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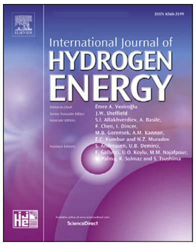

The role of hydrogen in the transition from a petroleum economy to a low-carbon society

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HIGHLIGHTS

- Hydrogen is a pre-requisite for reaching decarbonization targets in Norway.
- Our analyses indicate that hydrogen has potential to be a source for new income.
- Renewable power will be used for hydrogen production.
- National and European coordination is needed to build a hydrogen economy.
- Combining models and socio-technical perspectives should be further explored.

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ABSTRACT

A radical decarbonization pathway for the Norwegian society towards 2050 is presented. The paper focuses on the role of hydrogen in the transition, when present Norwegian petroleum export is gradually phased out. The study is in line with EU initiatives to secure cooperation opportunities with neighbouring countries to establish an international hydrogen market. Three analytical perspectives are combined. The first uses energy models to investigate the role of hydrogen in an energy and power market perspective, without considering hydrogen export. The second, uses an economic equilibrium model to examine the potential role of hydrogen export in value creation. The third analysis is a socio-technical case study on the drivers and barriers for hydrogen production in Norway. Main conclusions are that access to renewable power and hydrogen are prerequisites for decarbonization of transport and industrial sectors in Norway, and that hydrogen is a key to maintain a high level of economic activity. Structural changes in the economy, impacts of new technologies, and key enablers and barriers in this transition are discussed.

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Introduction

Norway has adopted national climate targets with emissions cuts of 80–95% by 2050 compared with 1990. To become a low-emission society, decarbonization of the energy system is crucial. At the same time, maintaining national value creation is a political ambition. In 2019, 46.9% of the Norwegian export revenues were from the oil and gas production. This paper studies a radical decarbonization pathway for the Norwegian society towards 2050, where Norwegian petroleum export is gradually phased out. There is a focus on the role hydrogen can play in the transition.

According to the European Commission's hydrogen strategy released July 2020, from 2030 onwards, hydrogen will be deployed at a large scale across all hard-to-decarbonize sectors. EU's priority is to develop clean, renewable hydrogen, produced using mainly from wind and solar energy as the most compatible option with the EU's climate neutrality goal in the long term. However, in the short and medium term, other forms of low-carbon hydrogen are needed to rapidly reduce emissions from existing hydrogen production and support the development of a viable market at a significant scale. EU will secure cooperation opportunities with neighbouring countries and regions and work to establish a global hydrogen market [1].

Presently Norway is supplying about 25% of Europe's demand for natural gas and the petroleum sector contributes to about 30% of the Norwegian CO_2 emissions. Norway has a power sector based on renewables mainly in terms of hydropower with large reservoirs. Furthermore, Norway has one of the best wind resources in Europe both onshore [2] as well as offshore [3,4]. Since the power system is already decarbonised, the wind resources represent a potential for new industries, e.g., hydrogen production. In addition, natural gas can be used to produce hydrogen with low emissions, using steam reforming and Carbon Capture and Storage (CCS).

The hypothesis behind this paper is that EU will need to import hydrogen to reach its decarbonization targets, that Norwegian gas and renewable resources can be used for large-scale production of sustainable hydrogen, and that this new industry can substitute parts of the income from the present oil- and gas sector. Starting from this assumption, we consider the impacts on the overall energy and economic system of a transition towards a low carbon energy production and consumption in Norway. We particularly focus on the reallocation of the sectoral value between the different sectors and on the overall GDP dynamics over time. The analysis performed does not directly consider the effects of unemployment because it assumes that the workforce will be available for any possible wage rate. Nevertheless, the study on the evolution of the wage rate, compared to the consumption price index suggests an overall increase in unemployment rate. The job losses in the oil sector are only partially collected by the hydrogen sector, due to the lower export compared to today's exports of oil and gas. In the transition pathway analyses we examine how the reduced revenue from oil and gas can be replaced with an increasing revenue from other industrial sectors, including hydrogen produced from natural gas and renewables. This paper has a holistic approach and studies both the impact this transition has on the overall economy, which role hydrogen can play in decarbonising the domestic energy system, the role of hydrogen as an export product, as well as the drivers and barriers for large-scale production of hydrogen in Norway. We combine three analytical perspectives. The first uses bottom-up models to investigate the role of hydrogen in an energy systems perspective (TIMES) and a power market perspective (EMPS), without considering hydrogen export. The second analysis takes the same starting point but uses a regional economic equilibrium model (REMES) to examine the potential role hydrogen can have in continued value creation when petroleum exports are phased out and hydrogen exports are an option. The third analysis is a socio-technical case study on the drivers and barriers to develop hydrogen as an energy carrier in Norway, shedding light on long-term patterns and uncertainties.

