas infrastructure may be used for hydrogen, and that the level of electricity production required to produce the needed volumes by electrolysis would require substantial investments in grid capacity. As an indication of future demand, the concept for the H21 North of England project on hydrogen for heating in Great Britain will require more than 2 million tons of hydrogen per year (H21 NoE, 2018).

These figures are often used to highlight the considerable potential for value creation associated with production and export of blue hydrogen (SINTEF, 2018). However, continued export of natural gas is possibly a more likely outcome, given the high transportation costs and available infrastructure for export of natural gas. On-site production in the recipient countries may also increase the market acceptance of blue hydrogen in those countries. In the studies regarding H21 North of England and the Magnum plant in the Netherlands,[29] the respective concepts involve production in the recipient countries. For Equinor, the main aim is to secure a future market for natural gas. On the other hand, Equinor recently sought permission to initiate production of grey hydrogen to stimulate market uptake of hydrogen technologies before CCS comes into place.[30] In the Netherlands, Gasunie envisages around 444 PJ of hydrogen by 2050. The largest share (194 PJ, or around 9% of the national energy mix) would be imported, but 178 PJ would come from dedicated domestic hydrogen production, and 109 PJ from residual electricity (Schutte, 2018). Thüga, likewise, sees a considerable role for decarbonized gas in Germany. However, both note that a business case for blue hydrogen so far is lacking.[31] Other stakeholders are uncertain about the future demand for blue hydrogen in the EU, and a high level of public and political skepticism towards CCS has prevailed until recently, especially in Germany (Dütschke et al., 2016).[32]

The technological interrelatedness with CCS is a major challenge. Norway has more than 20 years of experience with CO_2 storage and large storage capacity under the North Sea. CCS is a national priority due to the associated value creation potential (SINTEF, 2018). Yet, to date, there has been a lack of investment in industrial CCS projects. One of the main obstacles is that it is unprofitable and requires large capital investments. CO_2 leakage rates over time are uncertain. While offshore geological storage is available in Norway this is associated with higher transportation and injection costs than geological storage onshore (Cuellar-Franca and Azapagic, 2015).

Globally, there are several carbon capture, utilization, and storage (CCUS) projects already, including one at the oil field Sleipner. However, a demonstration of the full CCS chain as a climate mitigation tool is only coming up now as a public-private partnership facilitated through Gassnova. Currently, the project is in an advanced study phase. By 2020 Gassnova will submit its recommendation to the government, and according

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[27] https://www.hydrogen.no/hva-skjer/aktuelt/utviklet-verdens-forste-bunkringsskip-for-hydrogen
[28] https://www.norskpetroleum.no/en/production-and-exports/exports-of-oil-and-gas/
[29] https://group.vattenfall.com/press-and-media/news--press-releases/newsroom/2017/vattenfall-aims-for-carbon-free-gas-power
[30] https://www.tu.no/artikler/equinor-vil-lage-hydrogen-fra-gass-ber-om-a-slippe-co2-rensing/460459?key=XLA6PLg6
[31] Presentations by René Schutte (Gasunie) and Eva Hennig (Thüga), EU HyLAW workshop, December 2018.
[32] https://www.cleanenergywire.org/news/merkel-puts-contentious-ccs-technology-back-german-agenda

to plan operations will commence by 2023/2024. While this is promising, the business case for CCS remains uncertain.

With increasing focus on industry and maritime deployment, the case for blue hydrogen in the home market is strengthened. Still, lack of identified customers and a predictable future demand represent a considerable barrier. Main proponents, such as Equinor and Reinertsen New Energy argue for the development of a larger “showcase” combining production, storage and distribution for several uses, including industry, maritime and road transport. Among public stakeholders and potential users, there is a certain skepticism about the overall sustainability of blue hydrogen. However, there is also a widespread understanding that in order to meet the climate goals, blue hydrogen must be included in the energy mix. Still, some of the early users say that given a choice between different suppliers, they will go for hydrogen from renewable sources.

Green hydrogen – flexibility and fragmented efforts

One of the strongest arguments for blue hydrogen is that the potential for large-scale production of green hydrogen, at least in the short term, is limited by the availability of renewable energy sources and costs. A prevailing perspective is that electrolysis has more potential for decentralized production and in the longer term, when technologies grow more mature and costs may be brought down (DNV GL, 2019).

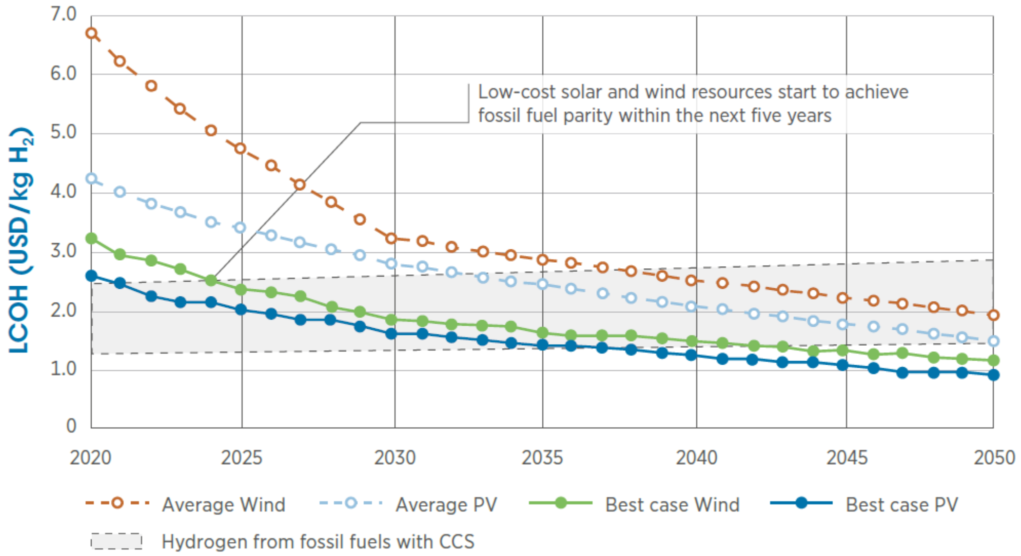
Considering transportation costs, there will be a competition between large-scale and decentralized production of green hydrogen. Apart from demand, this will depend on the price of electricity versus future costs of storage and distribution. Still, as we have seen, there are several large-scale initiatives with rather high ambitions. This may indicate that actors in the business, who are closer to the technology development and more updated on the business opportunities in specific regions and markets, see a larger potential than anticipated in the reviewed literature of model-based system wide analyses. However, it may also be that goals and ambitions are overstated in an early phase to promote business development. As we have seen, the modularity of electrolysis makes it relatively easy to scale production up and down.

While electrolysis up to recently was associated mainly with production for the domestic market (DNV GL, 2019), the studied initiatives also consider export/import opportunities, such as to the European continent and shipping to Svalbard. A main barrier, in the case of green as well as blue hydrogen, is the ‘chicken or the egg’ dilemma, which leaves prospective suppliers uncertain of the demand and potential users uncertain of the supply of hydrogen.

Another challenge noted by several interviewed stakeholders is the costs. To be profitable, green hydrogen production depends on cheap energy. As a consequence of the large share of adjustable hydropower, the Norwegian power system is relatively flexible, leading to more stable prices than in other countries. This was one of the major factors influencing the German owners' decision to establish Norsk H_2. The current power surplus in Norway is also expected to increase towards 2030. According to NVE (2018a), the production will increase by 31 TWh from 2018 to 2030. This represents an opportunity for increased production of green hydrogen. However, the increased capacity may also be targeted for other industries, electrification of transport and possible export to Europe.

In Norway, hydrogen production via electrolysis is exempted from the state electricity grid tariffs, from 2019. The cost of connecting to the grid and the regular electricity grid tariff varies across regions. Connecting the facility directly to a power production plant will eliminate these costs, but this will reduce the flexibility of the hydrogen production and require more storage capacity. The latter option is part of the present concept in Kvinnherad. In several of the cases, these matters are currently being negotiated. While electricity grid tariffs are to be non-discriminatory, this is an area where public-owned energy companies may choose to facilitate or not, depending on the overall energy situation and perceived benefits of green hydrogen production in the given region.

Most of the interviewed actors and workshops emphasized the cost reductions for green hydrogen production from electrolysis that can be expected towards 2030 (cf. NOW, 2018; IEA, 2018; IRENA, 2019). As illustrated by the IRENA graphic below (Fig. 17), this is linked to anticipated decreases in costs of renewable energy production, as well as decreasing costs for electrolysers and increasing CO_2 prices.



Low-cost solar and wind resources start to achieve fossil fuel parity within the next five years

Note: Remaining CO_2 emissions are from fossil fuel hydrogen production with CCS.
Electrolyser costs: 770 USD/kW (2020), 540 USD/kW (2030), 435 USD/kW (2040) and 370 USD/kW (2050).
CO_2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050).

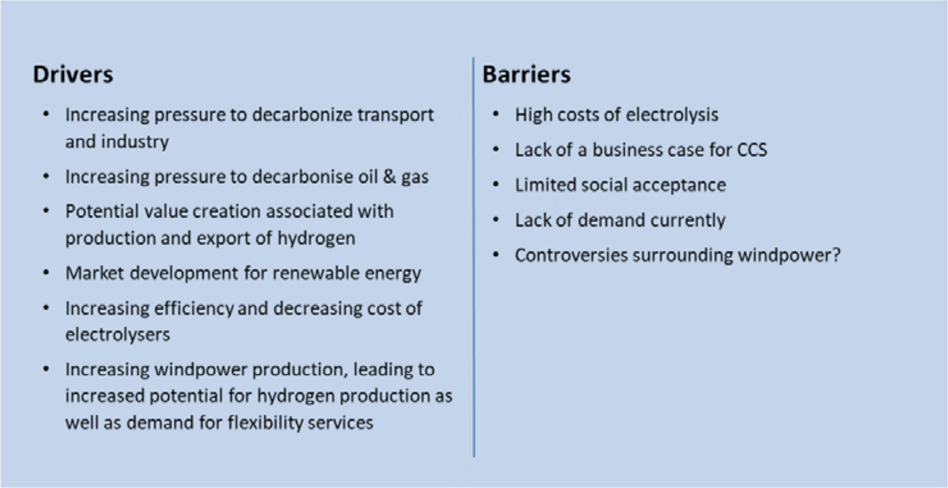
Figure 17: Cost of green hydrogen from different energy sources vs. cost of hydrogen from fossil fuels with CCS (IRENA, 2019: 34). The unit on the y-axis is levelized cost of heating in US dollar per kg of hydrogen.

Many of the consulted stakeholders anticipated that increasing carbon taxes and demand for zero emission alternatives will make largescale green hydrogen production profitable within a few years. The expectation of decreasing costs is supported in recent research. A worldwide overview of Power-to-Gas projects found substantial cost reductions for electrolysis as well as for methanation during the recent years, and a further price decline to less than 500 euro per kilowatt electric power input for both technologies until 2050, if cost projection follows the current trend (Thema et al., 2019). Other international studies expect a 60% reduction of investment costs for electrolysis from 2019 to 2050, based on an efficiency increase between 66 and 77% (Teske, 2019). Recent studies in Norway indicate that it is possible to reach production costs of around 30-50 NOK (3-5 euro) per kg, for example via a hydrogen-wind system in Smøla from 2024 (Endrava, 2019). However, there is still considerable uncertainty, and the price of the produced hydrogen will amongst other depend on plant size and operating hours/downtime.

In the cases of electrolysis linked to hydropower, mature technologies will be deployed. At Raggovidda, where electrolysis linked to wind power is in focus, there are more questions regarding technology development and regulatory issues. While there is considerable potential for the establishment and expansion of existing wind farms for power and hydrogen production, the Norwegian Environment Agency, especially, emphasize the dilemma between increasing the capacity for green energy production and preserving other socio-ecological values. Also, while it is possible to envisage huge wind farms and multiple power-to-gas installations in vast tundra areas, this would raise other questions to do with control over territory, security, etc. Such costs and risks are not taken into account in techno-economic assessments and cost-benefit analysis.

Another concern is the risk of 'lock-in' into large onshore facilities at a time where offshore wind shows promising results. Danish Orsted, the world's largest offshore wind developer, plans to increase its installed capacity from 5.6 GW to 15 GW by 2025. Part of their recent bid for the Holland Coast South 3&4 wind farms is to produce hydrogen for industrial customers. According to Siemens Hydrogen Solutions, current wind power costs can support wind power hydrogen electrolysis if the production level reaches 3500-4000 hours per year.[33] In August 2019, Enova granted Equinor 2.3 billion NOK for a project to construct 11 floating wind power turbines, each of 8 MW, on the Norwegian shelf. Hywind Tampen, as the project is called, will produce 384 GWh annually, to replace around one third of the gas consumed by Norwegian oil and gas installations today and reduce CO_2 emissions by around 200 000 tons CO_2e every year.[34] Local fishermen are resistant, but according to the plan, the turbines shall be operating from 2020.[35] In September, Equinor also got the license to construct the world's largest grounded offshore wind park at Doggerbank, in the North Sea. The total capacity will be 3.6 GW and the park will deliver power at a price of around 0.45 NOK per kWh, according to the current exchange rate.[36]

The main drivers and barriers associated with the production part of the value chain are summarized below (in Figure 18).



Drivers

- Increasing pressure to decarbonize transport and industry
- Increasing pressure to decarbonise oil & gas
- Potential value creation associated with production and export of hydrogen
- Market development for renewable energy
- Increasing efficiency and decreasing cost of electrolysers
- Increasing windpower production, leading to increased potential for hydrogen production as well as demand for flexibility services

Barriers

- High costs of electrolysis
- Lack of a business case for CCS
- Limited social acceptance
- Lack of demand currently
- Controversies surrounding windpower?

Figure 18: Main drivers and barriers associated with hydrogen production.

An increasing pressure to decarbonize the oil and gas sector and the potential for value creation associated with largescale export are main drivers for production of blue hydrogen. Considering the required volumes, blue hydrogen production is also gaining relevance with the increasing focus on hydrogen in maritime transport. The potential for green hydrogen production is influenced by the market for renewable energy and development of costs and efficiency of electrolysis technologies, as well as the increasing pressure to implement green solutions in transport and industry. Here, too, the potential for local value creation is a conducive factor. An expected growth in wind power production will increase the potential for largescale hydrogen production, both for flexibility and for use as an alternative fuel. With increasing economies of scale, the sunk cost of investments in technology for electrolysis will go down.

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[33] http://newenergyupdate.com/wind-energy-update/offshore-wind-hydrogen-could-be-subsidy-free-within-10-years
[34] https://www.skipsrevyen.no/article/equinor-faar-23-milliarder-i-enova-stoette/
[35] https://www.aftenposten.no/norge/i/pL4Kjj/Equinor-far-2_3-milliarder-i-havvind-stotte-fra-statlige-Enova
[36] https://www.tu.no/artikler/equinor-far-muligheten-til-a-bygge-verdens-storste-havvindpark-i-storbritannia/474473

On the other hand, the lack of a convincing business case for CCS is a critical factor. This uncertainty, stemming from the dependence of blue hydrogen on the development of CCS, is the form of lock-in Klitkou et al (2016) termed technological interrelatedness, which also influences the huge capital investments required to establish blue hydrogen production. Available technologies for green hydrogen production are modular and associated with less financial risk, but the establishment of large windfarms is associated with socio-ecological dilemmas. In both cases, high costs and uncertain demand are main barriers.

5.2 Storage and distribution

The storage and distribution of produced hydrogen is associated with technical as well as economic and regulatory barriers. While the hydrogen used in Norwegian industry today mostly is produced on-site, large-scale production and deployment of hydrogen as an energy carrier will require storage and transportation at different scales. This requires conversion of the produced gas into forms with higher density.

Compressed gaseous hydrogen

The common method up until now is compression, which leaves the hydrogen in gas form but reduces storage and transportation costs. Compression to 350 or 700 bars, which is the current standard for the hydrogen used in cars, results in a storage density of more than 40 kg/m^3. However, this also takes away approximately 8% of the original energy content. Lower levels of compression, such as 350 bars, requires less energy but leaves a higher volume and may therefore require more investments in storage capacity. For intermediate storage in high-pressure tanks or gas cylinders, pressures of up to 1,000 bar are technically possible. Only special solid steel or steel composite pressure vessels are suitable for high-pressure storage (Adolf et al., 2017).

Compressed gaseous hydrogen may also be stored in underground natural caverns, which presently are used for storage of compressed natural gas. Blue Move (2017) discusses how this, amongst other alternatives, may be relevant for Denmark, which has two such storage areas. Their capacity is huge, and this may be particularly relevant for long-term storage and balancing purposes. The possibilities for storing gaseous hydrogen in offshore caverns are currently being explored in Norway, under the Deep Purple project, run by Technip FMC, which aims to see turbine-level electrolysis feeding seabed hydrogen tanks where output from offshore wind farms can be stored.[37]

Hydrogen, as a low-flashpoint gas, falls under the legislation for dangerous substances and the regulation on the handling of inflammable, reactive, and pressurized substances, in addition to the equipment and facilities used in the handling of such substances. It is not poisonous, but like LNG, it is associated with high explosion risk and therefore special rules and standards apply, especially if it is stored in volumes of 5 tons or more. This has implications in terms of acceptability as well as costs. Still, Rivard et al. (2019) note that compressed gas is the most well-established hydrogen storage technology, offering a functional solution for mobility applications.

Liquid hydrogen

By reducing the temperature to –253°C hydrogen converts to liquid form, which is more suitable for distribution of large quantities. Liquid hydrogen storage is also a mature technology (Rivard et al., 2019). Liquid hydrogen at 0,1 MPa (1 bar) contains about four times more energy per volume unit than compressed hydrogen at 250 bar and almost three times as much as for 350 bar (Berstad et al., 2009). However, the method to achieve this also consumes 25-35% of the original energy content (IDEALHY, 2013) and the extremely low temperature required is associated with technical challenges. A liquid hydrogen tank is designed to reduce heat

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[37] https://www.rechargenews.com/wind/deep-purple-seabed-hydrogen-storage-for-offshore-wind-plan/2-1-617947

transfer to a minimum. Since the tank is not designed to hold high pressure, hydrogen is allowed to escape to a relief valve, or "boil-off", which means that an unused reservoir eventually will deplete itself (Rivard et al., 2019). This means that liquid hydrogen is most applicable where high energy density is required and boil-off is less of a concern.

Currently, liquid hydrogen is not produced in Norway. The liquefaction capacity in Europe is only 20 tons per day (NCE Maritime Cleantech, 2019). A major reason for this is cost. According to the EU IDEALHY project, an energy efficiency of 6.4 kWh/kg can be achieved. However, the estimated plant size for this to be technically and commercially feasible is 40 - 50 tpd, and the estimated investment cost of such a plant would be 105 million euro at 50 tpd (Essler et al., 2012). It should be noted, however, that Linde Kryotechnik (Cardella et al., 2017) recently presented a roadmap for scale-up to large-scale liquefaction processes suggesting the potential to reduce the liquefaction costs by 67% for a 100 tpd LH_2 plant.

Ammonia

The possibility of using ammonia as a hydrogen carrier is increasingly discussed. Compared to other hydrogen storage materials, ammonia has the advantages of high hydrogen density, a well-developed technology for synthesis and distribution and easy catalytic decomposition (Klerke et al., 2008). According to Rivard et al. (2019), the energy density is only marginally better than for liquid hydrogen, but the vapor pressure is much lower and this simplifies the tank design. On the other hand, the utilization of ammonia, as well as methane, is more difficult than pure hydrogen. Solid oxide fuel cells (SOFC) are the most likely route, but as noted above this technology is only emerging. The drawbacks are mainly the toxicity of liquid ammonia and tracing levels of ammonia in the hydrogen after decomposition (ibid). However, several of the consulted stakeholders, including Statkraft and Bellona, see this as a promising alternative for maritime deployment. DNV GL (2019) projected that 75% of the hydrogen consumption by 2030 will be used for ammonia and ethanol production.

Liquid Hydrogen Organic Carriers (LHOCs)

LOHCs are chemical compounds with high hydrogen absorption capacities, which represent another option for binding hydrogen chemically (Von Wild et al., 2010). The advantage of these technologies is the ability to use existing infrastructure, such as tankers and tanker trucks (He et al., 2015; Rivard et al, 2019). Nierman et al. (2019) found that methanol is the cheapest LOHC option for storage and transportation. For a storage time of 60 days under defined assumptions, this solution showed economic advantages compared to compressed hydrogen. Even though LOHC options are still at early stage, they show potential for long-term storage/long distance transport applications. Among the interviewed stakeholders, only Statkraft mentioned this option as a solution with potential for the future.

Solid storage

Hydrogen may also be stored in the form of metal hydride where it is bound to one or more powdered metals, either in a porous material, or on the surface of carbon cones or carbon pipes. This way large amounts may be stored without significant increase in pressure. However, the high temperatures, high energy, and slow kinetics involved are a problem for reversible storage. There is a lot of ongoing research to overcome these disadvantages, but so far, the efficiency is not optimal (Ley et al., 2014; Rivard et al., 2019).

Distribution

Compressed hydrogen is typically transported in 1000-1500kg high pressure trucks, with a current transportation cost of around 1.3 euro/kg (Ødegård, 2018). For liquid hydrogen, distribution by truck cryogenic tanks is the most mature alternative. Today trailers can transport about 4000 kg of liquid hydrogen (NCE Maritime Cleantech, 2019).

Figure 19: Tube trailer for hydrogen transport. Photo: Hexagon Composites.

For effective distribution of larger volumes, bunkering vessels and/or tankers must be developed for operation along the coastline. Bunkering stations for maritime use are not yet available on the market and throughout the value chain (DNV GL, 2017). Further work on regulations, standards, and codes for the maritime use of liquid hydrogen is needed (Floristean et al., 2019).

Economically, liquid hydrogen is not competitive with other fuels today. While the current retail price for compressed hydrogen currently is 9 euro/kg, NCE Maritime Cleantech's recent assessment suggests a retail price for liquid hydrogen around 15 euro/kg, making the cost of delivered kWh to the propeller more than eight times higher than for marine gas oils. It is, however, estimated that technology development and establishment of large production and liquefaction facilities in Norway could bring the cost down to 3.5-7.5 euro/kg (NCE Maritime Cleantech, 2019). Hydrogen produced from trapped wind power may reach a cost level of less than 4 euro, while hydrogen from natural gas has the lowest expected costs. Converted to euro/kWh, hydrogen with the lowest cost estimate may thus compete with bio diesel and methanol in 2030 (ibid.). The cost estimates are, however, dependent on scale and clearly show the economics of scale in hydrogen production. For larger volumes and distances (1000-4000 km) pipeline distribution is more suitable (CSIRO, 2018). Hydrogen pipeline systems do exist, mostly in the USA, but so far this does not seem relevant for Norway.[38]

In this context, several of the interviewed stakeholders felt that tube trailer transport of compressed gaseous hydrogen is the only realistic option in the short term. In a medium term, liquid tanker transport may come into play, linked with advanced liquefaction techniques. Pipeline transport was mostly considered as an alternative in a long-term perspective.

According to some, current distribution costs are so high that a user spending more than 500 kg/day must have production in near proximity to the point of use. Others stated that the cost of distribution is not a major barrier in Norway, since existing solutions allow a transportation cost of less than 1 euro/kg. It was noted, however, that this is for local transport within Norway or to Sweden – not for longer distances. At the same time some, notably the interviewees from Statkraft and the non-profit environmental organizations Bellona and ZERO,

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[38] The possibility of export of compressed hydrogen through existing gas pipes from Norway to the European continent is another matter, which briefly will be discussed in section 6.6.

stated that ammonia is very interesting. Although there may be room and need for several alternatives, increased development and deployment of ammonia-based solutions may reduce the need for liquefied hydrogen.