The study raises several questions that may be of interest for other regions both from the insights from the analysis itself and from a methodological perspective. The key insights are related to what type of changes are needed in the economy and in the energy- and power system to achieve two sometimes conflicting objectives: reducing or removing climate gas emissions and maintaining or increasing economic growth.

Literature

Hydrogen produced from renewable electricity has emerged as a promising fuel due to its high energy density, high conversion efficiency, the potential for storage and the advantage of a clean fuel [5–7]. Studies including hydrogen produced from natural gas with CCS [8,9] are also getting increased attention. A recent publication on the modelling, data and scenario framework supporting the EC's “Clean Planet for All” shows that climate-neutrality in the EU by 2050 necessitates disruptive options, which depend heavily on policies facilitating investment [10]. Among these, hydrogen is seen as critical. However, there are several challenges to overcome before hydrogen can play an important role in transition to a sustainable energy system and economy.

The scope of total hydrogen value chain (Power-to-X) demonstrations and pathways has evolved in recent years, mainly to include industry applications [11]. However, a broad review of the emergence of hydrogen within low-carbon pathways from different integrated energy system models finds that hydrogen mainly emerges after 2030, although some applications of hydrogen emerge in the 2020s and other hydrogen technologies as late as 2050 [12]. The review is divided into global, multi-regional and national integrated energy system models, where drivers, marginal abatement costs and timing of hydrogen emergence are assessed. The global models generally showed the emergence of hydrogen in the transport sector, though some use in industry and the residential sector also appeared. The multi-regional models showed hydrogen in natural gas blending and thermal generation. While electricity emerges as a main competitor for hydrogen in transport, this can allow hydrogen to emerge in other sectors. The review found that bioenergy can act as both a competitor and driver for hydrogen energy. While recent research suggests that the hydrogen market is growing significantly [13], the use of hydrogen in energy systems is complex, given its relationship with other energy sources. It will also to a large extent depend on suitable policy interactions. The difficulty of representing hydrogen in energy system models adds further to the uncertainty. Scenario analysis including adoption of new technologies, such as hydrogen vehicles, can be both too optimistic and too pessimistic [14].

The high potential and uncertainty surrounding hydrogen are also underscored in a recent study exploring four scenarios incorporating hydrogen city gas blend levels, nuclear restrictions, regional emission reduction obligations and CCS deployment [15]. Analyses using a global linear optimisation model (DNE) found that hydrogen may supply approximately two percent of global energy needs by 2050. Delaying the introduction of CCS had an impact when nuclear restrictions were implemented, leading to reduced production of hydrogen from fossil fuels. On the other hand, modifying regional targets to require equal mitigation from both OECD and non-OECD nations reduced the overall production, import and export of hydrogen, causing a shift towards local production and consumption.

A recent European study analyse how variable renewable energy sources and production of green hydrogen can contribute to a cost effective sustainable development, and which European countries that might be exporters or importers of hydrogen and electricity in the future [16], and demonstrated how hydrogen production mainly occurs in regions with low electricity costs. In the study Norway is a main exporter of both electricity and green hydrogen. If also hydrogen from natural gas had been included in the analysis, Norway's role as hydrogen exporter could have been even more significant. A case study from Texas evaluate the cost-optimal electricity and hydrogen infrastructure needed to serve future electricity and hydrogen demand across a range of policy and technology scenarios analyse [17]. The analysis demonstrates that increasing CO2-prices favours hydrogen from electrolysis, while increasing hydrogen demand, favours hydrogen from natural gas (with CCS). This underpins the importance of scale.