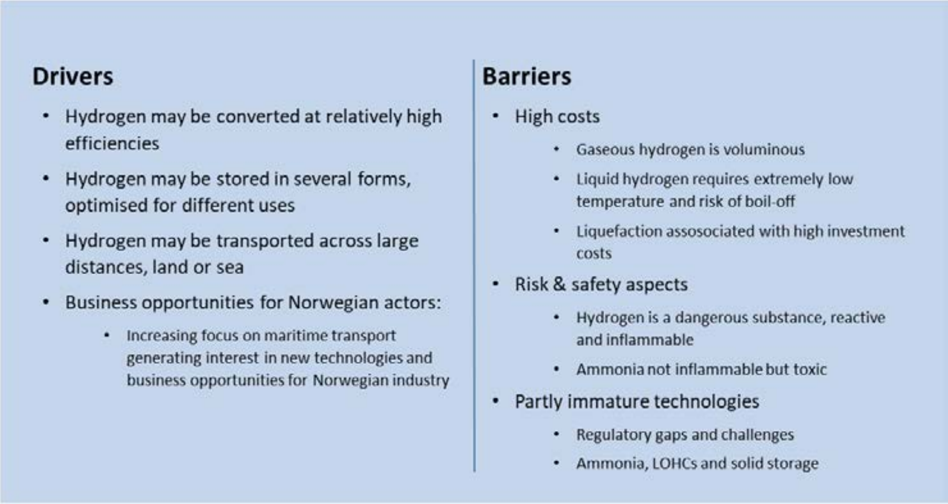
Pros and cons associated with the main alternatives

The perceived advantages and challenges associated with the discussed storage and distribution alternatives are summarized below (Table 5):

Table 5: Pros and cons associated with main storage and distribution alternatives.

Storage/distribution form	Advantages	Challenges
Compressed gas	- Mature technology - Existing standards - Applied in road transport - Available in Norway	- Voluminous - Pressurized, explosive gas - Risk and safety requirements - High operating costs
Liquid hydrogen	- Mature technology - High hydrogen density - Designs for shipping (on-board transport) developed	- Lower energy efficiency - Boil-off - No liquefier in Norway presently - Low temperature – technical challenges and risk - High capital investment & operating costs
Ammonia	- Well-known from industry - High hydrogen density - Low vapor pressure - Simplifies tank design	- Toxic - Utilization – combustion or SOFC, need for more R&D
LHOCs	- Ability to use existing infrastructure - Promising for long-term storage and long-distance transport	- Early stage of development - Costs
Solid storage	- Does not require high pressure - Promising for long-term storage	- High temperature, high energy loss and slow kinetics - Reactive, risk of ignition

The main drivers and barriers associated with this part of the value chain may be summarized as follows (Fig. 20):



Drivers

- Hydrogen may be converted at relatively high efficiencies
- Hydrogen may be stored in several forms, optimised for different uses
- Hydrogen may be transported across large distances, land or sea
- Business opportunities for Norwegian actors:
  - Increasing focus on maritime transport generating interest in new technologies and business opportunities for Norwegian industry

Barriers

- High costs
  - Gaseous hydrogen is voluminous
  - Liquid hydrogen requires extremely low temperature and risk of boil-off
  - Liquefaction assosociated with high investment costs
- Risk & safety aspects
  - Hydrogen is a dangerous substance, reactive and inflammable
  - Ammonia not inflammable but toxic
- Partly immature technologies
  - Regulatory gaps and challenges
  - Ammonia, LOHCs and solid storage

Figure 20: Main drivers and barriers associated with storage and distribution.

5.3 Hydrogen in a more distributed and flexible power system

Both the Energy Transition Commission (2018) and the EU study *Clean Energy for all* (2018) expect hydrogen to play a significant role as a provider of flexibility by 2050 (ETC 2018, European Commission 2018). Energy system flexibility can be provided through sector coupling. As illustrated in Figure 21, sector coupling refers to the idea of interconnecting (integrating) the energy consuming sectors - buildings (heating and cooling), transport, and industry - with the power producing sector. In addition to producing hydrogen that is converted back to electricity, the hydrogen may also be used as fuel for vehicles, gas for heating, etc.

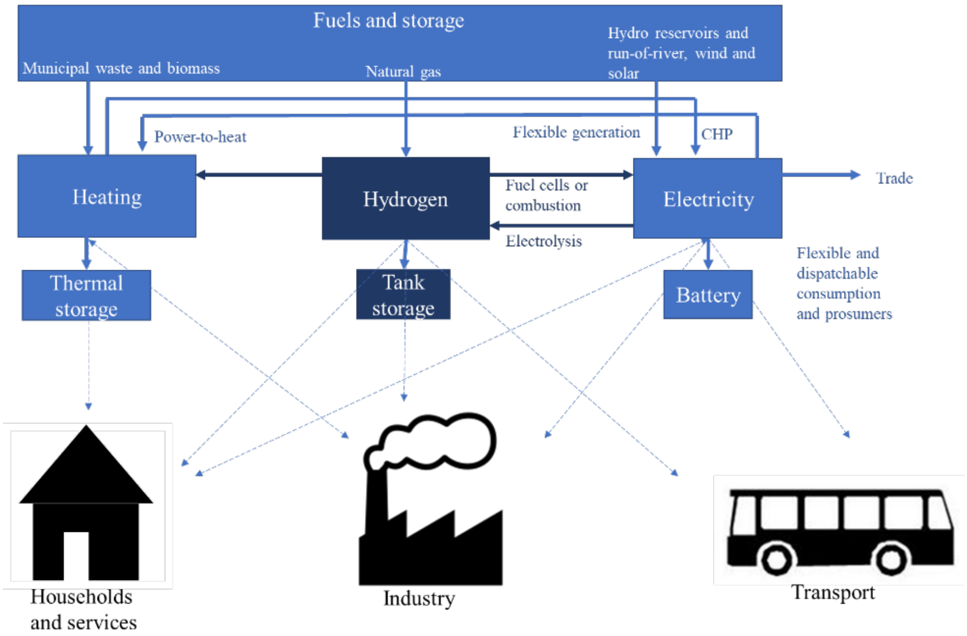


Figure 21: Energy system flexibility and sector coupling.

One crucial aspect of sector coupling is an indirect electrification of energy processes that cannot be electrified directly (e.g. high-temperature industrial processes using hydrogen produced from renewable electricity).

A flexible energy system is balancing the supply and demand for energy, is overcoming uncertainties, while at the same keeping the system's reliability (Ma et al., 2013). Lund et al. (2015) reviewed nearly 400 studies on energy system flexibility. They found that hydrogen can be an important flexibility provider to the electricity systems both on the supply and the demand side. Electrolysis plants have low start-up costs and can thus contribute to balancing the electricity system, for instance by producing hydrogen from wind power when there is a power surplus and ceasing when there is a power shortage and electricity prices are high (Ram et al., 2019). Hydrogen can be stored in large quantities for a long time and later be used as fuel for electricity generation (Buttler and Spliethoff, 2018).

Electrolysers use just a few minutes from a cold start and can serve the short time flexibility need. An immediate interruption of electricity transmission to electrolysers may be one option to satisfy the short-term flexibility need. Stored hydrogen for electricity generation can serve the medium- and long-term flexibility needs, for instance as back-up if the wind or solar radiation fail (Götz et al., 2016).

Figure 22 shows a simplified load distribution for an electricity grid for 24 hours. There is low electricity demand at night and demand is highest in the afternoon and early evenings. Electrolysers can contribute to "valley filling" at night when the electricity demand and the electricity price are low. When the electricity demand is high, the hydrogen companies can switch off the production. This is called peak shaving. By using hydrogen from natural gas reformation in the transport sector or for heating, hydrogen will contribute to conservation. By increasing the number of electrolysers in operation, one can get load growth in the system. If, however, these supplements operate flexibly, the load curve will become smoother. Moving consumption from peak load periods to low load periods is called load shifting and contributes to a smoother and more efficient load curve.

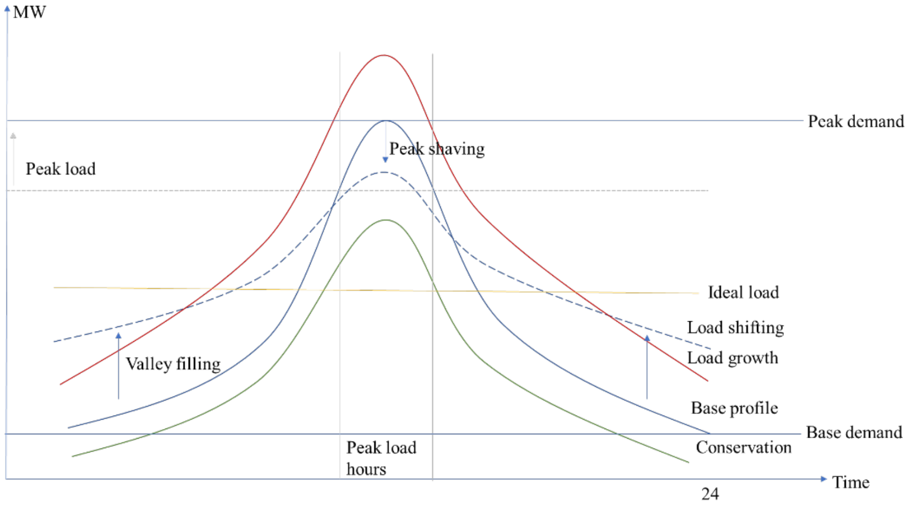


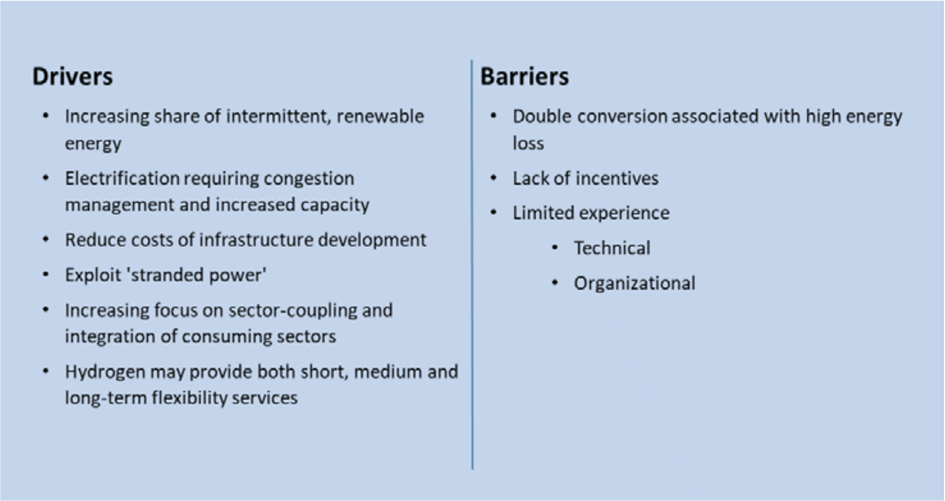
Figure 22: Flexible electricity supply and demand and load curves.

A way to incentivize flexible electricity demand is through peak load pricing. This is quite common for electricity transmission because electricity’s non-storability, which means that it is used at the time of purchase. Because the electricity grid operators are natural monopolists, they can control the price. To steer consumption away from the peak load hours, the consumer price can be set higher for peak hours than base load hours. The electrolysis plant can be offered an interruptible electricity grid tariff, which implies a lowered electricity grid tariff, often in the form of a reduced load demand tariff if the electrolysis plant is willing to be disconnected from the grid when there is a power deficit in the system (Wang et al., 2018).

Both sectors can benefit from flexible operation. With a smoother load curve, the electricity producers sell their electricity, even at night, and the hydrogen producers can enjoy a low electricity price. The network operation costs are also high when the load is high, while close to zero when the load is below a critical peak load. The electrolysers can contribute to a more efficient utilization of the grid capacity by increasing the load when it is low and contribute to reduce peak loads. The deployment of electrolysers and the contribution to a flexible energy system, however, depends on the competitiveness of hydrogen to other fuels. The process of going from electricity through hydrogen and back to electricity has a very low efficiency (down to 30%). (Bailera et al., 2017; Buttler and Spliethoff, 2018).

The need for energy system flexibility will depend on the rate of development of wind and solar power, as well as the degree of electrification in different sectors and regions and subsequent needs to increase electricity grid capacity. Statkraft, in their low emission scenario (2018), expects the demand for flexibility services to increase in all markets. In Northwestern Europe (UK, Germany, Poland, France, Austria, the Czech Republic, Netherlands, Belgium and Switzerland) they suggest the need for flexibility will double by 2040. In the Nordic countries the demand will also increase, though less. While better use of existing infrastructure and hydropower are key solutions, hydrogen is associated with considerable potential. Statkraft notes that hydrogen's capacity for energy storage is much higher than that of batteries, but the double conversion is associated with a 60-70% energy loss. Still, they foresee that the energy system will become more distributed and electricity-hydrogen-electricity may become relevant for smaller plants, especially in isolated places and islands without grid capacity.

Statnett (2018), likewise, sees an increasing need for flexibility resources in their system operation. Currently, the price for flexibility services is too low, experience is limited, and it may be difficult to meet the product requirements. However, there is an ongoing process to align with the EU and develop the market for flexibility services at multiple levels. The main drivers and barriers in this part of the value chain may be summarized as follows



Drivers

- Increasing share of intermittent, renewable energy
- Electrification requiring congestion management and increased capacity
- Reduce costs of infrastructure development
- Exploit 'stranded power'
- Increasing focus on sector-coupling and integration of consuming sectors
- Hydrogen may provide both short, medium and long-term flexibility services

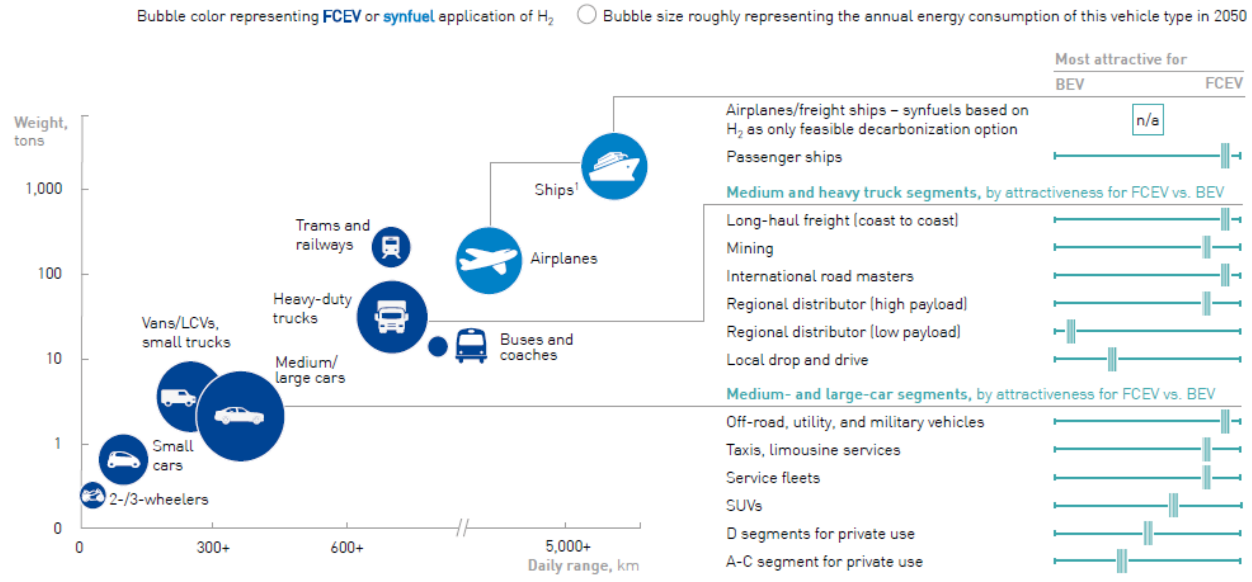
Barriers

- Double conversion associated with high energy loss
- Lack of incentives
- Limited experience
    - Technical
    - Organizational

Figure 23: Main drivers and barriers associated with application of hydrogen for flexilibility services.

5.4 Use in transport

According to the *Hydrogen Roadmap Europe*, the EU alone needs to eliminate about 72% of CO_2, equal to roughly 825 Mt, from the transportation fleet by 2050 (FCH-JU, 2019). On a tank-to-wheel basis, FCEVs and battery-electric vehicles (BEVs) are the only fully CO_2 emission free alternatives. Hydrogen provides sufficient power for long ranges and high payloads due to its superior energy density, and hydrogen infrastructure, while initially a barrier, has significant benefits at scale compared to fast charging. Lastly, hydrogen is considered as a promising option for trains and ships, as are hydrogen-based synthetic fuels for aviation. The overall prospects for hydrogen in transport towards 2050 are positive, as illustrated below (Figure 24):



1 H_2-based fuels or fuel cells

Figure 24: **Comparison of range, payload, and preferred technology towards 2050 (©FCH JU 2019:27).**

The projections for hydrogen deployment in the transport sector do, however, vary significantly. Most forecasts expect battery electric vehicles to take the largest market share of the transport sector. Battery capacity, weight, and price will be important factors for the future share of battery electric vehicles. Battery performance is increasing, but as demand increases, prices of input factors such as depletable resources will increase. Vaalma et al. (2018) point out that even with low-cobalt cathode materials, the demand for Lithium and Cobalt until 2050 will outpace the world's known reserves.

Globally, DNV GL (2018) expects a higher proportion of biofuels than hydrogen in the fuel mix in the transport sector, and thus only a modest hydrogen share in the transport sector in 2050. For heavy vehicles they expect a hydrogen fuel share of less than 5%, and for light vehicles they expect a fuel cell electric vehicle share of 5 to 13% in 2050. They do, however, foresee that the share of hydrogen will increase onwards. Shell Sky (2018) does not include biomass in the transport sector and expects this sector to continuously depend on fossil fuels, with a less than 3% hydrogen share in transport in 2050.

IEA's technology roadmap for Hydrogen and Fuel Cells (2015) predicted a global market share of 25% leading to a 14% reduction in climate gas emissions in the transport sector from 2050 onwards in their high-uptake scenario. In the Mission Possible report, hydrogen is expected to gain a 10% market share (ETC, 2018). Nordic energy technology perspectives (2016) found limited prospects for hydrogen in the transport sector, even in their carbon neutral scenario. According to their study, the decarbonization of heavy-duty transport in the Nordic region would be expected to be covered by biomass resources.

Land transport in Norway

Transport accounts for 31% (16,5 mill tons) of the total CO_2 emissions from Norway (NTP 2018-2029). In line with the national climate targets, the National Transport Plan (NTP) sets ambitious aims: By 2025 all new private cars, city buses, and light duty vehicles shall be emission free. By 2030, 75% of all long-distance buses, and 50% of all trucks shall be emission free. The distribution of goods in cities shall also be nearly emission free (NTP 2018-2029). Norway has one of the best incentive systems for FCEVs in Europe (Floristean et al., 2019) and is making considerable efforts in research and development towards these aims. Still, there are only around 140 FCEVs in the country so far (Statistics Norway 2019). Oslo's public transport operator, Ruter, has five hydrogen buses in operation and has ordered ten new buses to be put into operation by 2020. Food wholesaler ASKO has ordered four rebuilt Scania trucks to be hydrogen powered and these will be put into use during 2019. The unit share supplier of agricultural products and services, Felleskjøpet, has reserved 50 Nikola tre trucks to be in use from 2022. Still. while some operators have ordered hydrogen trucks, the Association for transport and logistics in Norwegian enterprise sees more potential in biofuels.

While previous studies (e.g. Tomasgard et al., 2016) suggest considerable potential, DNV GL (2019) finds that improved battery technology and total cost of ownership will continue to favour BEVs for private cars. By 2030, they expect that 40% and 50% of new buses and trucks, as well as two railway lines, will be operating on hydrogen, leading to the following number of vehicles and fuel demand (Table 6):

Table 6: Summary of DNV (2019) expected number of FCEVs and related fuel demand by 2030.

Segment	Number of vehicles	Fuel demand (ton H_2/year)
Heavy truck	5 000	29 000
Buses	2 220	7 000
Train/railway line	2	1 900

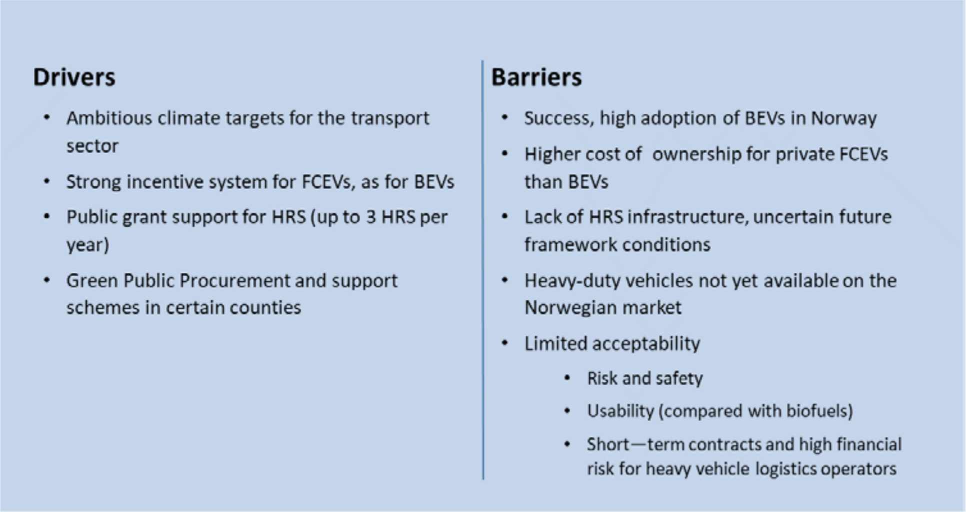
The Norwegian Institute for Transport Economics also finds that hydrogen is competitive for trucks on long distance routes in challenging topography and cold climates, or when there is no time to charge during the day (Jordbakke et al., 2018). While most of the actors still see a market for private cars, the focus in the hydrogen business in Norway has also shifted towards heavier vehicles, including buses, trucks, forklifts and production machinery. The Norwegian Hydrogen Association is working to get 1000 hydrogen trucks on Norwegian roads by 2023.

Land transport is part of the potential market for all the studied production initiatives, but none are focusing only, or mainly, on this. The current lack of hydrogen refuelling infrastructure is a main barrier (Jordbakke et al., 2018). There are currently four hydrogen filling stations in Norway: One Uno-X station in Bergen and two outside Oslo, plus one at ASKO in Trondheim, which is mainly for their own trucks. In addition, the newly established company Hydrogenisk will take over two of the HyOP filling stations that were closed in 2018. By 2021 the Norwegian Hydrogen Association expects that there will be 14 hydrogen filling stations. Uno-X previously stated its readiness to establish 20 hydrogen refuelling stations by 2020, and earlier this year they had specific plans for four new stations. There are also planned filling stations combined with plans of deployment of mobility solutions as hydrogen buses and ferries, and by the industry cluster at Herøya.

On the other hand, public support has so far only been offered for a maximum of three stations per year. The legal-administrative procedures for establishing stations are variable in practice and can take as long as three years. The uncertainty following the closing of Hyop's stations in 2018 increased with the explosion in June 2019.[39] All hydrogen stations in Norway, and many in Denmark and other parts of Europe, were closed. Others reopened when the root cause - tank leakage due to an assembly fault linked to a specific HRS model[40] – was established, and relevant safety measures had been identified.[41] However, Uno-X keeps their stations closed and has put its plans for new stations aside for an indefinite period.[42] The *National plan for alternative fuels infrastructure*, which came out July 1st 2019, states that the support for the development of hydrogen refuelling stations will continue but that increasing the number of vehicles is more critical, as refuelling stations can be put up quickly. Enova may assess the need for further support based on the demand development in coming years but support for larger, integrated user cases will be prioritized (Norwegian Government, 2019b).

When interviewed for this study, most stakeholders were convinced that we will see a rapid uptake in heavy duty transport once FCEV trucks become commercially available. Some were also confident that private FCEVs will increase after 2030, as more restrictions on fossil fuels are put in place. On the other hand, the national association for logistics and transport operators expressed skepticism, both regarding costs and the technology itself. Biofuels are more known and acceptable in terms of usability and safety. At the same time, truck owners in Norway usually own one or a few vehicles. They tend to have a profit margin of 3-5%, and typically operate on 3-4 years contracts. Hence, the aftermarket is important, and the current business model does not provide incentives to shift to radically new technologies. To meet this challenge, counties and municipalities in at least two regions are working to facilitate fleet collaboration that may reduce risk and bring costs down.

Several stakeholders emphasized that battery and hydrogen fuel cell solutions are complementary and should not be perceived as competing technologies. While the energy efficiency is higher with batteries, some were quite certain that the electricity grid capacity is not enough to manage full electrification and the range and total operation costs may favor hydrogen. The overall distribution will depend on technology development (speed charging and fuel cells) and overall costs, which we do not see until heavy duty BEVs and FCEVs become available in larger series. The main drivers and barriers associated with deployment of hydrogen in road transport are summed up in Figure 25.



Drivers

- Ambitious climate targets for the transport sector
- Strong incentive system for FCEVs, as for BEVs
- Public grant support for HRS (up to 3 HRS per year)
- Green Public Procurement and support schemes in certain counties

Barriers

- Success, high adoption of BEVs in Norway
- Higher cost of ownership for private FCEVs than BEVs
- Lack of HRS infrastructure, uncertain future framework conditions
- Heavy-duty vehicles not yet available on the Norwegian market
- Limited acceptability
  - Risk and safety
  - Usability (compared with biofuels)
  - Short—term contracts and high financial risk for heavy vehicle logistics operators

Figure 25: Main drivers and barriers for hydrogen in Norwegian road transport.

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[39] https://www.tu.no/artikler/hydrogenstasjon-i-brann-etter-eksplosjon-i-sandvika/467327
[40] https://www.tu.no/artikler/slik-startet-lekkasjen-som-forte-til-hydrogen-eksplosjonen-i-sandvika/468765
[41] https://brintbranchen.dk/flere-brinttankstationer-genoptager-driften/
[42] https://unox.no/hydrogen, accessed 15. August 2019.

Maritime transport

Global shipping emitted almost 1 billion tons CO_2, or around 2.5% of the total global emissions. Traffic is projected to increase 50-250% by 2050 (IMO, 2014), implying that, with business as usual, total shipping emissions could account for 17% of global CO_2 emissions by 2050 (EP, 2015). In Norway, emissions from the maritime sector were 7.4 million tons CO_2e (about 14% of total national emissions) in 2015. The amount will increase to 11.5 million tons by 2040 unless action is taken. Alternative fuels are key to realizing the national target of 50% cut in the emissions from domestic shipping by 2030 (Norwegian Government, 2019a) and to meet the aim of the International Maritime Organization (IMO) to reduce the total emissions from the maritime sector 50% by 2050. Batteries are only viable for shorter distances, and, amongst other, OECD Transport (2018) note that hydrogen and ammonia are highly relevant alternatives. Figure 25 presents an overview of the efficiencies currently associated with different technologies:

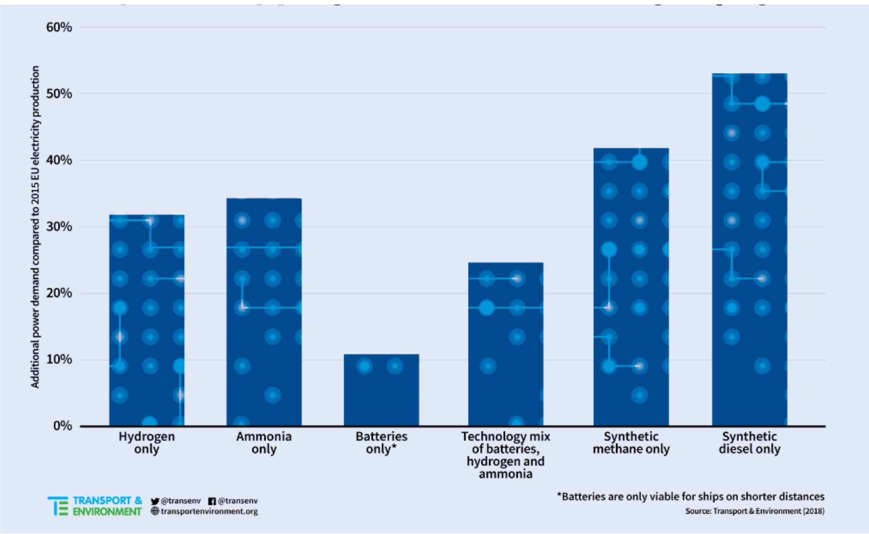

Figure 26: The most energy efficient ways to decarbonise the European maritime sector (Transport & Environment, 2018).

In the view of OECD Transport (2018), maritime applications require more research and development to become commercially viable. DNV GL (2018) expects a less than 2% hydrogen share in the fuel mix in shipping in 2050. That mostly accounts for the cruise ships with a clean energy certification. Shell Sky (2018) expects the hydrogen share in maritime transport to be neglectable in 2050 but growing from 2060.

However, Norway has at least 10 pilot projects on hydrogen powered ships that are very promising. The maritime industry is one of the most important sectors in the economy and has in recent years become a frontrunner in sustainable technology. Zero emission solutions for coastal passenger traffic are also actively encouraged through green public procurement. Under an innovation contract with the Norwegian Public Roads Authority, Norled works to develop the world's first seagoing hydrogen ferry to connect the national road 13 between Hjelmeland - Skipavik - Nesvik outside Stavanger from 2021.[43] [44] They have also received EU support through Flagships for the development of a second hydrogen vessel to operate the Finnøy ferry route, also near

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[43] https://www.norled.no/en/news/norled-to-build-the-worlds-first-hydrogen-ferry/

[44] In competition with a Scottish project, see https://www.electrive.com/2018/06/20/hyseas-iii-scotland-to-build-first-sea-going-hydrogen-ferry/. The Water-go-round, a demonstration passenger ferry to operate on San Francisco Bay, is also coming and scheduled to enter operation from September 2019 https://www.electrive.com/2019/06/13/fuel-cell-ferry-water-go-round-finds-fleet-investment/.

Stavanger.[45] The shipyard Fiskerstrand has a hydrogen ferry pilot in Møre and Romsdal, further north, and Trøndelag county is running a competitive innovation process for the procurement of a zero-emission highspeed passenger vessel, where hydrogen is in focus. Five consortia and a total of 19 companies are participating. The concepts, including the two hydrogen ships depicted in Figure 26, were presented in September 2019, and the vessels may enter operation in 2022-2024.[46]

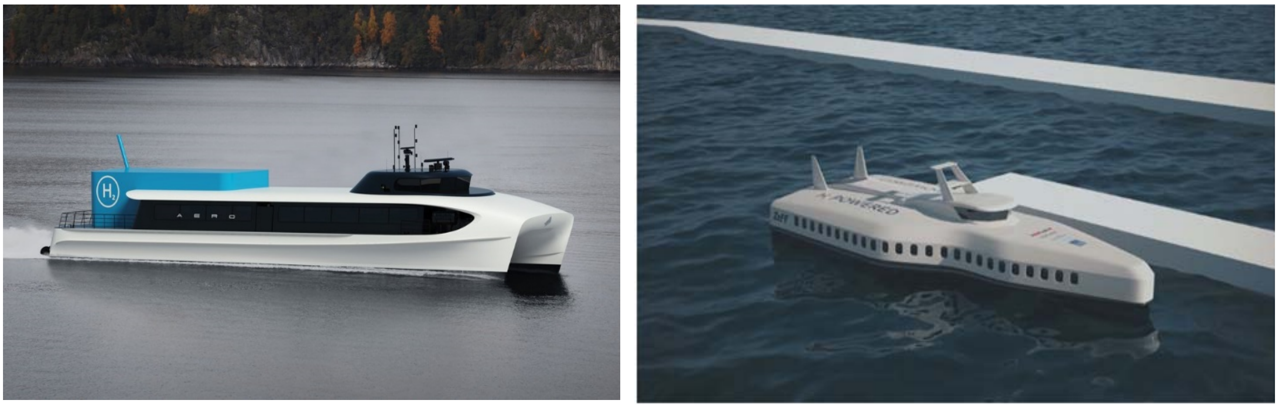

Figure 27: Illustrations of innovative hydrogen fueled highspeed passenger vessel concepts. Left photo: Brødrene Aa. Right photo: Selfa Arctic.

In addition to the regular research programs, the Norwegian government has established Pilot-E as a large support scheme for public-private partnership in development and piloting of green shipping solutions. Under Pilot-E, the companies Selfa Arctic and Flying Foil both lead collaborative projects to develop emission-free high-speed passenger vessels based on battery or fuel cell propulsion systems. Norwegian shipyard Havyard has been granted 104 mill NOK, or around 10 mill euro, to develop a 'high-capacity hydrogen energy system' for one of four cruise ferries being built for the new Norwegian coastal operator Havila Kystruten. Samskip has also been granted support to develop a short-sea container ship with hydrogen and fuel cell propulsion. A resolution by Parliament in 2016 encourages the use of development contracts for hydrogen ferries, and the Government's recent ban of any kind of carbon emissions in Nærøyfjorden and Geirangerfjorden from 2026 onwards is another driver.

Furthermore, Moss Maritime, Equinor, Wilhelmsen, and DNV-GL recently developed the design for a bunkering vessel for liquid hydrogen (figure 24). The project was sponsored by Innovation Norway, as the solutions for storage and handling are crucial for wider uptake of hydrogen as an energy carrier.

DNV-GL (2019) identified 186 vessels in local shipping with an operation pattern that makes them likely as early adopters of hydrogen fuel cell propulsion systems. Based on an assessment of the maturity of hydrogen solutions for different vessels, they estimate that a total of 18 vessels may be converted to hydrogen by 2030, creating an annual demand of 17 900 tons/year.

Most of the consulted stakeholders see considerable potential in the maritime sector. As noted above, maritime opportunities are also in focus in most of the studied production initiatives, especially at Jelsa, Kvinnherad, and Tjeldbergodden. The potential was also highlighted in the attended workshops. Still, most of the activity is project-based. There is the need for parallel technology qualification and development of standards. A specific procedure for design type approval of hydrogen ships does not exist. Solutions and standards for bunkering facilities are also not in place.

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[45] https://www.norled.no/en/news/as-part-of-norleds-green-venture-we-are-pleased-to-be-part-of-an-exciting-eu-project-that-can-give-us-more-hydrogen-powered-ferries/

[46] https://www.nrk.no/trondelag/utslippsfrie-hurtigbater_-_-det-naermeste-vi-kommer-science-fiction-1.14686953

Moreover, the lifespan of most ship types is 30-40 years and, internationally, there is a surplus of ships on the market that may slow the uptake of new technologies. When it comes to public tendered ships, contracts are usually 10 years. Generally, shipping is considered as a conservative market. Key actors in Norway are worried that the early movers will be locked in with first-generation ships that may not be competitive after the initial contract cycle. Considering the recently imposed CO_2 tax on LNG, there is uncertainty about the framework conditions. The fear of such lock-ins may increase with the range of new fuel options, from gaseous to liquid, ammonia, LOHCs, etc., that are coming up. Also, with the progress in battery technology, some stakeholders raise the question whether hydrogen is optimal for shorter routes, or if the focus rather should be on the longer routes in local shipping.

With *The Government's action plan for green shipping*, launched in June 2019, the focus of the national effort to decarbonise shipping is expanded from passenger vessels to more segments, including offshore supply and aquaculture vessels, fishing vessels, and cargo ships. This implies that a wider spectrum of low-emission solutions must be applied, and hydrogen, as well as ammonia, are considered promising in a longer-term perspective (Norwegian Government 2019a). According to Bellona, the technology and users will come. The limiting factor is the production and distribution of hydrogen, and what is lacking currently is a coordinated effort to plan where, and how, hydrogen will be supplied. If the target group includes fishing and freight vessels, fuel must be widely available and there may be the need to expand the power grid. There is enough energy, but the load capacity may be limited.[47] Equinor is offering a solution to this 'chicken or the egg' dilemma by way of grey hydrogen production, but, so far, users, such as Trøndelag County, insist that the hydrogen must be zero-emission and preferably from renewable sources.

The main drivers and barriers to deployment of hydrogen in the maritime sector are summarized in Figure 28.

Drivers

- National climate targets for the maritime sector – reduce 50% of emissions from coastal shipping by 2030
- IMO initial strategy to reduce GHG emissions
- Business and transition potential for the maritime industry, regional development
- Volume and market for blue hydrogen
- National plan for green shipping
- Substantial incentives, support schemes for zero-emission shipping
- Green public procurement
- BE solutions only viable for shorter routes

Barriers

- Technology still under development
- Regulatory gaps, need to develop rules and standards
- Lack of predictable supply of hydrogen
- Multiple solutions competing for attention
- High costs
- Long life-span of ships (30-40 years)
- High financial risk
- Uncertain framework conditions (bad experience, changes in fees/taxes for LNG)
- Current lack of bunkering facilities

Figure 28: Main drivers and barriers to deployment of hydrogen in the maritime sector.

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[47] https://network.bellona.org/content/uploads/sites/2/2018/08/Utslippsfri-kyst-2040-brosjyre-Arendalsuka-2018.pdf?__utma=123600408.718982001.1533026688.1558187972.1560084782.7&__utmb=123600408.2.10.1560084782&__utmc=123600408&__utmx=-&__utmz=123600408.1560084782.7.6.utmcsr=google|utmccn=(organic)|utmcmd=organic|utmctr=(not%20provided)&__utmv=-&__utmk=127685133

5.5 Use in industry

IEA's *Technology roadmap for Hydrogen and Fuel Cells* (2015) finds the greatest potential for hydrogen in industry. The Energy Transition Commission (2018) likewise expect the market share for hydrogen to be largest for industry applications. The industry sector accounts for one fifth of the world's direct global greenhouse gas emissions and has so far had very little progress on decarbonisation (Stafell, 2019). Hydrogen is already widely used as feedstock and produced as a by-product in chemical manufacturing processes. Hydrogen may also replace natural gas as a fuel; burners and furnaces may need replacement, but industry application will not require high purity. Stafell (2019), notes that hydrogen could be introduced into several high-temperature industries including steelmaking and cement. However, commercialisation is not expected before 2030 due to low maturity, uncertain costs, the likelihood of needing fundamentally redesigned processes, and the slow turnover of existing systems. This is in line with the Shell Sky scenario (2018), which anticipates a hydrogen share in industry in 2050 of 3%.

Several studies highlight the potential for emission reductions associated with introduction of renewable hydrogen into gasoline production. A recent study for Ontario, Canada, finds that renewable hydrogen may decrease 4.6% of the natural gas consumption of the gasoline cycle, and thereby minimize carbon intensity by 0.15 kg CO_2e per 100 km (0.5 g CO_2e per MJ) of the fuel (Alsubaie et al., 2019). A comprehensive review of realized power-to-gas projects in Europe (Wulf et al., 2018) also indicates that the application in industry, and for reducing the carbon footprint of refineries, will be important in future.

The world's largest plant for production of green hydrogen, under construction by Shell in Cologne, will produce up to 1,300 tons of hydrogen per year and significantly reduce the footprint from one of the largest refineries in Europe. The plant will be completed in 2020.[48] The potential of hydrogen for greening refineries and fossil fuels is also noted by Norwegian stakeholders, especially by Statkraft.

The Swedish Energy Agency is investing heavily in an initiative called "Hydrogen Breakthrough Iron-making Technology" (HYBRIT). This is still in the experimental stage, but the ambition is that the iron and steel industry in Sweden will have zero emissions by 2045 (PR, 2017). A pilot plant for production of fossil-free steel using hydrogen as feedstock is being built in Luleå and will be the first of its kind worldwide (Karakaya et al., 2018). The plant will have a 4.5 MW alkaline electrolyser and operate as pilot from 2021 until 2024, when the project will enter a demonstration phase with the goal to have an industrial process in place by 2035.[49]

For the industry sector in Norway, Enova (2017) found that hydrogen has an emission reduction potential of 4-6 million tCO_2e. This is associated mainly with fertilizer production, but also with ferro-alloys and replacing natural gas in the offshore petroleum sector and refineries. However, the capital costs for electrolysers are a critical factor. Applying hydrogen from natural gas with CCS is another option, and hydrogen produced from natural gas with soot ("carbon black") as a by-product is a third but less energy-efficient alternative.

Many of the stakeholders interviewed for this study were convinced that the costs of electrolysers will be significantly reduced, and several pointed to the potential for reducing emissions from industry. As noted in chapter 4, substituting the current use of coal in titanium and iron ilmenite upgrading with hydrogen is associated with a considerable potential for emission reductions. An anticipated increase in future carbon costs is also an important driver. On the other hand, the management of TiZir states that it is demanding to replace cost-effective production with a new process that is not technically and industrially proven. Converting to hydrogen may also require significant additional investments, amounting to an economically suboptimal

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[48] https://fuelcellsworks.com/news/construction-starts-on-the-worlds-largest-hydrogen-plant-at-shells-rheinland-refinery/

[49] https://group.vattenfall.com/press-and-media/news--press-releases/pressreleases/2019/hybrit-orders-norwegain-electrolyzers-for-fossil-free-steel-production-in-lulea

solution even if carbon emission prices are increasing. Thus, the corporate perception of net present value of future green-house emission costs is imperative. Public support will be crucial to reduce risk and facilitate a full-scale implementation of a hydrogen-based process.

The other major case is Yara, which has launched a project for greening its fertilizer production, where hydrogen is an important part of the solution. The expectation that the cost of intermittent renewable energy will become lower than fossil energy is a main driver in this case, too. Using renewable energy for fertilizer production will require more flexible technology and increase capital expenditure, and green hydrogen as well as green ammonia may provide the needed flexibility. Yara's concept is currently under development. Pilot operation of the hydrogen-solution will commence by 2022, while a pilot operation of the full, green fertilizer production is scheduled for 2026.[50] The project is co-developed with NEL Hydrogen and financed through Pilot-E. The aim is to build the first next-generation plant at Herøya, in southern Norway, by 2030. At the same time, Yara is looking into opportunities for using green ammonia as fuel for maritime applications and as hydrogen carrier for long distance transport of hydrogen.

The Norwegian Clean Energy Cluster (NCEC) recently established a "Hydrogen Valley" project, where the vision is to decarbonize the process industry in Haugalandet, in the southwestern part of Norway, and export large volumes of hydrogen to Europe via the existing subsea gas network.[51] Green hydrogen based on wind-power may also be a part of the solution for electrification and emission reductions from offshore petroleum activity. The Deep Purple project, mentioned above, aims to develop technology for hydrogen production in the stems of offshore windmills, with storage solutions on the seabed. The ambition is to provide oil and gas platforms with renewable energy, with maritime transport as a second market. The aim is to reach technology readiness level (TRL) 5 by 2020 and go commercial by 2024. In the later stages, Technip FMC will need operators as partners. Whether this will be possible will to a large degree depend on political signals and the development and future role of offshore wind farms.

Enova (2017) notes that a major challenge is that in order to cut emission by 40%, companies must develop and lead the implementation of immature technologies. Individual companies have few incentives to take on such long-term R&D investments. On the other hand, leadership within decarbonisation may provide competitive advantage as requirements increase and the sale of new technology may provide added business opportunities, as illustrated in Yara's exploration of applications for green ammonia.

The main drivers and barriers to use of hydrogen as energy carrier in the Norwegian industry sector are presented below, in Figure 29.

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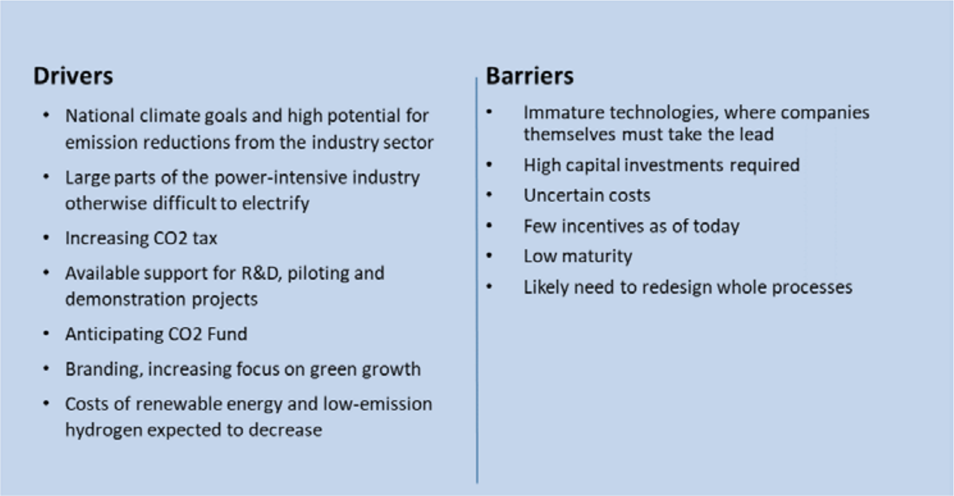
[50] Yara presentation at H2 Mission workshop, SINTEF 2018. https://www.heroya-industripark.no/aktuelt/yara-og-nel-satser-paa-ren-hydrogen-og-groenn-gjoedsel.-bygger-pilotanlegg-paa-heroeya

[51] https://www.maritimt-forum.no/haugalandet-og-sunnhordland/nyheter/2019/tar-posisjon-med-hydrogen-valley-pa-haugalandet



Drivers

- National climate goals and high potential for emission reductions from the industry sector
- Large parts of the power-intensive industry otherwise difficult to electrify
- Increasing CO2 tax
- Available support for R&D, piloting and demonstration projects
- Anticipating CO2 Fund
- Branding, increasing focus on green growth
- Costs of renewable energy and low-emission hydrogen expected to decrease

Barriers

- Immature technologies, where companies themselves must take the lead
- High capital investments required
- Uncertain costs
- Few incentives as of today
- Low maturity
- Likely need to redesign whole processes

Figure 29: Main drivers and barriers to hydrogen solutions in the Norwegian maritime sector.

5.6 Use for heating

Hydrogen is also associated with a large potential of decarbonizing the heating sector in countries reliant on natural gas. DNV GL (2018) sees a great potential in areas with an existing natural gas infrastructure. Both the Energy Transition Commission (2018) and The Hydrogen Outlook Europe (2019) expect hydrogen to cover 10% of the heat demand in 2050. This application is less relevant in Norway but important with a view to the future export opportunities for hydrogen and natural gas. Chapman et al. (2019) estimate that most of the hydrogen for heating will come from natural gas reformation with CCS.

A review of the existing research literature suggests that it is feasible, technically and safety-wise, to introduce a hydrogen share of up to 20% into the existing gas infrastructure without significant interventions (Hodges et al., 2015). The hydrogen - natural gas mix - has a slightly lower efficiency, both in terms of heating value and density (Dashtebayaz et al., 2019). However, climate gas emissions will be significantly reduced, and there are huge savings to be made by utilizing the existing infrastructure for natural gas transmission and storage (Nastasi and Basso, 2016).

Hydrogen for heating is a prioritized topic in Great Britain, where 86% of the population is connected to the natural gas grid for heating and cooking and the renewable share in electricity generation is only around 30%. Several projects are ongoing. HyDeploy is a programme running from 2017-2023, which involves three separate trials of blending hydrogen at 20 vol% into the gas distribution network and aims to provide the safety case and kick start the hydrogen blending market. The project considers several deployment pathways, including bulk supply as well as power-to-gas (Isaac, 2019). One of their pilots is currently operational, and a similar project is run by Engie in Northern France.

Equinor is one of the partners in the project H21 North of England, which has developed a concept for largescale conversion of natural gas to hydrogen with CCS and injection of the hydrogen directly into the natural gas grid. The H21 NoE report (2018) concludes that this solution would be considerably cheaper than electrification. The profitability of replacing natural gas with hydrogen from natural gas reformation with CCS in 2050 is however disputed, as solar and wind power is continuously becoming cheaper.[52] The Danish

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[52] TU August 5th 2019. URL: https://www.tu.no/artikler/liten-tro-pa-equinors-hydrogeneventyr-urealistisk-mener-eksperter/468299?key=Z3Gl8vhF

research project FutureGas[53] is looking into how hydrogen can be utilized for district heating. Denmark has an extensive natural gas grid used for heating and a very ambitious target for climate gas reductions within 2030.[54]

DNV GL (2018) concludes that hydrogen for heating will mainly come from steam reformation of natural gas. This further implies implementation of CCS technology. Other studies highlight the potential of producing hydrogen from excess wind power production and use it for heating, as well as transport, power and cooking (Samsatli and Samsatli, 2019). A review study on existing power-to-gas projects shows a great potential, but injection of hydrogen into the natural gas grid is still in a research and development phase and need further investigation on technical and economic feasibility. Their estimation is a 20% market share for renewable hydrogen in the heating market (Quarton et al., 2018).