The earliest analyses of the impact of large scale hydrogen production in an economy were developed in 2009, mostly focusing on the transport sector [18–20]. Ref. [18] applies the analysis to the European economy and finds an improvement of economic performance, depending on the assumed learning curve of hydrogen transportation and on future hydrogen production costs [19] performs analyses on a global scale and provides cost targets for hydrogen compared to fossil fuel to make hydrogen a viable option, without commenting on the wider economic effects. The analysis of the impact of transition from petroleum to a hydrogen economy in Taiwan [20] shares similarities with our analysis, as it focuses on the production side. They consider hydrogen production based on coal and nuclear electricity and conclude that a new hydrogen sector will lead to increased GDP (Gross Domestic Product) due to the decrease in production costs but will entail an increase in energy prices. A study of dynamic economic impacts of building a hydrogen economy in Korea depending on different subsidy levels [21] concludes that the effect on GDP is moderate, but with a negative effect on household consumption due to the increase in taxes for subsidizing the hydrogen sector [22] uses the GTAP CGE (Computable General Equilibrium) model combined with LCA to forecast the development of the hydrogen supply chain and CO2 emissions in Japan. A recent study of the effects on emissions and overall economy of penetration of hydrogen-based transport [23] claims that the introduction of a hydrogen-based transport would lead to an increase in real GDP, supplemented by a power cost reduction.

Most modelling approaches for hydrogen supply chains have focused on mathematical optimisation including MILP (Mixed-Integer Linear Programming), stochastic multi-period, and multi-objective optimisation problem-based modelling [24]. These enable generalised formulation of future hydrogen supply chains. However, they are mostly limited to specific scenarios, with a focus on cost, environmental and risk factors. Further work is needed to encompass other variables such as clean feedstock, technical feasibility, and performance of a renewable hydrogen supply chain. There is also increasing focus on the non-economic barriers (NEBs) to hydrogen deployment. In a broad European study, five main NEBs were identified: 1) complex legal-administrative procedures, 2) lack of information guidelines and standards, 3) lack of public knowledge and awareness, 4) local acceptance of hydrogen and infrastructure as safe technologies, and 5) lack of government initiatives to increase the transmission and distribution networks and use of hydrogen vehicles [25]. For Norway specifically, limited understanding of the overall global challenges and enactment of unclear energy policies was presented as a challenge. This underscores the need to address systemic change, combining different disciplinary perspectives [26]. Socio-technical analysis links technology implementation to systemic change, highlighting different kinds of agency and the multi-directionality of transitions. Early work combining socio-technical scenarios and quantitative modelling of pathways for hydrogen emphasized four main areas of uncertainty; technology development, user practices, the strategies of governance and large incumbents, and the development of the wider energy system [27].

Methodology

This study builds on a combination of quantitative and qualitative methods. The key elements are described below. The qualitative story line, called industry society (IND), is developed in interaction with important Norwegian stakeholders from national government, energy- and grid companies and NGOs through a series of workshops. The storyline describes a development towards 2050 where the global society has implemented low carbon strategies, and the global economy is phasing out the use of oil products. Thus, the demand for Norwegian oil and oil products are gradually reduced towards 2050. Even though the oil sector is phased out, the global natural gas sector is maintained. The natural gas is used to produce hydrogen by steam methane reforming CCS, both in Norway and globally. The breakthrough in hydrogen is supported by the breakthrough in CCS-technology. Hydrogen will play a central role in the transport and industry sectors in Norway, and as a new export industry. In particular, the economic analysis, conducted using a dynamic multi-region Computable General Equilibrium model of Norway, assumes that hydrogen demand abroad will be large enough that the Norwegian hydrogen sector will replace half of the value generated by oil and gas in 2007. The largest part of this value will come from exports of hydrogen. This assumption has been adopted in accordance with the Norwegian Government's hydrogen strategy document [28]. Norway covers around 3% of the global natural gas demand and today's global demand for hydrogen is around 70 million tons. We assume a growth of the global hydrogen demand set at 3.5% per year towards 2050, in accordance with [29], and we assume the market share for Norway exports at the same level as the one for today's gas exports. This leads to an export of roughly 5.5 Million tons hydrogen in 2050. In the results of the economic analysis this amount, together with the amount sold internally, corresponds to a value added comparable to half the one generated by exports of oil and gas in 2007. To perform the analysis, the CGE model of Norway has been implemented applying a system of taxes and subsidies to reduce the extraction of oil, the production of fossil fuels and stimulate an increase in the demand for hydrogen abroad.

In the IND scenario the demand for passenger transport and for freight are expected to follow the National Transport Plan, NTP 2018–2029 [30]. The population growth is assumed to be in accordance with Statistics Norway middle scenario [31] with a corresponding growth in energy demand. To be able to sustain national welfare, the future industry society includes a substantial growth in industrial activity and production. The production in the Norwegian petroleum sector follows the forecast in the Long-Term Perspective report 2017 [32], and the trend from 2030 to 2040 is extended to 2050, giving a value added from the petroleum sector in 2050 of 20% compared to its value in 2010. The qualitative story line (IND) is used to align input data to the quantitative modelling (TIMES, EMPS and REMES). While the starting point used in the IND scenario is the same for the energy system analysis and the economic analysis, the purpose is different. The energy system analysis focuses on how hydrogen may play a role in the Norwegian energy transition, while the economic analysis focuses on how it can help maintain economic growth as petroleum exports are phased out.