Power for remote areas

In remote areas where electricity transmission is expensive, the fossil solution will also be expensive due to high transport costs. In remote islands, the cost of developing and maintaining the power supply from shore through sea cables may be ten times higher than for urban areas. In such areas, hydrogen stands out as a profitable alternative. Trønder Energi, with support from Enova and SINTEF, participates in an EU project called REMOTE where a demonstrator plant in a small Norwegian island is made self-sufficient through microgrid with locally produced wind and solar power and hydrogen as energy storage medium. This hyper-local network will be disconnected from the main power grid.[55]

Hydrogen for heating and electricity in buildings could also be a future option for Svalbard, where Norway's only coal-fired power plant currently produces approximately 70 GWh of electricity and 40 GWh of district heating annually. At the Longyear energy plant about 250 000 tons of coal are used for the heat and power generation. CO_2 emissions have increased since 2014, when measurements started, and counted 73 000 tons in 2017. In addition, Barentsburg has a coal power plant from 1974. The coal-fired power plants release around 200 000 tons of CO_2 annually. In 2017 it became known that the government will wind up coal operations in Svalbard. The Ministry of Petroleum and Energy commissioned a report concluding that a gas-fired power plant without CCS would be the most cost-effective replacement (Thema and Multiconsult, 2018). This triggered a search for more sustainable solutions. Using stranded wind power in Finnmark to produce hydrogen for transport to Svalbard is promoted as an alternative by both Statkraft, Statnett and SINTEF (Møller Holst et al., 2018; Statnett, 2019).

The main drivers and barriers discussed in this section are presented below, in Figure 30:

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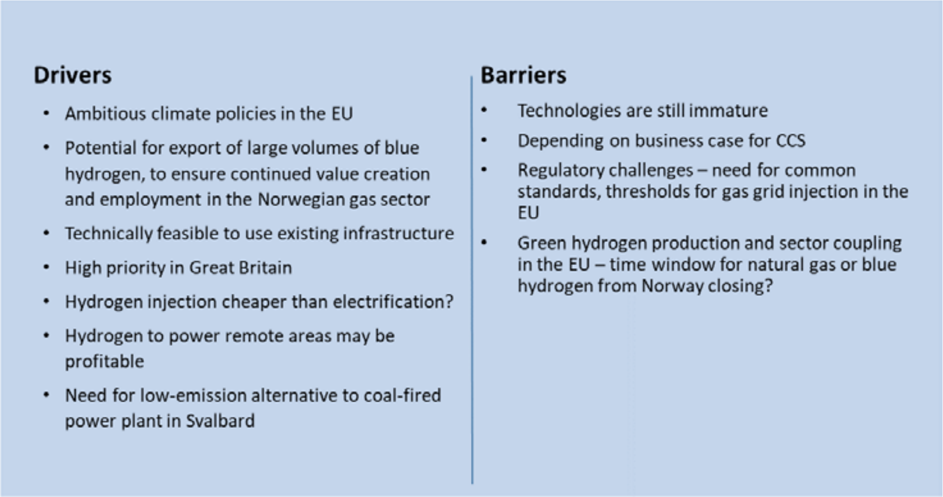
[53] https://futuregas.dk/

[54] Altinget 25.6.2019. URL: https://www.altinget.dk/misc/Retf%C3%A6rdig%20retning%20for%20Danmark_2019-06-25_ENDELIG.pdf

[55] ? https://www.remote-euproject.eu/



Drivers

- Ambitious climate policies in the EU
- Potential for export of large volumes of blue hydrogen, to ensure continued value creation and employment in the Norwegian gas sector
- Technically feasible to use existing infrastructure
- High priority in Great Britain
- Hydrogen injection cheaper than electrification?
- Hydrogen to power remote areas may be profitable
- Need for low-emission alternative to coal-fired power plant in Svalbard

Barriers

- Technologies are still immature
- Depending on business case for CCS
- Regulatory challenges – need for common standards, thresholds for gas grid injection in the EU
- Green hydrogen production and sector coupling in the EU – time window for natural gas or blue hydrogen from Norway closing?

Figure 30: Main drivers and barriers linked to decarbonisation of district heating and power supply for remote regions.

6 A multilevel perspective on the scope for hydrogen in Norway's energy transition

In the initial chapters we outlined certain trends in the wider social landscape which create a changing context for the development and uptake of new energy solutions. We also touched on policy developments and historical events at the national level that have affected hydrogen as an energy carrier, before discussing selected production initiatives and perceived opportunities and barriers in different parts of the value chain. In this chapter, we apply the multilevel perspective for a more detailed discussion of the main influences and interaction between these levels, and how they affect the transition potential associated with largescale hydrogen production in Norway.

6.1 A changing global landscape

Increasing focus and awareness of climate change

The IPCC Special Report emphasizes that global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (IPCC, 2018). It shows that the consequences of 1°C of global warming already are apparent, i.e. in more extreme weather, rising sea levels and diminishing Arctic sea ice, and highlights impacts that could be avoided by limiting global warming to 1.5°C, as compared to 2°C or more. According to the IPCC, pathways reflecting the national ambitions submitted under the Paris Agreement will not limit global warming to 1.5°C, even if supplemented by very challenging increases in emission reductions after 2030.

Pathways limiting global warming to 1.5°C with no or limited overshoot will require rapid and far-reaching transitions in energy, land, urban development and infrastructure, and industrial systems. The scale of these transitions is unprecedented and implies that together with improved policy instruments, acceleration of innovation and behaviour change, a significant upscaling of investments in a wide portfolio of mitigation options is needed (IPCC, 2018).

The clear messages from IPCC have placed the climate challenge higher on the public agenda. Activists such Greta Thunberg and US Congress representative Alexandria Ocasio-Cortez, as well as David Attenborough through "Our Planet" have helped translate the message and engage the masses. Notions such as "meatless Monday" and "flight shame" are associated with a higher level of public engagement, reflected in tendencies towards behaviour change: According to a recent survey by Swedish Railways, 37% of respondents chose to travel by rail instead of air, as compared with 20% in early 2018, and journeys went up 8% in 2019 due to environmental concerns.[56] In Norway, the sale of red meat has stagnated and figures from the major food chains indicate a 4% drop from 2018 to 2019.[57] While the impact so far may be small, the importance of collective action in socio-technical transitions should not be under-rated (Klitkou, 2015). As noted by Williamson et al. (2018), the abstract, large-scale, distant, and impersonal characteristics of climate change do not trigger the brain to action in the way more concrete and immediate problems might, and actionable strategies to inspire and empower individuals are therefore of critical importance.

Sovacool (2017) draws attention to RE100.org, an initiative whereby many of the world's largest multinationals in ICT, services and modern consumer goods have made a commitment to go "100% renewable".[58] While the role of the World Business Council for Sustainable Development (WBCSD) has been debated, amongst other by Greenpeace, it is stepping up its climate ambition. Its *Low-Carbon Technology Partnerships initiative* brings together 235 major companies to accelerate low-carbon solutions and reduce emissions in line with the Paris Agreement. The latest WBCSD Vision 2050 report is, allegedly, the largest concerted corporate sustainability action plan to date, addressing rising greenhouse gas emissions.[59]

Scope for hydrogen in integrated energy scenarios

The messages from the IPCC are based on and aligned with a wide range of research and scenario reports. These underscore the challenges and high level of uncertainty regarding future energy solutions. In the New Policies Scenario of World Energy Outlook 2018, the global energy demand is expected to grow by more than 25% to 2040, mostly from developing economies. To meet the sustainable development goals, cheaper renewable energy technologies, smart integration and increasing importance of electricity are important. In advanced economies, electricity demand growth will be modest, but there will still be a huge need for investment as the generation mix will change and infrastructure will need upgrading (IEA, 2018). The Energy Transition Commission (ETC) suggests a pathway to the two-degree target which largely is dependent on electrification and implies a rise in power production from 20 000 TWh to 150 000 TWh annually. In this scenario, the share of wind- and solar in the power system is suggested to reach 85-90% on a global scale. Hydrogen will play a significant role in decarbonizing the sectors and segments that are hard to convert, and energy efficiency measures and the adaptation of CCS seem crucial (ETC, 2018).

According to IRENA (2018), the share of electricity in global energy consumption must increase to 40% in 2050 in order to achieve the targets of the Paris Agreement. Renewable energy's share of global final energy consumption must increase to 65%, and variable renewable energy will make up around 60% of all electricity generation in 2050. Again, this will require more flexibility, and renewable hydrogen could, potentially, be the "missing link", allowing large amounts of renewable energy to be stored, distributed and channelled into sectors where electrification is otherwise difficult, such as transport, buildings and industry.

As regards the EU, *A clean planet for all* expects a more than 80% share of renewable electricity generation in 2050, increasingly consisting of offshore wind, and a 15% share of nuclear (EC, 2018). Kanelloupolos and Blanco (2019) used a European TIMES model to find pathways to achieve the European low carbon emission

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[56] http://www.mynewsdesk.com/se/sj/pressreleases/klimatoro-ger-kraftig-foeraendring-av-svenskars-resvanor-2881081
[57] https://www.klartale.no/norge/nordmenn-kjoper-mindre-rodt-kjott-1.1556051
[58] http://there100.org/companies
[59] https://www.theguardian.com/sustainable-business/sustainability-case-studies-world-business-council

goal of 95% reduction within 2050. In their scenario, an 88 % renewable share is assumed for the European power system in 2050, and 400 GW will still be generated by conventional thermal power plants. Hansen et al. (2018) used the energyPlan model to assess different paths towards a 100% renewable energy system in Germany. Their study suggests that the largest barrier is to arrive at a sustainable use of biomass resources. Even with conversion to hydrogen in the transport sector, the threshold for biomass consumption will be exceeded. At the same time, the model suggests that hydrogen in the transport sector will generate higher system cost than electrification and biomass options.

Although the Norwegian energy system for a large part is renewable, we will also notice the transition, especially through electricity grid expansion, not only for trade, but also for a substantial increase in power consumption. The system operator Statnett and the Norwegian Water Resources and Energy Directorate (NVE) assume an increase in power consumption between 20 and 80 TWh by 2040, where the highest estimate is from a scenario with a high uptake of electrolysis. An increase of power consumption above 50 TWh requires large electricity grid investments (Statnett, 2018; Statnett, 2019; NVE, 2019).

The Nordic Energy Technology Perspectives (NETP) 2016, likewise, suggested that electricity export will increase significantly. To serve electrification of the transport sector and increasing export, electricity generation will increase by 59 TWh, with 54 TWh in Norway. The wind power generation will be five times higher than in 2013. Hydropower will increase, and biomass will increase 45%. Although with a significantly lower share, the model results include coal, oil and natural gas in 2050, implicating that CSS will be competitive in 2050 at the assumed carbon price of 146 USD per Mt CO_2.

Kanelloupolos and Blanco (2019), in a scenario where hydrogen mostly is generated by electrolysis, find an electricity generation in Norway of 600 TWh in 2050. They expect a domestic electricity consumption according to current level, resulting in excess power of 75% of the power generation. The wind power generation is expected to increase to 420 TWh, and solar power approximately 10 TWh. Norway will have the highest power surplus in Europe, which may lead to an expanded grid capacity of 16 GW (Kanelloupolos and Blanco, 2019).

Thus, key studies suggest that the scope for hydrogen production in Norway will increase in coming years, and some also indicate that there will be a business case for hydrogen from natural gas reforming with CSS. Two recent academic reviews of international integrated assessment model scenarios (Hanley et al., 2018; Gambhir et al., 2019) also note a considerable potential. They further highlight the uncertainty and complexity associated with hydrogen, given the range of possible production methods and energy sources, and coupling with other technologies, such as carbon capture and storage (CCS). According to Hanley et al. (2018), hydrogen mainly emerges after 2030. With high use, hydrogen may reduce global emissions by 250 Mt by 2050. In the study by Gambhir et al. (2019), the median share of hydrogen in all scenarios is below 10% of final energy throughout the period to 2100. The considerable potential, in combination with high uncertainty, influences the political and market acceptance of hydrogen as energy carrier.

Trends in the development and design of energy markets

The recent years have seen a remarkable rate of cost deflation for solar and wind energy, as illustrated in the following table from IRENA:

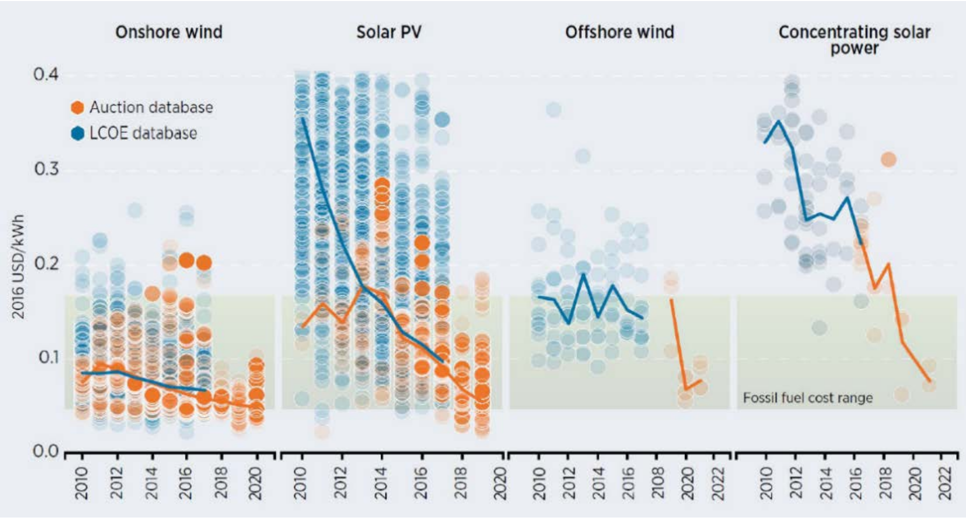

Figure 31: Cost deflation for solar and wind energy, 2010-2022 (©IRENA, 2017).

Whether and how these trends will continue is one of the core issues addressed in integrated model studies. However, they are also important landscape factors in themselves, exerting an impact on niche actors and their motivation to invest, as well as on public decisionmakers and their perceptions of the speed, opportunities and barriers in sustainable energy transition.

The decreasing installation costs are associated with a rapid growth of the market for listed as well as unlisted renewable energy infrastructure investments. Unlisted assets typically include property, infrastructure (including power grids), and private equity (investments in start-up or existing private companies). McKinsey & Company estimate that the value of the global renewable energy infrastructure market will grow by almost 50% from 2017, to reach 4.2 trillion USD in 2030 (McKinsey & Company, 2018). Approximately 70% of the investable market for 2018-2030 will be in unlisted assets of which around 85% is solar and wind power, and around 55% will be in Asia, mainly in China and India. As the assets have low liquidity and high transaction costs, investors in renewable energy infrastructure tend to take high ownership shares and thus be more vulnerable to political, regulatory and reputational risk than for many other types of investment. Solar and wind are associated with lower risks than hydropower, but often exposed to risk of retroactive changes in governmental support regimes. In the initial years, around 45% of the market will be in OECD countries, but towards 2030 the technological and geographic composition is expected to shift, leading to a higher level of political, regulatory and reputational risk (McKinsey & Company, 2018). Thus, while the study underscores the big potential for renewables development, it also highlights the uncertainties in a longer-term perspective.

Increasing market reforms in the energy sector – both globally and in Europe – is another development influencing the transition to a renewable, more distributed energy system and hence the future role for hydrogen. Since the early 1980s, there have been efforts to make the sector more cost efficient by introducing competition. This may be seen as part of an ideological trend, of increasing faith in market forces. However, it has also been an effort to attract investments and improve environmental performance (Karan and Kazdagli, 2011). The EU started a liberalization process aiming towards an integrated electricity and gas market in the 1990s. The 1995 *Green paper on Energy* laid out a strategy with 3 pillars: a) Securing energy supply from multiple domestic and foreign sources, b) developing a more competitive internal energy market, and c) supporting development of clean and renewable energy sources (Barozzo, 2006). This led to two electricity market reforms: The *First Energy Package* defined common rules for an internal electricity market and introduced the idea of competition in generation and third-party access, as well as the idea of unbundling of generation, transmission and distribution. Then, following the Lisbon strategy of 2000, the *Second Energy Package* was adopted, including a second *Directive on the electricity (and gas) market*, which allows suppliers to enter markets in other Member States' and consumers to choose their supplier (Pepermans, 2018). This has led to increased trading, both via over-the counter markets and energy exchanges, such as Nordpool.

The *Third Energy Package*, of 2009, aimed towards an integration of the established energy and environmental objectives, for optimal utilization of capacity. Its main elements are separation of generation and retail activities from transmission activities; the obligation for all member States to establish a National Regulatory Authority, and the establishment of the Agency for the Cooperation of Energy Regulators (ACER). The recently adopted *Clean energy for all Europeans* package contains new rules for eight legislative areas. Amongst other, the new *Electricity Directive* and *Electricity Regulation* aim to adapt the market to a system with more variable renewable energy, by attracting investments in energy storage and incentivising consumers to contribute actively to stability. A new limit for powerplants eligible to receive subsidies as capacity mechanisms is introduced. The updated market design aims for more flexibility to accommodate an increasing share of renewable energy in the grid. Pepermans (2018) argues that while a well-functioning market should provide the price signals needed to encourage investment in new generation capacity, most Member States have so far adopted capacity mechanisms to foster local investment in generation capacity (Auer and Burgholzer, 2015), with a national focus. One of the conclusions drawn by Pepermans is that a paradigm shift is needed: Away from a conventional energy system towards a more decentralized system that allows for demand for distributed generation and storage.

At the same time, there are differing estimates of the costs of decarbonisation by means of a combination of electrification and gas compared with electrification alone. There are arguments that renewable electricity will be consistently cheaper than fossil gas, let alone renewable or decarbonised gas, before the end of this decade (Fischer, 2018). On the other hand, a range of studies conclude that a gas/electrification combination will be cheapest (c.f. CERRE, 2018; Pöyry, 2018; Ecofys, 2018). The carbon reduction benefits of coal and oil to gas switching and the advantages of gas in backing up intermittent renewables are emphasized, and coal to gas switching is presented as 'low hanging fruit' for rapid, low cost emission reductions. Stern (2017a) cites the example of the UK where a significant carbon floor price has led to progressive out-phasing of coal-fired power stations before 2025. Also, the gas community is working to develop a new decarbonisation narrative, including a range of actions to reduce the carbon (and methane) footprint of natural gas and a timeframe for rolling out low or zero carbon gas projects, as well as technical, legal, fiscal, and carbon price/tax frameworks (Stern, 2019). The extent to which this narrative will be embraced will influence the scope for hydrogen production from natural gas with CCS.

Trends in international climate and energy policy

As noted by amongst other IRENA (2017) and Statkraft (2019), sustainable energy transition depends, for a large part, on political will. While the Paris Agreement was an important step, the recent years have also seen a tendency towards decreasing trust and rising conflicts about climate and energy concerns. Donald Trump's announcement that the US will withdraw from the Paris Agreement, while at the same time starting negotiations to re-enter on better terms, has created uncertainty about the future impact of the agreement. Whether Trump is re-elected in 2020 or the Democrats win and the US decides to re-enter within a matter of months is a critical question. While Trump has questioned if climate change is real and pledged to roll back regulations placed on the oil and gas industry, the Democrats may embrace more radical programs. The proposed *Green New Deal* resolution pushes for a transition to 100% renewable, zero-emission energy sources, including investment into electric cars and high-speed rail systems and implementing the "social cost of carbon" that was part of the Obama administration's plans for addressing climate change within 10 years (Chohan, 2019).

A majority of Americans – about 69% – wants the US to remain in the Paris Agreement. State governments and municipalities that account for almost $10 trillion in GDP have committed to bold actions on climate change, exemplified by New York's announcement of a state plan for building a zero-carbon economy (Chatham House, 2019). On the other hand, it is noted that climate action at state level is polarized. Some states, such as California and 9 north-eastern states which have established the Regional Greenhouse Gas Initiative (RGGI), are deeply committed. Others are not rushing to make emission reductions a priority (Wallach, 2019). While China and India are driving in the right direction, persuading emerging economies to follow suit may get harder with the present uncertainty regarding environmental commitments from the US.

Given the severe challenges they face, in form of ecological degradation, food and water scarcity, etc., both India and China have embarked on halting yet deliberate climate diplomacy over the years, while also voicing the concerns of the developing world and ensuring that issues of equity and justice are addressed (Mizo, 2016). Brazil was previously seen as a global leader in climate action, amongst other reducing deforestation by about 80% between 2005 and 2012. Since the election of Jair Bolsonaro, however, their commitment has been thrown into doubt. Legislation that weakens the institutional and legal framework to fight deforestation and other environmental offenses has been passed, and the participation of civil society, including pro-environment groups, has been substantially weakened (Climate Action Tracker, 2019). The challenges were highlighted by the forest fires in the Amazon last year: Satellite data recorded more than 41,000 fires in the region in 2019, mostly started by farmers clearing existing farmland.[60] Brazil rejected support for firefighting from the G7 partners, and the situation caused a diplomatic row, as well as public demonstrations in several countries.[61]

Underneath the common Climate Action, the commitment in the EU countries also varies. In May 2019, eight governments (France, the Netherlands, Belgium, Sweden, Denmark, Spain, Portugal and Luxembourg) launched an appeal to boost the climate action by signing up to a European Commission plan to achieve net-zero greenhouse gas emissions “by 2050 at the latest”. The appeal proposes that the fight against climate change should be a cornerstone of the European Strategic Agenda 2019-2024. It calls on the EU to raise its greenhouse gas reduction target for 2030, ahead of the United Nations climate action summit in 2020.- The eight governments emphasize that “at least 25%” of all EU spending should go to projects fighting climate change. They also call for transformation of the European Investment Bank, to make green financing its top priority.[62]

On the other hand, a recent analysis by the LIFE PlanUp project found a lack of climate commitment in terms of governments' ambitions, concrete sectoral measures and public participation in Italy, Hungary, Poland and Romania (PlanUp, 2019). These findings are reflected in an assessment of the draft integrated national energy and climate plans by the European Commission in June, 2019. The assessment found a certain gap between the national plans and the EU 2030 target levels for renewable energy and a substantial gap, ranging from 85 to 26 Mtoe (corresponding to attaining 26.5% to 30.7%) for final energy consumption. When it comes to greenhouse gas emission reduction in the sectors covered by the *Effort Sharing Regulation*, the measures included in the draft national plans can achieve a 28% greenhouse gas emission reduction by 2030 but will fail to achieve the mandatory 30% (COM(2019) 285 final).

Stern (2019) notes that European-level assessments of the costs of different decarbonisation options may be problematic in terms of their relevance for individual countries. Coal to gas switching, hydrogen (with or without CCS) and biogas/biomethane may be important, immediate, and low cost in some countries – and particularly certain regions of countries – but marginal or irrelevant in others. Currently, large scale methane reforming to hydrogen with CCS is under serious consideration only in the UK, while in southern Europe there is greater emphasis on biogas and biomethane. The choices made will differ, implying that the paradigm of gas markets transporting a homogenous product through a unified network will change significantly post-2030.

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[60] https://www.sciencemag.org/news/2019/08/theres-no-doubt-brazils-fires-are-caused-deforestation-scientists-say

[61] https://www.theguardian.com/world/2019/aug/27/amazon-fires-brazil-to-reject-20m-pledged-by-g7

[62] https://www.euractiv.com/wp-content/uploads/sites/2/2019/05/Non-paper-Climate-FR-SE-PT-DK-LU-ES-NL-BE.pdf

A recent amendment of the EU *Gas Directive* aims to ensure that the core principles of EU energy legislation will apply to all gas pipelines to and from third countries. Critical voices claim the proposed amendment creates bureaucratic hurdles and shifts energy policy powers from member states to Brussels.[63] At the same time, LNG transportation or liquefaction would not be subject to the same regulations, which could lead to higher gas prices (Blyhammar et al., 2018).

Thus, there is increasing momentum. However, multiple interests and contestation are also shaping the broader landscape of energy transition, both globally and regionally. The "yellow vests" in Paris, arguing that increased fossil fuel prices have a disproportionate impact on the peri-urban working class, is a case where internal conflict was brought to world attention, with adverse influences on popular perception of the justice in global climate action. With a view to such interactions Sovacool (2017) sees energy justice and recognition as one of the main sociotechnical challenges for the Nordic decarbonization.

System perspective and hydrogen strategies in frontrunner countries

While limited 'energy literacy' (Sovacool, 2017) has been a challenge and the public debate around renewable energy may sigger from outdated perceptions regarding its competitiveness (IRENA, 2017), it has also been suggested that the understanding of environmental challenges has seen a shift, from addressing individual issues based on cause-effect principles, towards systems and systemic causes (EEA, 2017). This tendency is also reflected in national hydrogen strategies, which increasingly take a holistic approach (Staffell et al., 2019).

Among the frontrunners, Japan's *Basic Hydrogen Strategy* of 2017 reiterates the country's commitment to pioneer the world's first "Hydrogen Society" (Nagashima, 2018). It aims to arrive at commercial-scale supply chains by 2030, with an annual procurement of around 300 000 tons (amounting to 1 GW of power), in future increasing to 5-10 mill tons (15-30 GW). Other specific targets are to have 800 000 vehicles and 900 hydrogen refuelling stations by 2030. Japan's strategy has global implications, especially since it involves international partnerships on fossil-fuel based production of hydrogen and thereby relies on CCS. Renewable energy expansion and regional revitalization are also stated aims. Here, the ambition is to develop power-to-gas technology to cut the unit cost for water electrolysis to 50 000 yen/kWh by 2020, and to commercialize power-to-gas systems by 2032. Also, of interest with respect to volumes and potential for hydrogen produced in Norway, Japan aims to demonstrate a liquefied hydrogen supply chain by the mid-2020s.[64]

South Korea launched their roadmap to become a world leader in hydrogen in January 2019.[65] This includes goals of producing 6.2 million FCEVs and building 1200 HRS by 2040. There shall also be a supply of 15 GW of fuel cells for power generation by 2040, covering the energy demand of 940 000 households. The total annual supply of hydrogen will reach 5 260 000 tons. An "overseas production base" is foreseen, to stabilize production, import, supply and demand. A special purpose company called HyNet will lead the construction of hydrogen charging infrastructure. HyNet consists of 13 companies, national and international – including NEL.[66] HyNet's objective is to build 100 HRS by 2022, using initial investments by Hyundai and Korea Gas Corp. and state subsidies of 1.5 billion won for each station.[67] There will also be systematic efforts to cultivate small and medium-sized enterprises.

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[63] https://www.atlanticcouncil.org/blogs/energysource/gas-directive-red-commissars-in-charge-of-the-eu-gas-market

[64] https://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf

[65] http://english.hani.co.kr/arti/english_edition/e_business/879097.html

[66] https://nelhydrogen.com/press-release/press-release-nel-joins-hynet-aiming-to-establish-100-hydrogen-fueling-stations-in-south-korea-by-2022/

[67] https://fuelcellsworks.com/news/south-korean-government-launches-company-to-grow-its-hydrogen-fuel-cell-vehicle-infrastructure/

In China, hydrogen is part of the “Made in China 2025”, as well as in the “13th Five-Year Plan” from 2016. Specific aims are to have more than 100 HRS by 2020, and more than 1000 HRS with more than 50% renewable hydrogen by 2030. Within the latter timeframe, the aim is to have 1 million+ fuel cell electric vehicles in service (Li 2018). In 2018, the fiscal subsidy policies for new energy vehicles were adjusted in favour of FCEVs. Large state-owned enterprises in the energy production and industry sectors jointly established the China Hydrogen Alliance (Verheul, 2019). Until 2025 hydrogen will be generated from both fossil and renewable sources. By 2020 the goal is to have a distributed hydrogen production system with locally produced hydrogen (via onsite electrolysis) at refuelling stations. Liquid hydrogen transport is also expected but will require regulatory changes (Verheul, 2019).

The US Department of Energy (DOE) established a hydrogen vision in 2001, driven by the desire to decrease dependence on foreign oil and reduce the environmental impact of the transportation sector. A $1.2 billion initiative to promote a hydrogen economy was announced by the second Bush regime in 2003. The *Energy Policy Act* of 2005 calls for a wide-reaching research and development program. The ambition was lowered with Obama's 'all-of-the-above' energy strategy, but a substantial effort has been continued under the Hydrogen and Fuel Cells Program. The focus has been on the transport sector, but in 2018 the primary efforts were in H2@Scale, an initiative to advance affordable hydrogen solutions and increase impact in multiple energy sectors. Its premise is that hydrogen can be generated and used in various industries by leveraging low-cost intermittent sources of energy (such as solar or wind) as well as baseload power (DOE, 2018). There are federal incentives and laws regarding hydrogen in the transportation sector, and several states also incentivise hydrogen stationary power technologies. In California, 94 refuelling stations are anticipated by the end of 2023, and it is an aim to have 200 stations by 2025. The California Fuel Cell Partnership, an industry-government collaboration, targets 1 million FCEVs and 1 000 HRS by 2030 (CAFCP, 2018).

With the Commission’s Clean Energy and Mobility Plans, the EU aims for decarbonised, fully integrated energy and transport systems where hydrogen will have a key role to play. The deployment of FCEVs will also be achieved through green public procurement and new incentives and CO_2 emissions standards for cars, light and heavy-duty vehicles as well as increased refuelling infrastructure through the *Connecting Europe Facility* and its related Trans-European Networks. Moreover, Germany has an ambitious *National Innovation Program for Hydrogen and Fuel Cell Technologies (NIP)*. In the first phase the target was on market preparation of respective technologies. The present phase (2016-2026) is focused on (i) continued R&D to further reduce costs and (ii) market activation. Via H_2 Mobility Germany, the aim is to arrive at 400 HRS already by 2020 (Staffell, 2019). Development of hydrogen production based on renewable power (electrolysis), incentive programs for fuel cell vehicles (especially rail and busses) and green logistics (fuel cell applications at production sites, airports etc.) are other focus areas. In July 2019, the federal government further announced the forthcoming opening of about twenty “real laboratories”, which will test integrated systems of hydrogen applications on an industrial scale and be funded up to 100 million euro per year.[68]

In France, the “plan Hydrogène” has a budget of 100 million euro from 2019 and a strong focus on transition in the transport sector, but targets industry and the energy market as well.[69] 100 hydrogen filling stations are to be installed within 2023, and by 2028, the number of hydrogen refuelling stations shall increase to between 400 and 1,000. By 2028, the ambition is to have 20,000 – 50,000 light commercial vehicles and between 800 and 2,000 heavy-duty trucks.[70] A parliamentary mission is to look into the feasibility of hydrogen trains, France also wants to instil hydrogen in the industry, aiming for 10% by 2023 and 20-40% by 2028.

In other words, integrated and quite ambitious hydrogen strategies are being implemented. Other countries, such as Denmark and the Netherlands are also well advanced, but on the other hand only 14 member states

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[68] https://fuelcellsworks.com/news/germany-100-million-euros-per-year-for-hydrogen-research/ , accessed 20.08.2019.
[69] https://www.gasworld.com/french-minister-unveils-100m-hydrogen-plan/2014840.article
[70] https://www.electrive.com/2018/06/04/france-to-utilise-hydrogen-across-all-sectors/

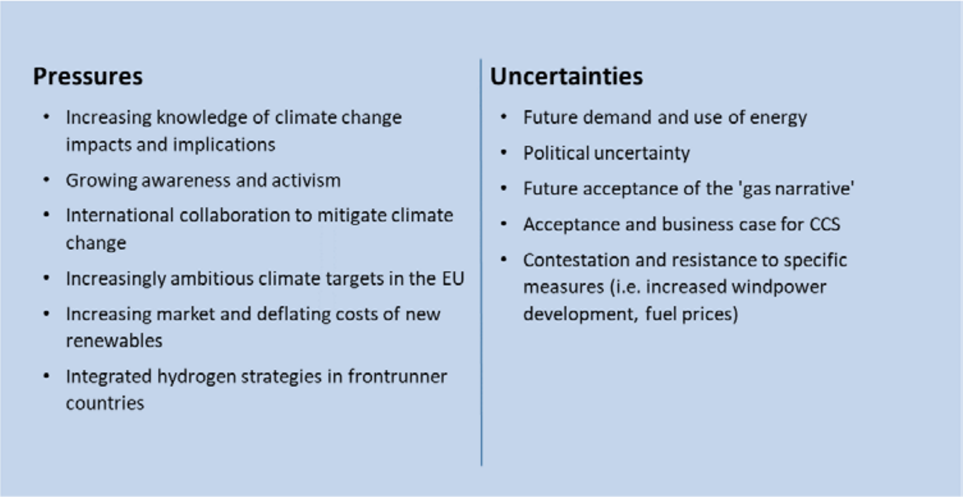
have so far included hydrogen in their national plans for alternative fuels infrastructure. For hydrogen's potential role in energy transition to be realised, the fuel cells and hydrogen joint undertaking argues that a joint rollout of solutions is required (FCH-JU, 2019). The development of a national hydrogen strategy for Norway will be important in this context.

Main pressures and uncertainties

This section discussed a number of development and trends in the wider socio-technical landscape around hydrogen. Increasing knowledge about the causes, impacts and implications of climate change, as well as growing awareness and activism are factors exerting pressure on the regime of established energy solutions. Increasingly ambitious climate and energy policies, especially in the EU, are also challenging the actors, institutions and practices in the current energy system, to move beyond incremental change and implement radically new solutions. The increasing market for new renewables, and especially the cost deflation for wind and solar power in recent years, is driving a development towards an increasingly integrated power system, where hydrogen may provide needed flexibility services and enable sector-coupling for optimal use of available energy resources. The ambitious national hydrogen strategies in European as well as non-European frontrunner countries is another factor that will shape the future market for hydrogen produced in Norway, both nationally and internationally.

We also find considerable uncertainties, both regarding the timing and share of hydrogen in future energy scenarios, and regarding the energy policies and climate targets of important countries, both globally and within the EU, where different member states are in different energy situations. Different priorities and contested realities within states cause uncertainty regarding the availability of cheap energy and acceptance for hydrogen solutions in the coming years. The so-called gas narrative emphasizes the need for natural gas to replace heavier fossil fuels,and may in this sense be associated with institutional lock-ins, linked to differentiation of power and institutional learning effects (Klitkou et al., 2015). Its strength and direction in the coming years will also influence the scope for hydrogen production, especially when it comes to natural gas reforming with CCS.

The main pressures and uncertainties are highlighted below, in Figure 32.



Pressures

- Increasing knowledge of climate change impacts and implications
- Growing awareness and activism
- International collaboration to mitigate climate change
- Increasingly ambitious climate targets in the EU
- Increasing market and deflating costs of new renewables
- Integrated hydrogen strategies in frontrunner countries

Uncertainties

- Future demand and use of energy
- Political uncertainty
- Future acceptance of the 'gas narrative'
- Acceptance and business case for CCS
- Contestation and resistance to specific measures (i.e. increased windpower development, fuel prices)

Figure 32: External pressures and uncertainties influencing the transition potential associated with largescale production of hydrogen in Norway.

6.2 National regime developments

Due to the rich natural basis for hydropower, Norway has been able to benefit from low electricity prices. The industry development since the early 1900s, the electricity market and society as a whole have for a large part been built around hydropower. Electricity production is higher than in most other countries, and electricity has become the naturally chosen energy source. On the other hand, the development of the petroleum sector transformed Norway into an international energy nation. Currently, around 16% of Norway's GDP and 40% of its exports stem from the petroleum sector, excluding the service and supply industry (Norwegian Petroleum, 2019).

Two forces in Norwegian energy politics

Moe (2015) argues that the two streams of activity linked to different energy resources are associated with two dominant forces in Norwegian energy politics, one focused on hydropower and electrification, and the other on the petroleum-based industry. Beside specific arguments, the two are associated with vested interests, related to the huge investments made in each sector and the institutions that sustain the activities. A recent study on non-economic barriers to hydrogen, based on an expert survey across Europe, found that Norway's economic dependency on oil and gas has led to a situation where governmental ministries have different approaches: the Ministry of Finance does not challenge the petroleum-oriented income and revenue, while the Ministry of Climate and Environment is trying to frame a reality outside the petroleum economy. The Ministry of Petroleum and Energy and the Ministry of Transport and Communications are also focused on different topics, and according to the experts interviewed this results in a general lack of inter-ministerial common understanding (Garcia, 2017).

In a transition perspective one may argue that the two forces are associated with various lock-in effects (Klitkou et al., 2015), that can make it difficult for radically new perspectives and energy solutions to enter. The institutions are associated with institutional learning effects, both in the way that mandates, organizations, and procedures make them complex and difficult to change, and by way of cognitive routines and mindsets that "blind" actors to developments outside their focus (Nelson and Winter, 1982). It may, for example, be argued that the centralised system based on hydropower up to recently made for a strong focus on cable connections to make Norway a "green battery" for Europe, which limited the attention to new renewables and more distributed solutions. On the other hand, the early focus on CCS, failed "moon landing"[71] and current effort to establish a full-scale value chain for CCS may be associated with technological interrelatedness, network externalities and institutional lock-ins linked to fossil fuels. Though it sees carbon capture as part of a broader mix of technologies that could lead to carbon neutrality, the EU has taken a more cautious stance on CCS.

Weak coupling between climate and energy policy?

The *2008 Climate Accord (St. meld. Nr 24 (2006-2007*) laid down a target of 20% GHG emission reduction by 2020 and specified that 2/3 of the reductions should be within Norwegian territory. It also defined basic principles in Norwegian climate policy; the precautionary principle, polluter pays, emphasis on general instruments, and aiming towards significant emission reductions both home and abroad. The *2012 Climate Accord* (*Meld. St. 21 (2011–2012)*) focused on measures such as increasing the national Climate and Technology Fund, prohibition of fossil fuel for building heating, incentives for zero-emission cars, increased support for collective transport and future increase of funding for research on environment-friendly energy. An important reference was the *"Klimakur 2020"* (Climate Cure 2020) national assessment of measures to reduce greenhouse gas emissions. Based on sector-by-sector assessments, the synthesis report from the assessment identified a total of 160 measures, which could realize a total of around 22 Mt CO_2e by the target year 2020 (Klima- og Forurensningsdirektoratet, 2010).

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[71] Project to establish a pioneering carbon capture and storage (CCS) at the Mongstad refinery, which was referred to as Norway's 'moon landing' by the Prime Minister in 2007, but abandoned in 2013 after escalating cost overruns and delays.

Klimakur 2020 identified a set of four 'menus' of instruments emphasizing different concerns, such as cost efficiency and stimulating the adoption of measures, protecting domestic industry, and achieving long-term learning effects. It was followed by a GAP-analysis consisting of 3 reports from the Norwegian Environment Agency, to further assess measures and possible trajectories towards a low-emission society in 2050. The reports underscore the technical, administrative and economic challenges associated with a 60-80% reduction of GHG emissions. Hydrogen is included as a measure that may gain increasing relevance for road transport towards 2050, but not quantified. The second report, on trajectories towards 2050, warns against carbon lock-in and foresees a big increase in bioenergy, while recognizing that this may be associated with dilemmas. Furthermore, it points out that new demonstrations, of low-emission solutions for transport or CCS, will provide increased knowledge of the challenges. The third report, on measures and trajectories towards 2030, emphasizes the need to apply stronger policy instruments (Norwegian Environment Agency, 2014b).[72]

With the *New emission commitment for Norway for 2030 – towards joint fulfilment with the EU (Meld.St-13, 2014-2015)*, the present priority areas in Norwegian climate policy were defined. As noted above, these include reduction of emissions from the transport sector, low-emission technologies for the industry, CCS, strengthen Norway's role as supplier of renewable energy, and environment-friendly shipping. These are also laid down in the *Climate Act (LOV 2017-06-16 nr 60*), together with the overall emission reduction targets.

The *White paper on energy (Meld.St. 25 (2015-2016)* builds on the premise that energy supply in Norway shall be effective and environment friendly. There is a strong emphasis on hydropower as the "backbone" of the Norwegian energy system. Market-based development of the transmission and distribution network, with new technology and market solutions to strengthen Nordic collaboration and ensure reliability of supply, is emphasized. Continued support for long-term development of wind power and technologies for new renewable energy are mentioned, but not clearly specified. Hydropower is also in focus as regards enterprise development, where new options for energy-intensive industry are highlighted. More efficient and climate-friendly use of energy is mainly associated with electrification and increased budget allocations to Enova, with a mandate that includes hydrogen and an increasing orientation towards new solutions. In addition, specific strategies for CCS and hydrogen will be developed. Norway's role as oil and gas producer is not discussed. The white paper contains few targets and measures to reduce climate gas emissions. It has been criticised for not discussing future out-phasing of oil and gas, and according to key stakeholders it shows that a clear connection between Norwegian energy and climate policy is lacking (Damman et al., 2016).

The latter may, in part, be seen as a result of the above-mentioned lock-ins. It may also be related to the wider politico-economic set-up. Arguably, Norway is characterized by consensus-seeking and partnership-based policymaking arrangements, which tend to facilitate long-term policy planning and coordination, but may impede deeper reforms (Ćetkovic and Skjærseth, 2019). With a strong petroleum sector corporate influence and tight and consensus-seeking policymaking this seems to work in favour of incremental niche support rather than ´creative destruction´ elements in the climate policy mix. Norway has continued to rely on carbon-tax as a key control policy, to increase environmental efficiency and stimulate incremental innovations in the oil and gas companies (Ćetkovic and Skjærseth, 2019).

Hydrogen for climate change abatement and/or value creation?

The combination of a hydropower and a petroleum-related power factor has also shaped Norway's engagement in international collaboration on hydrogen. Other countries, notably Japan and the US, were initially motivated by energy security concerns and business opportunities for the automotive industry, but these were not major issues for Norwegian stakeholders. When a national expert group was set up to assess the potential of hydrogen

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[72] The reports will be followed by a "Klimakur 2030", due in December 2019.

as future energy carrier in 2003, their mandate emphasized the need to find a more sustainable way to exploit Norway's natural gas, as well as the potential for decarbonization of the transport sector (NOU, 2004). The expert group recommended a research and development program, whose key elements were realized through the initial hydrogen strategy for Norway, of 2005. Their report further led to the establishment of the Hydrogen Council (Hydrogenrådet), which suggested that hydrogen produced in Norway should cover a substantial share of EU's demand in 2020, and that efforts to facilitate deployment should be at the same level as in EU (Hydrogenrådet, 2006).

Thus, the effort in Norway has been associated with multiple objectives, and especially with the future exploitation of natural gas, since its beginning. While most were strongly positive, two of the stakeholders interviewed for the present study discussed whether hydrogen as energy carrier really is a climate abatement measure, or better seen as a value-creation opportunity to aid industrial transition in Norway. Both were somewhat sceptical about the energy efficiency of hydrogen and overall sustainability of blue hydrogen with CCS. The disparity in views on this may be related to another tension; as to whether the focus should be on domestic emission reductions, or on how Norway best can contribute to reducing global emissions. This is underlying several ongoing controversies that potentially may influence the future role for hydrogen, such as the pronounced resistance to wind farms in communities that see more disadvantages than benefits locally, and the harsh debates about road toll increases that threatened to bring the government down in 2019.

Regional initiatives and new national engagement

As noted above, Norway's energy strategy aims for a market-based development where hydropower and wind are the major energy resources. A large increase in wind power is projected. The map below provides an overview of present, planned and proposed wind projects.

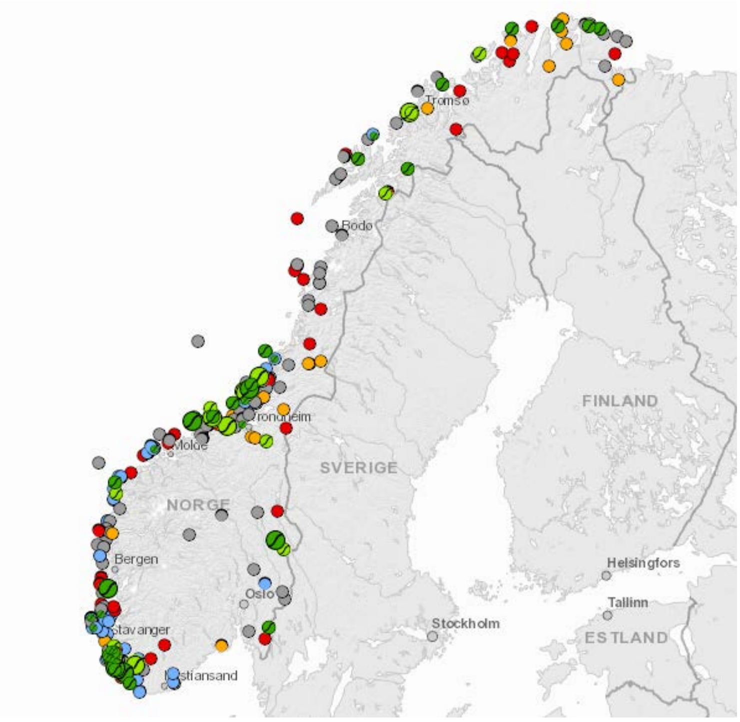

Figure 33: Wind farms – already built (dark green), approved or under construction (light green), proposed/in permitting process (orange), rejected (red), licenced (blue) planning completed (grey). Node size reflecting capacity; largest > 100 MW (NVE interactive map, accessed September 2019).

There is great potential for increased wind power generation capacity at both the European and national level ((Enevoldsen et al., 2019; NVE, 2018). The NETP (2016) predicts an onshore wind power capacity in Norway of 11 TW in 2050. In the fourth quarter of 2019 the capacity was 2 440 MW.[73] In Europe the total expected wind power generation capacity by 2050 is 400 TW, with 80% placed on shore (NETP, 2016). Concessions amounting 7 GW have already been granted,[74] but there is considerable uncertainty as to how much capacity that will be developed. Norway has a high share of adjustable hydropower. However, the expected development of intermittent renewable energy, together with extensive electrification, may lead to a more complex and distributed system, with more roles for hydrogen especially at the regional and local level, to even out geographical imbalances and reduce bottlenecks, thereby contributing to stable power supply and reduced need for grid expansion.

Currently, hydrogen is seen as promising, but still relatively immature for many applications, and as a "second alternative", for sectors, regions and applications where electrification is difficult. Although the present Minister for Climate and Environment has been an optimistic promoter, support from the national level has mainly been for research and development, through the Research Council of Norway (RCN) and the EU system. As we have seen, Enova also plays an increasingly important role. In 2018, Enova committed around 2.1 billion NOK to direct support for energy and climate projects. Only 3% of this was awarded to hydrogen projects; for infrastructure (currently limited to a maximum of 3 per year), hydrogen buses, and one research project. However, in June 2019, the Ministry for Climate and Environment required that Enova shall establish a special *Zero Emission Fund for business transport*, with 1 billion NOK for allocation to climate-friendly vehicles, including FCEVs, before the end 2020.