The IND scenario is compared with a reference analysis (REF) where the development follows current trends in domestic policies, the economy and in the energy and power sector, see Table 1 for the scenario description.

A more detailed descriptions of the models used in the study are provided in the next paragraphs.

REMES

REMES is a Regional CGE model [33–35], representing the Norwegian economy focusing on the energy system. It has a multi-region structure, which reflects the five national electricity price regions. The input data is collected from Statistics Norway [36] and from the CREEA project (Compiling and Refining Environmental and Economic Accounts, creea.eu/), while the values for the sectoral elasticities of substitution are based on [37]. The production of goods is represented through a three nests constant-elasticity-of-substitution (CES) function, assuming a typical CLEM (Capital, Labour, Energy and Material are aggregated in this order) structure. There are 11 energy commodities that concur in the development of final energy. Moreover, hydrogen and CCS are considered as backstop technologies. The production functions gradually shift towards a structure where all the sectors using natural gas will couple natural gas with CCS. Land and sea transport sectors undergo a technological change leading to the introduction of hydrogen as concurrent fuel alongside the existing ones.

EMPS

European Model of Power System (EMPS) provides time series with power prices for export/import between Norway and neighbouring countries to the TIMES model as a part of the linkage between the models [38]. The power prices in

Table 1 – Scenario description in the energy- and power system modelling.

	Reference (REF)	Industry society (IND)
CO_2-restriction	No	Yes
Demand		
Oil and gas	Oil and gas sector develop as in official Norwegian projection	Oil sector is reduced to zero. Gas sector is transformed to a H_2 sector
Industry	Energy demand as in 2015	Energy demand increases with the same rate as GDP
Service sector	Energy demand increases with the same rate as population	Energy demand increases with the same rate as GDP
Transport	As in the national transport plan (NTP)	As in NTP
Households	Energy demand increases with the same rate as population	Energy demand increases with the same rate as population
Technology		
CCS	No	Yes
Building Integrated PV	No	No
Hydrogen technology learning	Moderate	High
Biofuel	Follows todays trend, unlimited access, increased price	Restricted access, higher price
Energy efficiency	Limited to heat pumps and more energy effective vehicles	Energy efficiency measures included in all sectors

neighbouring countries will impact profitability of new production capacities in TIMES-Norway as well expansion of transmission capacities and power exchanges between Norway and other countries. EMPS is a stochastic optimisation model that maximizes the expected total economic surplus in the simulated power system through the dispatch of generation and transmission, given a consumption profile [39]. Input data about the power system in Europe is from the EU 7FP project eHighway2050 [40] and its scenario X-7.

TIMES

TIMES is an energy system modelling framework. TIMES (The Integrated MARKAL-EFOM System) [41–43] is a bottom-up modelling framework with a detailed techno-economic description of resources, energy carriers, conversion technologies, energy transmission and demand. It is mainly used for medium- and long-term analysis on the global [44], multinational [45] and national level [46]. TIMES models minimize the total discounted cost of the energy system to meet the demand for energy services over the analysed period. TIMES-Norway [46] is an optimisation model of the Norwegian energy system. The total energy system cost includes investment costs in supply and demand technologies, operation and maintenance costs, income from electricity export and costs of electricity import from countries outside Norway. TIMES-Norway is divided into five electricity market spot price areas. The model provides operational and investment decisions for 6 periods from 2015 to 2050. Each period is divided into 260 sub-annual time slices to capture operational variations in electricity generation and end-use. The model has a detailed description of the demand for energy services within industry, buildings and transport. Each energy service demand category can be met by existing and new technologies using different energy carriers such as electricity, bio energy, district heating, hydrogen and fossil fuels. Other input data include fuel prices; electricity prices in countries with transmission capacity to Norway, renewable resources and technology characteristics such as costs, efficiencies, and lifetime and learning curves. In this study import and export electricity prices are provided by the power market model EMPS model. The methodology for linking TIMES-Norway and EMPS is described in Ref. [38]. In the combined modelling framework used, the long-term energy system investment strategies explicitly consider the operational complexity of the power sector. The linkage is designed to improve the modelling of hydropower generation and import/export electricity prices in the energy system model, and to provide consistent assumptions concerning Norwegian electricity demand and capacity in the power market model.