The *Pilot-E* scheme provided by Enova, the Research Council of Norway and Innovation Norway for largescale development and implementation of environment-friendly technology has so far given high priority. In 2019, a total funding of around 120 mill NOK was awarded, with holistic value chains for hydrogen as a priority area. Other important facilities are *KLIMASATS*, for local and regional authorities, and the *Chart for green coastal traffic (Grønt Kystfartsprogram)*, a forum for co-creation of knowledge and innovative solutions in the maritime industry. The *Environmental technology scheme* targets companies in all sectors with the aim to stimulate innovation and reduce financial risk associated with promising solutions at an early stage of development (TRL 5-7), the *Support for climate and environmentally friendly shipping*, and the so-called *NOx Fund* to reduce emissions from industry.[75]

Regional and local authorities have been more active in promoting hydrogen solutions. Counties, and also municipalities, face increasing expectations when it comes to climate action and emission reductions, and in many cases some of the largest and most low-hanging fruits for this are in zero- and low-emission transport. The possible co-benefits of hydrogen in terms of value-creation, regional development and reduced local air pollution, may also be of influence. Oslo and Akershus have been important facilitators for a long time, while Sogn og Fjordane, Møre og Romsdal and Trøndelag have become more active recently, with the increasing focus on maritime applications. As we have seen, there is also increasing engagement by counties which see a regional development potential linked to exploitation of a renewable power surplus, such as Finnmark and Nordland. On the other hand, Rogaland, and Stavanger, which has official recognition as the oil capital of Norway, have been slower movers.

While regional support initially was centred on road transport and facilitation of hydrogen refuelling stations, green public procurement and innovation contracts for public tendered ferry and passenger vessels (Bjerkan et al., 2019), cluster development and local/regional fleet collaboration and, as we have seen, public-private

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[73] NVE quarterly report. https://www.nve.no/media/9095/q4_2019.pdf

[74] NVE licence statistics. https://www.nve.no/konsesjonssaker/

[75] Enterprises may join by making payments per kg NOx emitted, at a lower rate than the national NOx-tax. Support is paid back to the industry through the NOx Fund's support scheme.

partnerships in form of local development companies, play an increasingly important role. Akershus county has also established a support scheme for HRS operation.

Need to develop policy and regulatory frameworks

Considering the ups and downs in the short history of hydrogen in Norway, together with the regional variation and financial risk involved in the establishment of infrastructure, the need for national coordination and more predictable framework conditions was emphasized by the interviewed stakeholders. The anticipated national hydrogen strategy will be crucial. *The Government's action plan for green shipping* is also an important part of the picture. The plan confirms Norway's intentions to push for further climate action in the International Maritime Organization (IMO). Moreover, zero emission requirements for both offshore supply and aquaculture service vessels, as well as a new support scheme for renewal of cargo ships will be considered. A green advantage system linked to the NIS and NOR shipping registers will be established (Norwegian Government, 2019a). There are also signals of increased support for greener shipping through Enova. The importance of continued testing, knowledge sharing and reducing barriers through application in the coastal ferry segment is emphasized. There are no specific targets, except reference to the coming integrated hydrogen strategy, which also will include maritime applications.

The *National plan for infrastructure for alternative fuels in transport* has a strong focus on electrical charging infrastructure. For "immature technologies", including hydrogen, the emphasis will be placed on support for development of vehicles and vessels. Pilots integrating vehicle and infrastructure testing are encouraged. This would be for heavy duty vehicles, since there is no need to test already commercially available cars. While the industry has signaled that an initial network of at least 20 HRS is needed, hydrogen for cars and trucks is classified as "technology where infrastructure development in Norway will have limited impact on the technology development" which is best developed step-wise in accordance with the pace in technology development and vehicle production volumes (Norwegian Government, 2019b). Enova's support scheme for HRS will be continued but may be adjusted, and it is signaled that stations for heavy vehicles may get more focus. When it comes to hydrogen bunkering for ships, Norway will take a lead role in developing a regulatory framework to ensure smooth and safe operations. Again, the reader is referred to the coming hydrogen strategy for further details. While disappointing for the industry, which has argued that adequate infrastructure is an important prerequisite for market uptake of hydrogen cars, the two plans suggest a stronger effort to promote hydrogen for transport applications.

The national plans also note that there are important legal-administrative challenges. The lack of specific regulations for design type approval for hydrogen ships is identified as a main barrier (Damman et al., 2019), which Norway and other members currently are working to address through the IMO. Legal-administrative procedures for bunkering facilities must also be defined. When it comes to hydrogen refueling stations, regulatory frameworks and procedures are in place, but according to the operators the way permitting processes and requirements are handled varies significantly between municipalities and may in some cases involve unnecessary and costly delays. As to hydrogen production, some of the interviewed stakeholders mentioned that electrolysis is defined as a "mature technology". Several interviewees held the opinion that support for green as well as blue hydrogen should be considered. For integrated wind-hydrogen systems, there is no established framework as of yet, and for several applications technology qualification and standardization issues remain. Regulatory challenges are also noted when it comes to exporting and injecting hydrogen into European gas grids. While the dialogue with relevant authorities in Norway is good, areas where there is need for international harmonization tend to be more challenging (Floristean et al., 2019).

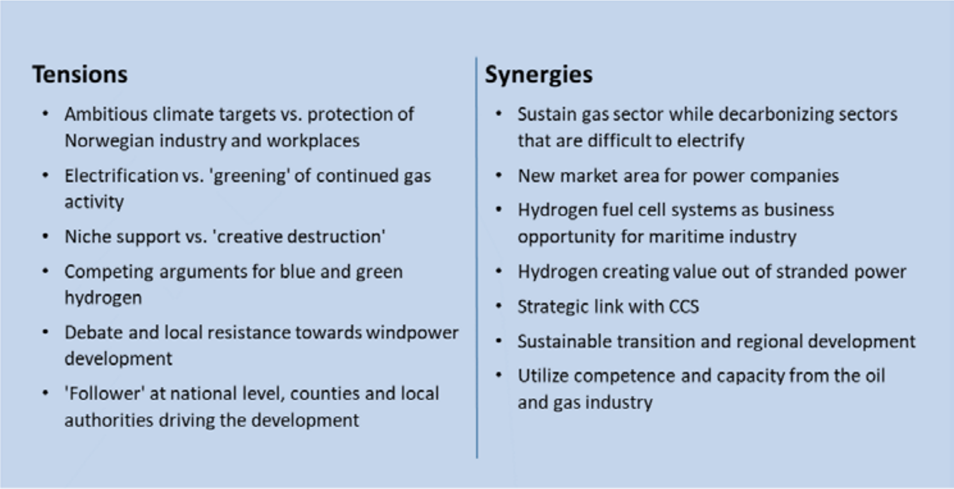
Key tensions and synergies

This section has thrown light on certain tensions at regime level, that influence the scope for hydrogen production in Norway. Hydropower and the offshore oil and gas industry are main pillars in Norwegian economy and society. Both have infrastructures and supply chains at regional, national and international level, that are associated with economic, technological and institutional lock-in mechanisms, which amongst other have positioned Norway well for a new ocean economy and made us a frontrunner when it comes to electrification and battery-electric solutions for the transport sector.

Drawing on previous research as well as own findings, we have argued that the two sectors are associated with institutions and learning effects that are complex, deep-seated and difficult to change. This seems to have influenced national energy and climate policies, in that the former emphasizes hydropower and market-based development of new renewables, whereas the latter has been centered on development and implementation of innovative solutions, with less focus on constraining the petroleum sector. It has also influenced the national effort on hydrogen, where green and blue production have been associated with different fractions, whereas the drive for battery-electric solutions has been strong.

At the same time, the potential for new business in areas with abundant renewable energy sources and need for transition in areas dominated by petroleum-related activity has given rise to local/regional symbioses. Counties and municipalities have played an important role, but there has been a growing call for national coordination and in this sense also tension between different administrative levels. The increasing landscape pressures and emerging opportunities for largescale production and deployment of hydrogen, especially in heavy duty and maritime transport, but also for decarbonization of industry, require joint efforts and new forms of public-private collaboration. There is an increasing availability of support and risk-reduction mechanisms, as well as efforts to address regulatory gaps and develop new partnerships.

The noted tensions and synergies are summarized below, in Figure 34.



Tensions

- Ambitious climate targets vs. protection of Norwegian industry and workplaces
- Electrification vs. 'greening' of continued gas activity
- Niche support vs. 'creative destruction'
- Competing arguments for blue and green hydrogen
- Debate and local resistance towards windpower development
- 'Follower' at national level, counties and local authorities driving the development

Synergies

- Sustain gas sector while decarbonizing sectors that are difficult to electrify
- New market area for power companies
- Hydrogen fuel cell systems as business opportunity for maritime industry
- Hydrogen creating value out of stranded power
- Strategic link with CCS
- Sustainable transition and regional development
- Utilize competence and capacity from the oil and gas industry

Figure 34: Tensions and synergies in the national regime that influence the scope for hydrogen production.

6.3 From niche to industry?

As noted in chapter 4, there have been ups and downs in the history of hydrogen as energy carrier. This can for a large part be related to developments in a wider social landscape, such as the 2008-2009 financial crisis and the rapid development in renewable energy in recent years. Another key influence is the Paris Agreement, which was followed by political measures that have increased the pressure and opportunities for development of sustainable hydrogen solutions, both nationally and internationally. The number and kind of actors engaged in the Norwegian hydrogen business have also changed. In 2006, OECD identified a small network dominated by researchers/consultants and a few large corporations who explored new energy options in R&D projects that were peripheral to their core activities. They assessed the hydrogen sector in Norway as rather weak and dominated by a few large companies already active in petroleum and electricity, as illustrated in Figure 35 below:

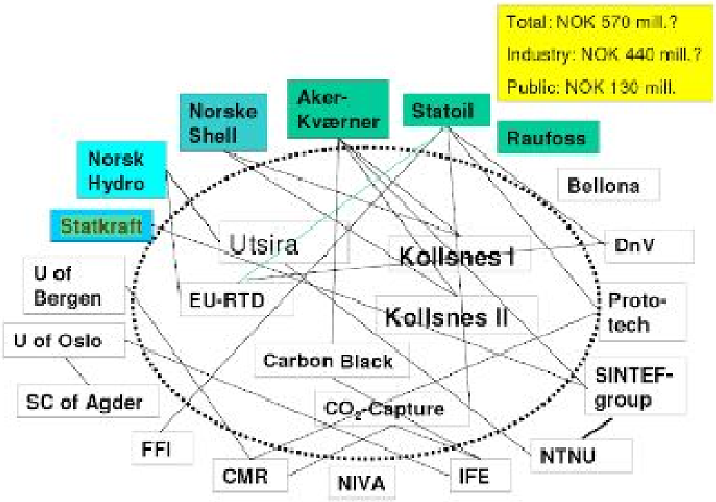


Figure 35: Actors and R&D activities in hydrogen technology in Norway, 2003 (OECD 2006:12).

The actors marked in shades of green are incumbent industry actors. The other actors on the outside of the marked circle are universities, research institutions and one non-governmental organization with a focus on environment and energy issues (Bellona). The boxes inside the circle refer to joint R&D efforts, including the Utsira and Kollsnes projects mentioned in chapter 5.1.

Compared to the innovation systems for hydrogen and fuel cells in other countries, the system in Norway was atypical, in that it lacked small and medium-sized enterprises (SMEs), and was without an automotive industry to stimulate the interest in fuel cell vehicles. The field was seen as rather immature, due to four main factors:

- Long timeframe for payback through commercialization of fuel cells
- Paucity of public or private venture capital
- Fragmentation and rivalry within the industry
- Rapid progress abroad, limiting the interest of policy makers and the general public

These were associated with a form of 'decoupling', i.e. lack of a coherent, unified national strategy that all actors may relate to.

By 2019, the number of actors has expanded. The membership of the Norwegian Hydrogen Association counted 29 industry actors, 6 knowledge institutions, and 12 others, including public offices and environmental organizations.[76] The interviews for the study at hand pointed to at least 23 additional companies, who play key roles in the industry. The total number of identified for the upstream value chain is listed below (Table 7). There are also a number of entities in the other categories, who do not participate in the Hydrogen Association, as well as early users, such as ASKO, Ruter, Boreal, Norled, Havyard, and TiZir, who contribute centrally to the promotion and uptake of hydrogen solutions.

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[76] According to the website of the Norwegian Hydrogen Association, October 2019.

Table 7: Key actors identified in this study.

Large incumbents	Major technology providers	Distributors and retailers	New entrants, spin-offs	Semi-public companies
Equinor Statkraft DNV GL Shell Aker Solutions Total Yara Kværner	NEL Hexagon Composites Ballard Umoe Reinertsen New Energy Ballard FMC Technip ITM Power PowerCell Wärtsilä Norway Fiskerstrand ABB Siemens Wilhelmsen	Nippon Gases AGA Linde Toyota Norway Hyundai Norway UnoX Hydrogen Aaby Auto Bilimportørenes landsforening Gasnor Ineos	Mem-tech Norsk H_2 PowUnit CerPoTech Agri-e Hystorsys HydrogenPro ZegPower Hyon Coorstek Membrane Sciences Greenstat CMR Prototech IFE Hynor Hydrogenisk	Energi Norge VarangerkraftHydrogen Nasjonalt Vindenergisenter Glomfjord Hydrogen Sogn and Fjordane Maritime Assoc. TrønderEnergi Sunnhordland Kraftlag

As the table shows, a much wider range of actors, across the whole value chain, are engaged now. THEMA (2019) found a total number of 77 actors in the upstream value chain. The majority of these – around 70% - were private business actors, but public actors, clusters or interest organizations, as well as research institutions are also included in their figure. Of the total, 33 were related to production, 7 to CCS, 4 to compression, 18 to transport and distribution, and 15 to storage of hydrogen. Downstream THEMA counted 57 actors, while noting that a significant number did not have hydrogen as their only or main activity. Sector-wise, these were distributed as follows (Table 8):

Table 8: Downstream actors identified by THEMA (2019).

Sector	Private actors	Public actors	R&D actors	Clusters/ associations
Maritime	12	1		2
Vehicles	9	2		3
HRS	8		2	1
Fuel cells	3		7	
Industry	5		1	
Subsea	1			
Aerospace			1	

The numbers are based on stakeholder interviews and dialogue with the Norwegian Hydrogen Association, and not necessarily accurate.

In 2019, consultants and researchers still play important roles, but a much higher number of actors is involved. Many of these are new entrants who specialize in hydrogen and fuel cell solutions, some are part of larger international enterprises, and some are stayers who have expanded their activity since the early 2000s. There is also a number of incumbents, who more or less pulled out with the demise of the hydrogen highway but now are back in.

On the other hand, several stakeholders noted a divide, between a set of actors focusing mainly on green hydrogen for road transport, and another group relating more to maritime, industry and the larger volumes associated with blue, as well as green hydrogen. This finding is in line with previous studies (Sovacool 2017, Enevoldsen et al., 2014) which note that stakeholders in Nordic hydrogen fuel cell research have been deeply divided over research pathways. It is also noted that efforts currently are scattered. There has been limited collaboration and a tendency that proponents of blue and green hydrogen down-talk the other alternative.

As we have seen, the ambition has also shifted: From the initial vision of a 'hydrogen' economy' with a strong focus on cars, to the vision of a renewable energy system, where hydrogen is part of a larger energy mix and may play several roles, not only in the EU, but also in a more flexible and distributed system in Norway.

With the changing context, the understanding of hydrogen as energy carrier has also developed. Hydrogen is no longer perceived as just an alternative fuel, but as a rather complex configuration of meaning, associated with other fussy constructions such as fuel cells, 'power-to-gas', and sector-coupling, in an increasingly complex and radically changed energy system. For many in the public, and even some decision-makers, the totality is difficult to grasp, making the benefits of hydrogen more difficult to 'sell'. At the same time, the association between hydrogen and high explosion risk is strong in the public mind. Some of the interviewed stakeholders felt that this has been exacerbated through earlier debate on the pros and cons of electrification vis-à-vis hydrogen. Some suggested that it is maintained by consultants, who overstate the need for research and assessments, rather than development of standards. On the other hand, the health and safety aspects were brought to the fore again with the 2019 HRS explosion. Public concerns regarding energy efficiency and overall sustainability may also be influenced by the tendency to present blue and green hydrogen, as well as hydrogen and battery-electric solutions, as competing alternatives.

Still, as noted in previous chapters, there is a growing momentum. Beside contextual changes, this has to do with technological advancement and commercial success. In 2018, NEL signed a mega-order for 448 electrolysers and refuelling equipment with Nikola, and a planned expansion of their electrolyser plant at Notodden will make it the largest in the world.[77] Hexagon is currently supplying tanks to three of the international car producers, as well as to the maritime market. They recently joined the prestigious Hydrogen Council and according to their own estimate, they will invest 400-600 million NOK the next five years.[78] There is also the success with maritime solutions, where especially shipyard Fiskerstrand has a central role, and with new membrane technology for natural gas reforming in Reinertsen New Energy and Mem-tech. The increased engagement by industry giants such as Equinor, Statkraft and Yara, and prospects such as that of H21 Northern England also generate further activity. It is also noteworthy that specific events and individual engagements matter: As noted in chapter 4, the enter by Spetalen was important, and in some of the production initiatives, the influence of a local entrepreneur or technology enthusiast is highlighted.

The increased funding opportunities have also been conducive. As we saw in chapter 4, this has stimulated most of the production initiatives. The formulation of more specific and ambitious climate targets across administrative levels and economic sectors has been a driver. Municipalities and counties have played a very

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[77] https://www.hydrogen.no/hva-skjer/aktuelt/nel-skriver-hydrogenhistorie-med-megaordre-til-nikola-motors

[78] https://aksjelive.e24.no/article/KvmEQE

active role in several of the studied production initiatives, as well as in building demand and supporting the development of hydrogen refuelling infrastructure.

At the same time, there are remaining technological challenges that need to be solved. As noted in chapter 5, liquefaction is a key, both when it comes to maritime application and for distribution of hydrogen across larger distances. CCS is a critical enabler for production of blue hydrogen. Transport of hydrogen in pipes, such as the existing pipelines from Norway to continental Europe, is another critical factor. Thus, the transition potential associated with large-scale production of hydrogen, and especially hydrogen based on natural gas reforming is contingent on continued technological development.

Niche actors are also working to address the above-mentioned legal-administrative challenges. Some of the key players take part in national and international standardization committees, and several of the larger research and development projects, such as HAEOLUS at Raggovidda, engage both private and public partners in order to address regulatory gaps and challenges. The recent years has also seen the establishment of larger centres for research and development collaboration, such as the national centre for Mobility Zero-emission Energy Systems (MoZEES) and the Norwegian Fuel Cell and Hydrogen Centre, which aims to stimulate innovation along the whole fuel cell and hydrogen value chain.

Several of the interviewed stakeholders commended the Norwegian Hydrogen Association for their efforts to coordinate. Still, many emphasized the need for more collaboration across projects and regions. In two of the attended workshops, several participants noted that proponents of blue and green hydrogen must work together and emphasize complementarity. They also called for joint efforts to develop a larger 'showcase' that may put an end to the 'chicken or the egg dilemma'.

According to Geels and Schot (2007), a fully developed niche innovation may be defined according to four indicators/proxies:

a) Learning processes have stabilized in a dominant design
b) Powerful actors have joined the support network
c) Price/performance improvements have increased and there are strong expectations of future improvement
d) The innovation is used in market niches, which cumulatively amount to more than 5% market share

The he initial phase of development of hydrogen as energy carrier in Norway did not have any dominant learning design, by way of an external learning environment. Powerful actors were on board, but the innovations had hardly reached the market. After the global financial downturn in 2008-2009, increasing price/performance improvements were expected. The investor Spetalen joined, politician Ola Elvestuen became an ardent spokesperson for hydrogen solutions, and the large incumbents became more active again. Since then, learning processes have stabilized in a design with relevant programs roles, common platforms, regular events, etc. Internationally, hydrogen fuel cell innovations are also increasingly applied in certain niches, as with forklifts and micro combined heat and power (CHP). For some applications we are "nearly there", as one stakeholder put it, but the niche innovation cannot be properly developed until there is a sizeable production and real demand in place.

In all, hydrogen has shifted from a predevelopment phase, when relatively immature technologies were explored by a limited circle of incumbents, researchers and technology providers, to a take-off phase where various technological options coexist, linked to different social networks with new entrants and partly diverging views and visions. As illustrated below (Figure 36) this is the result of increasing pressure from a landscape of exogenous factors, including complex interactions between renewables technology, global market and political developments, as well as increasing knowledge and awareness.

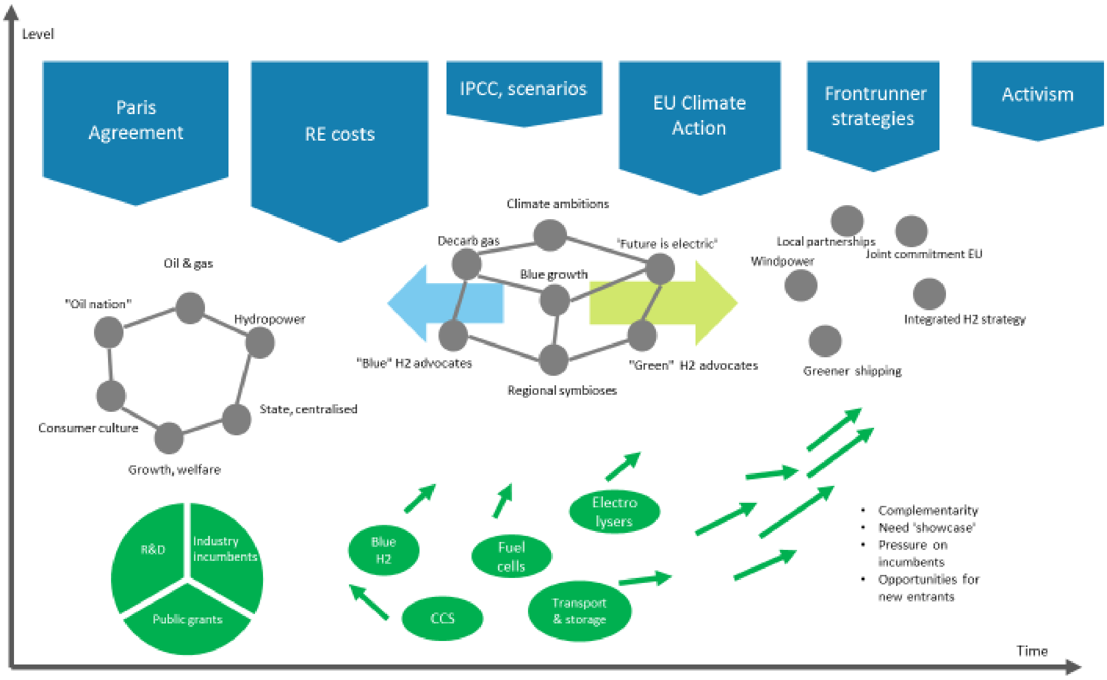

Figure 36: Multi-level perspective on the emerge of hydrogen in sustainable energy transition in Norway.

The trends at landscape level, in turn, have led to tensions in the national energy regime, which are linked to different scenarios, challenges and opportunities for the industry and power sectors, as well as differences in regional interest and priorities across administrative levels, and the cultural construction of national identity and more or less sustainable "blue" and "green" technology alternatives.

With the promising technological development, increasing investments and calls for collaboration and a common "showcase" at niche level it may be argued that we are nearing a critical tipping point. A tipping point is a phase in innovation uptake when the technology has matured enough to diffuse into a real market, mechanisms to communicate and promote it are in place, and enough mutual support is generated to enable a continuing process of propagation (Gladwell, 2000). While change up to now has taken relatively long, since sociotechnical systems are complex and multifaceted – we discussed the multitude of economic, technical and social drivers of barriers to hydrogen production and deployment in chapter 5 - the tipping point concept refers to a change of pace and/or course, towards achieving wider uptake and sustainable use of the technology with the shortest and most efficient route. We call it critical since there has been a gradual building of momentum, leading to the current point where there is the need for coordinated action to resolve the "chicken or the egg" dilemma and provide direction. The next steps from the national authorities, especially the forthcoming national integrated hydrogen strategy will be crucial to kick-start largescale hydrogen production. This point is also critical in the sense that action is needed now in order to progress towards the 2050 climate goals and reduce global warming.

7 Possible transition pathways

In this chapter, we use the findings from the preceding analysis to discuss the role of Norwegian hydrogen production in different energy scenarios for Norway towards 2050. Following a discussion of the concept of transition pathways, we present preliminary findings from the quantitative analyses in Norwegian Energy

Roadmap 2050, relating to two different energy scenarios. Each scenario is associated with a set of modelling results regarding the future role of hydrogen. We discuss these results in relation to the qualitative findings.

7.1 Types of transition pathways

The concept of transition pathways is widely applied in research and debate on sustainable energy transition. However, the interpretations and attributes of such pathways are rarely made explicit or subject to critical scrutiny. Rosenbloom (2017) carried out an analysis of existing written sources and identified three core conceptions:

1. ***Biophysical pathways*** – anchored within climate science and mapping of global emissions trajectories spanning diverse atmospheric stabilization levels and associated rates of temperature rise.

2. ***Techno-economic pathways*** – rooted in technology assessment and economics, understanding pathways as sequences of techno-economic adjustments linking current sector configurations to desirable low-carbon future states.

3. ***Socio-technical pathways*** – emerging from socio-technical transitions research, seeing pathways as unfolding socio-technical patterns of change.

A key point for Rosenbloom is that these are not mutually exclusive, but rather different perspectives that supplement each other. The multi-level perspective (Geels, 2004; Geels and Schot, 2007) understands socio-technical pathways as unfolding through different patterns of interaction among the niche, regime, and landscape levels.

Geels and Schot (2007) combine two criteria to distinguish between different types of transition pathways: The timing of landscape pressure on regimes in relation to the state of niche-developments, and the nature of interaction; if there are reinforcing relationships with the regime or disruptive relationships through pressure or competition. Combining the two dimensions gives four different pathways, plus the possibility of sequenced paths:

- ***P0 Reproduction***: no external pressure, regime remains dynamically stable.
- ***P1 Transformation:*** moderate pressure, niche innovations not sufficiently developed, regime actors may modify direction, cumulative adjustments.
- ***P2 Dealignment and realignment:*** landscape change divergent, large and sudden, but niche innovation not fully developed, regime actors lose faith in current regime, but there is no clear substitute. Multiple innovations compete for attention.
- ***P3 Technological substitution:*** High pressure, niche-innovation has developed sufficiently.
- ***P4 Reconfiguration***: symbiotic innovations developed at niche level are initially adopted in the regime to solve local problems. Subsequently triggering further adjustments.
- ***P5 Sequential pattern:*** landscape pressure in form of 'disruptive change' a sequence of transition pathways is likely

The pathways are non-deterministic ideal types. In the following section, we use this typology to present and discuss the scenarios and techno-economic pathways associated with the quantitative modelling in Norwegian Energy Roadmap 2050 up against our qualitative findings.

7.2 Hydrogen in model-based scenarios for Norway towards 2050

For the quantitative analyses, two scenarios were developed based on the assumptions that Norway shall reach its targets for reduction of GHG emissions in 2030 and 2050. . In addition, a reference scenario based on current trends was developed. All scenarios assume continued population growth in line with the projections by Statistics Norway. One of the low-emission scenarios, called the "Industry society" presumes continued growth and transformation in the industry, while the other, named the "Service society" replaces oil and gas with a growing service sector and behaviour change. The scenarios are further defined in Table 9, and elaborated in our Norwegian-language Energy Roadmap for Norway towards 2050 (Schäffer et al, 2020).

Table 9: Overarching scenario definitions, Norwegian Energy Roadmap 2050.

Reference scenario	**Industry society**	**Service society**
Industry - Energy demand as in 2015 incl. oil & gas production	Industry - Energy demand increasing in accordance with GDP growth excl. oil production and oil refineries	Industry - Energy demand as in 2015 excl. oil & gas production and oil refineries
Service – Energy demand is increasing with the population	Service – Energy demand growing in accordance with GDP growth	Sharp increase in energy demand from the service sector
No CCS	CCS	No CCS BIPV[79]
Transport demand as per National Transport Plan (NTP)[80]	Transport demand as per National Transport Plan	Person- and freight transport as pr. 2015, increase in public transport
Household energy demand following population growth, limited use of energy efficiency measures. Transport technology: Fossil fuels and green hydrogen	Household energy demand in accordance with population growth, emphasis on measures to increase energy efficiency. Transport technology: Battery-electric and hydrogen	Lower energy demand due to high consumer awareness, reduced consumption, high degree of urbanization. Transport technology: Battery-electric and biofuels

As more constraints are placed on the future size and structure of industries in order to reduce the greenhouse gas emissions, the model results show that GDP will be affected negatively. Both in the industry and service scenario, GDP in 2050 will be much lower than in the reference scenario, by 10 and 12% respectively.

"Industry society" scenario

REMES is solved for four time periods. 2007 is the benchmark year, and the model is further solved for the years 2020, 2036 and 2050. In order to meet the assumptions of a "green economy", the future size of some sectors of the Norwegian economy is constrained. In particular output constraints are applied to the size of fuels, oil refinery, coal and traditional natural gas production. New sectors are also introduced, to allow for new types of energy.[81]

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[79] BIPV: Building Integrated PhotoVoltaics.

[80] NTP: National Transport Plan 2018-2029.

[81] Appendix Table 1 shows the assumptions applied to the REMES model.

In the Industry society scenario, it is assumed that the oil sector is phased out and the gas sector is transformed into producing hydrogen with CCS.

In the model it is possible to produce hydrogen with steam reforming and electrolysis in 2020 and onwards. Hydrogen is allowed to be used either as energy inputs in the transport sector or exported to the foreign market. When CCS is considered alongside the utilization of natural gas, a 127% mark-up on the natural gas price is added.

Findings from the macroeconomic analyses using REMES suggest that hydrogen production has the potential to become an important industry in Norway towards 2050. The production technology of hydrogen with material inputs and inputs of capital and labour are based on data supported by the industry/reports (this information is not a part of data from Statistics Norway). Table 10 shows the different inputs to the production of hydrogen. There is a mix of use of natural gas and CCS (for steam reforming and blue hydrogen) and use of power production (for electrolysis). However, in 2050 natural gas and CCS are the dominating inputs of producing hydrogen in Norway.

The REMES models is solved at five regional levels in Norway, hence hydrogen output is analysed at the regional level. Hydrogen is produced by electrolysis in all regions, while hydrogen production by steam reforming of natural gas is present only in region 5 (western part (counties Vest-Agder and Rogaland) of Norway and the continental shelf).

Table 10: Inputs to production and total outputs of hydrogen in the Industry Society (million euro) in the REMES model

		2036	**2050**
Inputs of materials	Natural gas	1 136	5 859
	Carbon capture and storage (CCS)	3 636	21 903
	Electricity production	2 401	2 187
	Manufacturing	9	5
	Other services	361	1 769
	Labour	864	4 012
	Capital	5 515	26 073
Output	Total output of hydrogen	13 892	61 809

In the REMES analysis it is allowed for hydrogen to be used as energy inputs for all transport industries represented in the model. Figure 37 shows the energy inputs for land and sea transport. We see that hydrogen becomes more and more important as energy inputs towards 2050. In particular for sea transport, hydrogen will dominate as energy input.

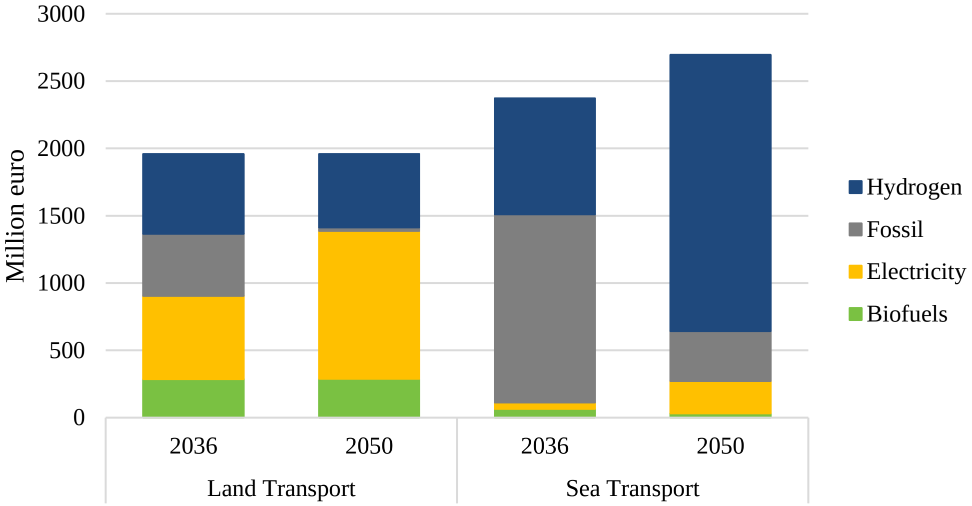

Figure 37: Energy inputs in the transport sector in 2035 and 2050 (million euro).

As shown in Figure 38, a large share of the hydrogen is exported to the foreign market. In 2050, about 96% of the product is exported, while the rest is sold to the domestic transport sector.

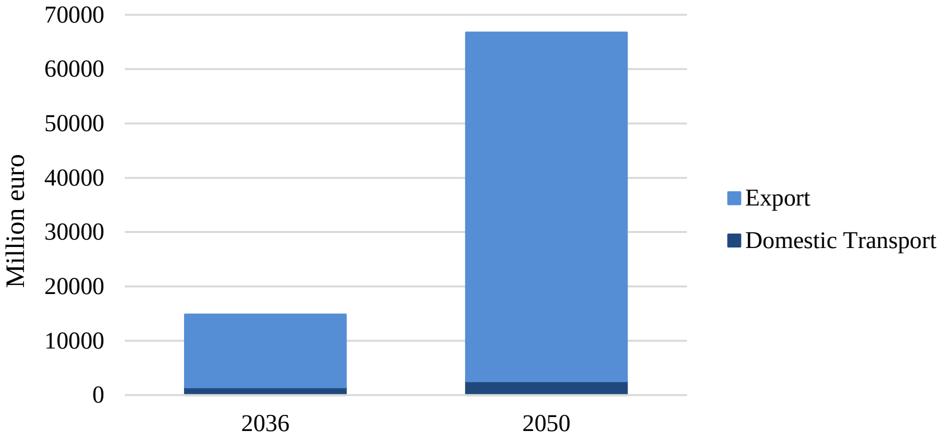

Figure 38: The share of domestic use and export of hydrogen in 2035 and 2050 (million euro).

Figure 39 shows the export mix of different products. The dominance of oil and gas in the Norwegian export mix is assumed to shrink in the model. In the base year 2007, oil and gas products have an export share of 38%. This share is reduced to below 1% in 2050. The estimated exports from hydrogen are high in the future export mix. In 2050 the hydrogen share in total exports is about 40%.

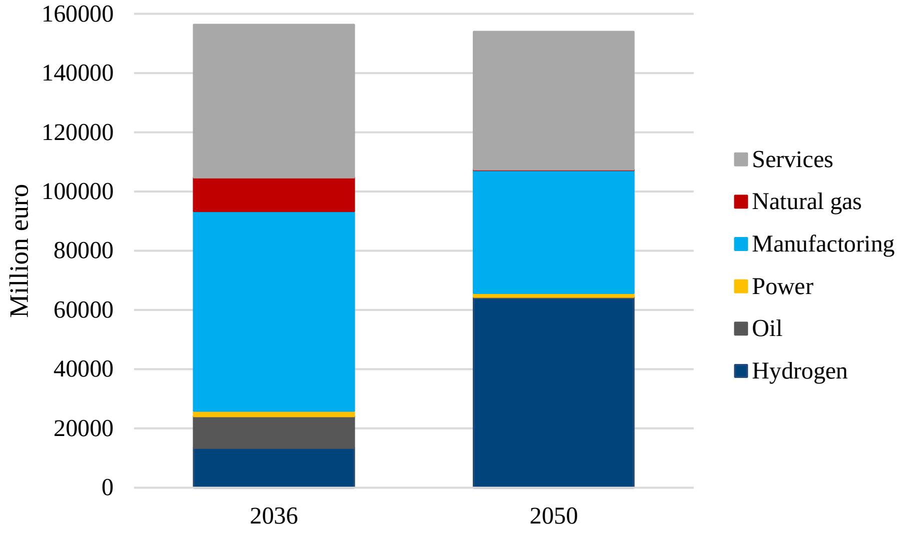

Figure 39: The share of export in the industry society scenario for year 2036 and 2050, in million euro.

In the analysis applying the TIMES-Norway model the industry scenario is based on a transformation of the oil and gas industry to production of blue hydrogen, with increased activities in all sectors and limited access to biofuels for transportation. It includes high technology development, particularly within hydrogen technologies, and one of the major assumptions is the availability of hydrogen from steam methane reforming (SMR) with CCS at a delivery price to customer of 1 NOK/kWh from 2025. A demand of 1/3 of used hydrogen for transportation to be produced from electrolysis was exogenously added to the model analyses, since it was not considered realistic that all parts of Norway could have access to hydrogen from SMR at the price assumed.

The analyses with TIMES-Norway result in a total domestic use of 26 TWh hydrogen in 2050 in the Industry Society, see Figure 40. Of this, 7 TWh or 27%, is used in industry and 19 TWh in the transport sector for de-carbonisation of these sectors. The electricity used for production of hydrogen by electrolysis is 19 TWh in 2050. An analysis without access to hydrogen from SMR, resulted in a hydrogen production of 21 TWh in 2050, and a considerable higher use of electricity, 32 TWh, since all the hydrogen then was produced by electrolyses.

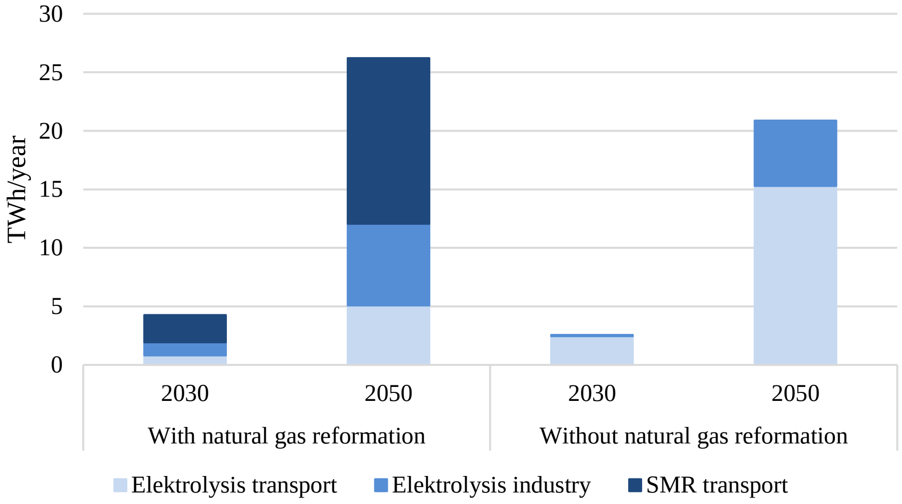

Figure 40: Hydrogen production by type for domestic use in the industry scenario analysed by TIMES-Norway, TWh hydrogen/year.

Within transportation, hydrogen has a high market share within heavy transport and sea transport, while all cars are battery electric vehicles in 2050, see Figure 41.

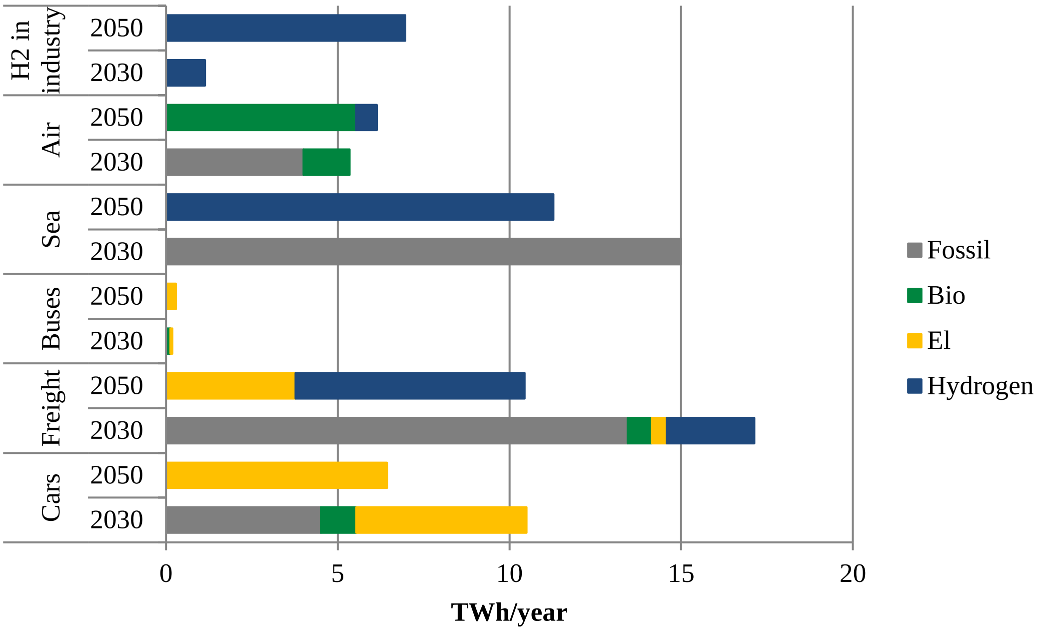

Figure 41: Energy use in the transport and industry sectors in the industry society scenario

The anticipated distribution of hydrogen consumption for the Industry Society in year 2030 and 2050 is depicted below, in Figure 42.

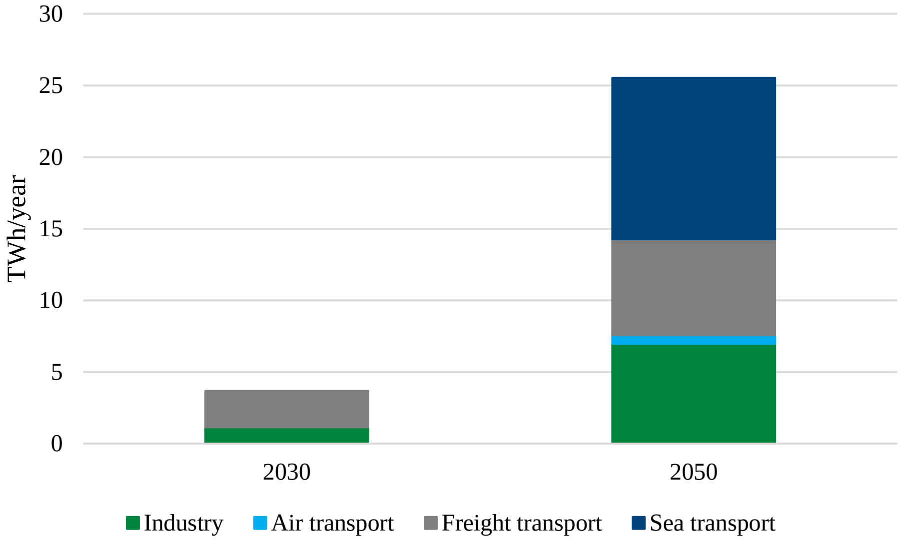

Figure 42:Hydrogen consumption in the industry society scenario for year 2030 and 2050.

The assumptions made for the Industry Society parallel the interactions associated with Geels and Schot's (2007) pathway type ***P3 Technological substitution***: There is a high pressure from landscape level, resulting in a decommissioning of the oil sector and forced, radical transition in the gas sector. This presupposes that niche innovations in the form of CCS and hydrogen technology for various applications, especially for transport, are mature enough to be implemented at the given points in time.

However, the qualitative study indicates that at its present pace, the full-scale CCS pilot under Gassnova will not enter operation until 2023/24. The very first pilot ferry will be launched in 2020/21, while the zero-emission passenger vessel under development in Trøndelag – which could be running on hydrogen – may be realised around the same time. Despite a strong optimism in the maritime sector, the other ongoing projects extend further in time. As noted in chapter 5, there is considerable uncertainty regarding storage and form of fuel, where the choice between compressed gas and liquefied hydrogen, as well as other alternatives and most notably ammonia have been brought in.

The Norwegian Hydrogen Association previously launched a vision of 1000 trucks 2023, but this may be difficult to realise, given the schedule of the truck producers, the anticipated demand in other countries and signals in the National plan for alternative fuels infrastructure, that the support for development of hydrogen refuelling stations will follow the development of demand. In industry there are two advanced projects, but as we have seen the timeline for TiZir is full-scale pilot within 2024, while Yara's full-scale pilot presently is scheduled to enter commercial production only by 2030.

When looking at the estimations of volumes of hydrogen that may be produced in Norway, we find considerable variation. While DNV GL (2019) sees a potential of 26 000 tons, or a little less than 1 TWh, in addition to the 220 000 tons already being produced for use in industry processes, Greenstat finds a potential of as much as 214 000 additional tons, or 7.1 TWh. The corresponding estimates, based on our mapping of production initiatives, are 43 950 tons, if only pilot implementation at Raggovidda is taken into account, and 61 200 tons, or around 2 TWh, with full-scale implementation of power-to-gas by VarangerKraft Hydrogen.

For hydrogen to be exported in large amounts, the challenges involved in transport and storage must be solved. One must also take into account the plans of own hydrogen production and sector coupling in many European countries. While there is a huge potential in building heating on the European continent, the findings in chapter

6 indicate that the time window for large-scale hydrogen production from natural gas with CSS may be narrowing down. As we have seen, there are also considerable technical, economic and legal-administrative barriers to injection and distribution of hydrogen through established infrastructure for natural gas.

The observations from the qualitative study show that there are huge uncertainties and indicate the need to intensify current efforts strongly, if the tecno-economic pathway associated with the Industry Society scenario is to be realised. There is the need for more support to facilitate research, development and demonstration in the maritime sector, and to speed up the development in CCS. Infrastructure to facilitate deployment in heavy duty transport will also be important. While CCS is given high priority in the national budget for 2020 and continued research and development of hydrogen solutions are part of *The Government's plan for green shipping*, the *National plan for infrastructure for alternative fuels in transport* holds few specific targets for hydrogen and fuel cell solutions.

"Service society" scenario

In the second scenario, termed the "Service society" scenario, both the oil- and gas sectors are decommissioned, and the service sector is assumed to grow and cover the income gap from the oil- and gas sector. A future new service sector with increased impact on export is created in REMES.[82]

REMES does not consider the development of a commercial hydrogen sector under the "Service Society" scenario. This means that there is no transition of the land and sea transport towards a hydrogen-based fuel technology and hydrogen is not assumed to become a strategic export commodity for Norway; this role is instead covered by services. In the Service Society biofuels will become an increasingly important part of the fuel mix, both for land and sea transport, as detailed in Figure 43 below:

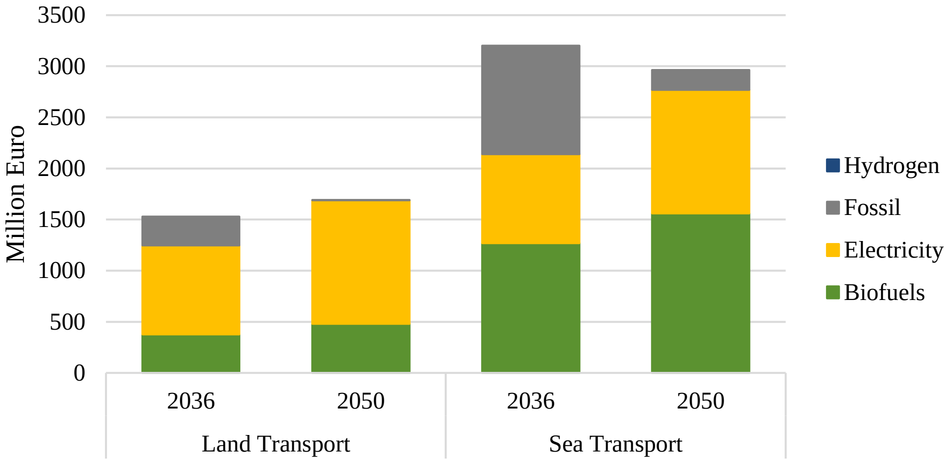

Figure 43: Energy inputs in land and sea transport in the service society scenario for 2036 and 2050.

In the TIMES analyses of the Service Society scenario, both industry activities and transport demand are assumed to remain at the same level as today, although the population is growing (i.e. the energy use per capita is considerable reduced). This implies that energy efficiency in all sectors (industry, buildings, transportation) is fully applied. People must change their behaviour and become very conscious in their way of living. The

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[82] Appendix Table 19 shows the assumptions applied to the REMES model.

technology development of particularly hydrogen technologies is less than in the Industry Society and unlimited quantities of biofuels for transportation are assumed available.

Under these circumstances, the use of hydrogen is much lower, see Figure 44. All hydrogen is produced by electrolysis. In 2030 the use will be limited to a very small share as industry feedstock. By 2050, the production of hydrogen may reach 3 TWh if the availability of biofuel is unlimited.

If we introduce a constraint on the access to biomass resources, and the development of hydrogen technologies is slightly higher (although not as high as in the industry scenario), the TIMES analyses suggest that use of hydrogen in the "Service society" will increase to 17 TWh in 2050. Hydrogen will be used for heavy transport and sea transport, as well as in industry, as depicted in the figure.

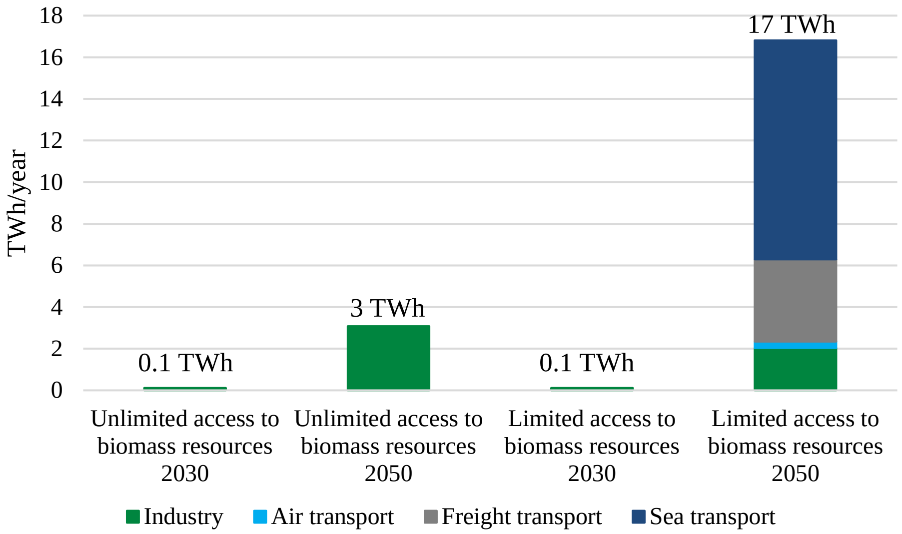

Figure 44: Use of hydrogen by subsector for the Service society scenario, results from TIMES-Norway, TWh/year.

The tecno-economic pathway explored through the "Service Society" may be related to pathway type ***P2 Dealignment and realignment*** in Geels and Schot's (2007) typology. The landscape change is assumed to be so large that it leads to a shut-down of both the oil and gas sector. There is no CCS and therefore no "blue" hydrogen. Battery-electric solutions keep developing. Green hydrogen from electrolysis is not mature enough to be of any significant impact by 2030. However, the TIMES model ascribes a more important role to hydrogen towards 2050, especially in model runs when the availability of biofuels is limited. At the same time, there are assumptions of building-integrated photo-voltaics and other innovations leading to unprecedented growth in the service sector. Regime actors lose faith in the current regime, but there is no clear substitute to fossil technologies. Multiple innovations compete for attention.

The qualitative analysis suggests that awareness and behaviour change are on the way. We have also noted that there is increasing uncertainty regarding the development of battery-electric solutions. Biomass has many different and partially competing areas of application, where high value utilization should in principle be prioritized. This means that only low value or residual products from biomass should be used for energy recovery, while food and pharmaceuticals are examples of high value uses of biomass resources. Some types of biomass also act as carbon capture agents, and they may need to be cultivated. Furthermore, the development of CCS can help reduce greenhouse gas emissions by capturing CO_2 from biomass combustion, which is already considered climate neutral. A recent study of pathways towards a 100% renewable energy system in

Germany concluded that it will be impossible to achieve a 100% renewable energy system without exceeding the threshold for sustainable utilization of biomass (Hansen et al., 2019).

On the other hand, an increase in energy demand from the growing service sector is leading to a high share of wind power, albeit not as high as in the Industry Society. This is in line with the qualitative findings, which suggest that hydrogen production in Norway may become large-scale and contribute significantly to sustainability transition also without CCS. If we get a development that falls closer to the Service Society, support for largescale production and implementation of sustainable hydrogen solutions will and should take a somewhat different form, with less emphasis on CCS, and more focus on flexible power-to-X solutions.

7.3 Sequential pathway and role in system change

In chapter 6, we showed how the context surrounding hydrogen production can be understood as a sociotechnical system with multiple levels that interact in various ways. Increasing knowledge and awareness, international agreements and successful implementation of renewable energy solutions put pressure on existing regimes and provide opportunities for sustainable niche innovations based on hydrogen. On the other hand, there are lock-ins linked to the embeddedness of fossil fuel institutions and infrastructure in society, as well as different national concerns regarding energy security and protection of local industry and workplaces.

In Norway, there is also the situation of having an oil and gas dependent economy as well as a largely renewable power system, with abundant opportunities for exploitation of new renewables. The need to decarbonize and diversify from oil and gas, support transition in the maritime sector and create new opportunities for blue-green growth and power-intensive industry are important drivers. However, there is also reluctance to properly address climate gas emissions from the oil and gas sector. The_strong focus on hydropower and electrification, which has led to great success with battery-electric solutions, may also be associated with lock-ins, in that a strong focus on batteries, charging infrastructure and onshore power supply may be associated with investments and economies of scale and scope, as well as institutional learning that pull attention away from hydrogen and other alternatives, which could become more sustainable for some applications. The two forces are also associated with different motivations and forms of hydrogen production, which sometimes are presented as one, and at other times come across as competing alternatives.

In chapter 6, we argued that these conditions have resulted in a hydrogen trajectory with different phases, from predevelopment to a take-off phase where various technological alternatives co-exist, and that we now see the contours of a third, decisive transition phase. Applying the typology of Geels an Schot (2007), we may analyze the emergence of hydrogen as energy carrier as a sequential pattern, where landscape pressure causes a sequence of transition pathways.

The global transition in the face of climate change, as a disruptive challenge, started at slow speed. Initially, it exerted only a moderate pressure on the established regime. Then, towards the late 1990s and early 2000s landscape pressures gradually increased, and the search for more sustainable energy solutions intensified. Norway followed up in international collaboration and national R&D initiatives, as well as through the national hydrogen strategy of 2005. As we have seen, the niche for hydrogen technologies around 2006 mainly consisted of a constellation of R&D institutions and large incumbents. The concept of a hydrogen economy was alluded to by niche actors, but the focus was on incremental innovation. The first *Climate Accord* specified a national policy but did not place emphasis on new technologies.

Following the financial crisis and demise of a hydrogen highway incumbents pulled back, while maintaining the focus on CCS. Hydrogen, as niche innovation, was unable to take advantage of landscape pressure on the regime, due to limited maturity and competition from battery-electric vehicles. Researchers played an important role in this phase, in translating landscape pressures and drawing attention to negative externalities, and as noted above, they and major regime incumbents were main actors. In the typology of Geels and Schot (2007) this, together with the kind of institutional negotiations, power struggles and adjustment of regime rules observed, is characteristic of a transformation pathway, where the direction of development and innovation activities is modified via cumulative adjustments, but the regime structure remains intact.

With the increasing landscape pressure and improved documentation of the climate challenges that followed, amongst other through the Climate Cure (Klima og forurensningsdirektoratet, 2010) and the follow-up assessments by the Norwegian Environmental Agency (Norwegian Environment Agency 2014a, 2014b, 2015), entrepreneurs and new firms were increasingly stimulated to develop radical niche innovations. Gradually, we have seen, regime actors such as Statkraft and Equinor, Yara and TiZir, have become more willing to incorporate symbiotic niche innovations and implement component changes. This is what we have seen since 2011, when there was a boost of capital and public interest in hydrogen solutions, followed by international success for Norwegian technology providers. The County Councils in Oslo and Akershus, took important steps to assess and promote hydrogen solutions around 2015-2016, as part of their own efforts to address climate gas emissions and local pollution in the capital region. Further momentum was added with the increasing focus on maritime applications, associated with co-benefits for the maritime industry and regional development in western Norway and most importantly, with larger volumes, and symbiosis with regards to hydrogen production from natural gas reforming with CCS.

As long as the regime architecture remains intact, this is still a transformation pathway. However, if additional adjustments trigger architectural changes, the result may be a reconfiguration pathway, where regime actors and new suppliers increasingly appear as main actors, and cumulative adjustments are followed by new combinations, changing interpretations and new practices.

The strongest focus remains on road transport, especially heavy-duty trucks and long-distance buses, and on maritime applications, where alternatives to battery-electric solutions are required, especially for longer routes and larger vessels However, there is an increasing orientation towards integrated user cases with several uses and energy solutions. This goes both for power-to-gas systems such as at Raggovidda, and for the concept envisaged by Greenstat in Tyssedal, where the aim is to supply hydrogen from electrolysis to both industry, maritime and a public-private partnership for regional road transport.

The green versus blue rhetoric remains in some quarters, but as we have seen there are also calls within the industry, for actors to join forces. Blue hydrogen is often presented as a key solution in the shorter term, to reach substantial volumes and kick-start implementation. Green hydrogen is still, in many cases, presented as a longer-term solution, more sustainable, but with higher costs and smaller volumes available in the shorter term. The change of rhetoric may be seen as a response to increasing pressure, both in that time is short for extensive technology development and major emission reductions towards 2050, and in that the amount of new renewables entering the market and the development of battery technology may imply that the window of opportunity for hydrogen derived from natural gas is narrowing.

Internationally, the social and material construction of a more distributed renewable energy system has reached quite far. It is uncertain how long the 'gas narrative' (Stern, 2017) will hold. Advanced local and regional solutions with sector coupling, multiple storage forms and smart solutions are now in focus in many countries, both in the EU and beyond. In Norway and the other Nordic countries, the level of awareness of these larger system changes appears low (Sovacool 2017). Norwegian households and businesses have benefited from relatively low electricity prices and the level of energy efficiency measures and the price elasticity on electricity have traditionally been very low. Some politicians and large parts of the population hold on to the perception that we have sufficient clean energy from hydropower and do not need to build wind turbines in anybody's back yard – we only need to electrify to cut emissions from transport and industry. However, most of the major actors see that the system is changing radically. Increasing electricity demands linked to new applications require new levels of flexibility in the system.

Statkraft, in their low-emission scenario (2019), see the costs of solar and wind-power as falling by 50% and 40% respectively, from 2020 to 2050. The renewable power sector makes electricity increasingly attractive as energy carrier in transport, building and the industry sector. This results in 44% lower climate gas emissions by 2050. Natural gas will be the largest source of climate gas emissions and the power sector will be 80% renewable in 2050. In the perspective of Statnett, replacing fossil fuels will increase the power consumption in Norway by 30-50 TWh per year. With a corresponding growth in renewable power production this will reduce the national climate gas emissions by 50%. Green hydrogen production towards achieving a zero-emission system, may increase the consumption by another 40 TWh (Statnett, 2019).

In line with NVE (2018) the models applied in Norwegian Energy Roadmap 2050 also find a large increase in wind power in both the Industry Society and Service Society scenario, which suggest that there will be a substantial potential for green hydrogen production in both scenarios. There is also increasing interest in deploying hydrogen from wind power in distributed solutions for stationary power, exemplified in the studies on deploying hydrogen from Raggovidda for stationary power in Svalbard and the solutions for remote communities that currently are explored in the REMOTE project in Trøndelag.

At the same time, new technological alternatives are emerging. While compressed gas is more available, liquid hydrogen will be needed for larger vessels and longer routes in maritime transport, and ammonia and LOHCs are other promising options. Thus, there are more roles for hydrogen than we realized ten years ago. At the same time, it appears that hydrogen in future will be part of a larger mix of energy carriers, applied in increasingly complex integrated solutions. This would be the new combinations, changing interpretations, and new practices characteristic of a ***P4 Reconfiguration*** pathway (Geels and Schot, 2007). We also see, in line with the same pathway type, that regime actors and new suppliers, such as NEL and Hexagon, play increasingly central roles.

7.4 A critical tipping point

As noted in chapter 6 and further illuminated through the discussion of pathway types, the development surrounding hydrogen in Norway seems to be at a critical juncture. A new momentum has been built, but there are also considerable uncertainties, both regarding global landscape developments, technological progress, business cases and public acceptance of hydrogen solutions. At the same time, national monitoring as well as international studies on the development of the energy system and progress towards the 2050 climate goals show that new solutions and intensified efforts are needed.

As time passes and a gap between the climate targets and realized emission reductions remains, we may eventually have to start using immature technologies. CCS and nuclear power may become more acceptable, and the willingness to pay for action is likely to increase. This will likely lower the barriers to hydrogen in both the transport, industrial and heating sectors. While breakthroughs in battery technology or biomass production may pull in the opposite direction, an increased share of unregulated renewable power may give increased opportunities for green hydrogen as a provider of energy system flexibility. Although there are dissenting voices, there is a growing conviction that the climate problem is pressing and that solutions must be found quickly, even if it costs.

Climate and energy policy are often based on technology neutrality, due to cost efficiency considerations. Within such a framework, a high carbon price is required for hydrogen to become cost-effective. Carbon taxes in Norway have increased rapidly in recent years. Taxes in the non-ETS sector vary, but the general tax on mineral oil is around 500 NOK per ton CO_2. In late September 2019, the prime minister announced that the

CO_2-taxes for all sectors, including oil and gas will increase 5%. This is a follow-up of the Granavolden platform, which is embraced by the present government and includes annual increases of this order up until 2025. The government has also disclosed that its total support for climate measures in 2020 will be 7 billion NOK.

Most of the consulted stakeholders emphasized that the CO_2 tax is important to create a market for largescale production of hydrogen in Norway. Furthermore, many of the actors argued strongly for a CO_2 fund modelled on the so-called NO_X fund, where enterprises may choose to contribute to an industry-administered fund for NO_X emission reductions rather than pay tax on NO_X, and in turn apply for support for emission reduction measures. However, national negotiations on a CO_2 fund have so far stranded, as the industry organizations want to administer the fund and require the option to avoid CO_2 tax, whereas the government wants to have the fund administered by Enova.[83]

The need for continued and increased support for research and development was also stressed. The high priority of CCS is critical for the development of blue hydrogen, and it may be argued that the national effort should be further intensified in order to accelerate full-scale demonstration. The need for more support to facilitate industry deployment and development of hydrogen solutions for the maritime sector were particularly emphasized.

To strengthen the joint efforts to introduce FCEVs in Europe, it is necessary to establish a basic network of hydrogen refuelling stations. However, the recent advances in battery technology and high level of acceptance of battery-electric vehicles, plus the shut-down of Hyop, put a wet blanket on the optimism regarding fuel cell electric vehicles in Norway. This was reflected in DNV GL's influential report on production and use of hydrogen, which suggests a very modest development when it comes to private cars, but a higher potential for heavy-duty vehicles (DNV GL, 2019). The HRS explosion at Sandvika dealt a further blow to hydrogen in Norwegian road transport. As noted above, the level of acceptance among logistics operators has also been limited so far.

The Norwegian Hydrogen Association has argued that a basic network of hydrogen refuelling stations must be facilitated to provide predictability for both business and private vehicle buyers. The *National plan for alternative fuels infrastructure* confirms that Enova will continue to offer grant support for hydrogen refuelling stations. However, it also states that the timing and number of grants may be adjusted to market response. The response from the industry is that the national plan is too general and contains few specific measures. On the other hand, there are public-private initiatives to establish fleet collaboration and develop more conducive business models for business vehicles. The Norwegian Hydrogen Association was also recently granted support for a Nordic partnership called Next Wave, to promote heavy duty hydrogen fuel cell vehicles, deliver a coordinated action plan and provide input to a Nordic hydrogen strategy.[84]

Considering the so-called chicken or the egg dilemma, some stakeholders suggested that public support should be offered for sustainable hydrogen production. Equinor has even argued that the zero-emission requirement from day one in public calls for tender for innovative zero-emission vessels should be dropped to allow initial use of grey hydrogen, in order to kick-start deployment and reach the volumes needed to invest in production of blue hydrogen with CCS.[85] Some suggested that support for green hydrogen production could serve the same purpose and would be needed only for a limited time-period, as electrolysis will become economically sustainable within very few years.

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[83] Press release from the government, 25.03.2019: https://www.regjeringen.no/no/aktuelt/co2-fond/id2637417/
[84] https://www.hydrogen.no/hva-skjer/aktuelt/fikk-ja-til-hydrogensatsing-pa-lastebiler
[85] https://www.tu.no/artikler/equinor-vil-lage-hydrogen-fra-gass-ber-om-a-slippe-co2-rensing/460459

Interestingly, some also felt that more public support may not be what is needed most. One of the actors, in particular, argued that the amount of research into different alternatives, safety aspects, etc. is increasing the public uncertainty about hydrogen, while many of the core technologies are well established. Several actors underscored the need for more coordination and collaboration, both within the industry actors and across the public and private sectors. The need to develop a larger "showcase" in order to demonstrate the economic, environmental and social sustainability of a full hydrogen value chain was expressed strongly in two of the attended workshops, both regional/national. A larger showcase would be a project combining production and several uses, at a certain level of scale. The call for such initiatives reflects recent developments in the EU where there is a tendency towards larger projects with a focus on sector coupling.

This further underscores the need to look beyond individual measures and apply "systems thinking". This may also apply to political measures and instruments. While regulations and environmental taxes have important roles to play, systemic change also depends on creating an environment where novel technologies, practices and business models may emerge. Both with a view to the complexity of the changing energy system and considering the historical trajectory of hydrogen in Norway, this means that communicative instruments, to increase knowledge and acceptance, are crucial. Against the background of the hitherto weak coupling between energy and climate policy, shared goals, broad stakeholder involvement and frameworks to manage and coordinate activity across sectors will be crucial. Long term planning and scenario studies to explore different strategic options are important elements.

8 Summary and conclusions

An exploratory review of publications on integrated energy scenarios shows that there is a considerable potential, but also a high level of uncertainty regarding the role of hydrogen in sustainable energy transition.

Our qualitative assessment of recent initiatives to establish new hydrogen production in Norway underscores the potential. There are at least six initiatives considering large-scale production. These are linked to different energy sources, including hydropower, natural gas and wind power. They involve different production technologies and are associated with different resources and motivations. Besides decarbonization of transport and existing industry, local value creation and regional development are important drivers.

While some of the initiatives are linked to energy companies with large capital and international networks, others are more local. There is a strong presence of consultants and municipalities, who are working actively to facilitate production and deployment of hydrogen. Some key actors and main proponents, such as NEL Hydrogen and Greenstat, are involved in several of the cases. Still, many of the stakeholders find that efforts currently are fragmented. There has also been a tendency towards dichotomization of "green" and "blue" hydrogen, which may have had adverse effects on collaboration and the overall acceptability of hydrogen solutions. Limited coordination is recognized as a challenge.

The opportunities linked to decarbonization of maritime transport are emphasized by most stakeholders. Industry and fleet vehicles are also associated with a large potential. While export up to recently was associated mainly with "blue" hydrogen, export is part of the long-term ambitions for several "green" production initiatives as well.

Prospective users consider lack of a sizable and stable supply of hydrogen as a barrier. On the other hand, none of the studied production initiatives do have a committed customer base today. The progress in battery-technology has strengthened the focus on electrification of transport, and the framework conditions for hydrogen refuelling stations remain unpredictable. Notwithstanding the many promising projects in the maritime, hydrogen technology for ships is still relatively immature. The cost of liquefaction and other solutions for storage and transport of large volumes of hydrogen is a main uncertainty. The development of regulations, codes and standards takes time given the international nature of the shipping industry.

Large actors in energy-intensive industry see hydrogen as a main decarbonization option, but this requires radical and very costly process change. When it comes to export, "blue" hydrogen could be produced in Norway and/or in the receiving country. This will in both cases depend on the business case of CCS and finding solutions to technical and legal-administrative barriers.

At the same time, the increasingly apparent climate change impacts, decreasing costs of renewable energy, increasing awareness and the development of more ambitious climate and energy policies are accelerating the development towards a more distributed renewable energy system, where hydrogen may play important roles with respect to flexibility and sector coupling.

It may be argued that hydrogen as an energy carrier was "hyped" earlier, when solutions were at a lower maturity level than they are today. Tensions in the national regime surrounding hydrogen have been pulling in different directions, one linked to the power sector and electrification and the other to the need to exploit natural gas in a more sustainable way. Presently, we see a converging trend. Current measures to reduce climate gas emissions in Norway are not enough to meet the 2050 targets, and there is the need to implement and test a broad mix of technologies, including both mature and less mature solutions.

Quantitative model-based assessment of two contrasting energy scenarios suggest that hydrogen may be a key to meeting the 2050 targets. In the "Industry society" hydrogen is brought in as a substitute for conventional fuels and has the potential to become an important industry. Domestically, hydrogen takes a high market share in heavy-duty and maritime transport, and by 2050 its share in total exports is about 20%.

In the "Service society", both the oil and gas sectors are phased out. In this scenario, as well as in the "Industry society" there will be a substantial increase in wind-power. The phasing-out of fossil fuels without the development of a backstop technology will pose pressure on the energy system, as electricity tends to have few possible competitors in providing energy without a radical breakthrough in battery technology or biomass production. Since biomass is a limited resource, hydrogen as far as we know now, will be needed to decarbonize industry and certain transport segments. Thus, both the qualitative and quantitative analyses suggest that largescale hydrogen production is associated with a considerable transition potential, and indeed may be crucial for Norway to reach its 2050 climate targets.

Up until now energy transition in Norway has followed a transformation path, with moderate pressure for change. Hydrogen and other niche innovations have been explored, while public and private decision-makers have made cumulative adjustments. These days, the pressure for climate change mitigation is increasing. There are also local symbioses, between hydrogen as energy solution, regional development and other environmental concerns that drive production initiatives in many parts of Norway. The international market will grow larger, as hydrogen will become increasingly relevant for countries with a high fossil share in their fuel mix and high electricity prices.

On the other hand, significant barriers remain. In addition to high costs, there are remaining technical challenges and social barriers, in the form of legal-administrative gaps, limited acceptance, and lack of coordination. This suggests the need for broad-based collaboration and communicative as well as economic and regulatory instruments to unleash the transition potential associated with largescale hydrogen production in Norway.

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Appendix

Table 11 REMES model assumptions in the "Industry society" scenario

Assumption / Case	Industrial Society Scenario
Population	Increase by 43%
Fuels	In 2050 no more than 7% 2007 level
Oil Refinery	In 2050 no more than 1% 2007 level
Coal	In 2050 no larger than 2007 level
Pulp and Paper	In 2050 no more than half size 2007 level
Export of Oil, Natural Gas, Diesel and Gasoline	In 2050 no more than 1% 2007 level
CCS	127% mark-up on Natural Gas Price
Power sector	Region based capacity constraint
Sectors using Natural Gas (replace with new sectors with CCS)	Transition towards joint use with CCS
Imports	Restriction of imports on oil and gas

Table 12 REMES model assumptions in the "Service Society" scenario

Assumption / Case	Service Society Scenario
Population	Increase by 43%
Fuels	In 2050 no more than 1% 2007 level
Oil Refinery	In 2050 no more than 1% 2007 level
Gas sectors	In 2050 no more than 1% 2007 level
Coal	In 2050 no larger than 2007 levels
Pulp and Paper	In 2050 No more than half size 2007 level
Export of Oil, Natural Gas, Diesel and Gasoline	In 2050 No more than 1% 2007 level
CCS	-
Power sector	Region based capacity constraint
Increase in export of Services	New sector with increased exports impact

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