Qualitative study

The qualitative case study on barriers and drivers to hydrogen production is grounded in socio-technical transitions research, which focuses on the co-evolution of social and material elements, including technologies, markets, policies and practices, and how this influences the directionality and dynamics of change in sustainability transitions [47]. Among the several approaches in this field, the Multi-Level Perspective (MLP) was selected as analytical framework. MLP addresses sociotechnical interactions via three analytical levels: 1) niches (the locus for radical innovation), 2) socio-technical regimes, (established practices and rules), which represent the institutional structuring of existing systems; and 3) landscape developments, that is exogenous trends, uncertainties and developments [48]. Different alignments between processes at the three levels are associated with different transition pathways, whereby existing socio-technical systems (e.g. energy systems) may be adapted or reconfigured.

Table 2 – Stakeholders interviewed.

Stakeholder category	No. of stakeholders
Established energy companies	4
New actors, focused on H_2 production	3
Technology providers	3
Distributor	1
Potential users	3
Researchers and consultants	2
Municipalities with H_2 initiatives	3
County Councils	2
Public agencies, national level	3
NGOs	2

The specific methods applied included an exploratory document study, stakeholder interviews and participant observation at relevant workshops in 2018–2019. The empirical starting point was six recent large scale (>5 MW) hydrogen production initiatives. A total of 26 semi-structured interviews were conducted. Their distribution across categories is presented in Table 2.

The studied workshops included four national and three international events. They were attended by 30–180 participants from different parts of the value chain. The authors took different roles, as organizer (1 event), presenter (2 events) and regular attendants (4 events). Presentations were collected, and together with detailed discussion notes and final workshop reports, this was included as material for the MLP analysis, together with the interviews and document study results.

Results

Energy system impacts

According to the TIMES-Norway analysis, the domestic energy demand increases from 240 TWh in 2015 to 275 TWh in 2050 in the IND scenario. However, if energy efficiency measures are implemented the energy demand in 2050 can be maintained at the same level as in 2015. Today, the main energy carrier in the Norwegian energy system is electricity, and its share will be increasing towards 2050. Bio energy and hydrogen are also increasing their shares, while the use of fossil fuels is significantly reduced. The demand for hydrogen increases from 4 TWh in 2030 to 27 TWh in 2050, see Fig. 1.

It is a prerequisite in this analysis that hydrogen technologies will be significantly improved towards 2050. A description of the TIMES-Norway and modelling assumptions are described in more detail in Refs. [49,50]. The improvement in hydrogen technologies permits a cost-effective production of hydrogen and use of hydrogen in heavy duty road transport, as well as in maritime and long-distance air transport. Also, the use of hydrogen in industrial processes contribute to reduced emissions.

Hydrogen production and demand is domestically balanced in the model. Thus, the demand for hydrogen must be met by the similar level of hydrogen production. There are two options for hydrogen production modelled in TIMES-Norway, either it can be produced from electricity, using electrolysis, or from natural gas with CCS. The analysis show that it is cost effective to use both electrolysis and steam methane reforming for hydrogen production (Fig. 2). The total demand for hydrogen increases to 27 TWh in 2050, of which approximately 50% is produced by electrolysis and 50% from natural gas. Almost 80% of the hydrogen produced is used in the transportation sector, while the remaining 20% is used in the processing industry.

The electricity needed for electrolysis is almost 20 TWh in 2050. If the total hydrogen demand should be produced with electrolysis, the total electricity demand would increase with 40 TWh annually towards 2050; an increase in the Norwegian electricity demand by more than 25%. As the model balances supply and demand, the increase in electricity demand can either be produced domestically or imported. Our analysis shows that the increased electricity demand for hydrogen production will be covered by an increase in renewable electricity production in Norway, mainly from wind power and hydropower, but also a small power production from solar PV (Fig. 3).

In total, the electricity demand increases from 130 TWh in 2015 to 155 TWh in 2050 in REF, and to 184 TWh in IND to meet the future domestic demand for electricity.

The total hydrogen demand in transport sector increases to 21 TWh in 2050 in the IND scenario (Fig. 4). The two main transport sectors where hydrogen will play a significant role is in land-based freight and in the sea transport. The Norwegian geography and topography (long distances, mountains, long coastline) makes the decarbonization of transport challenging. Especially long-haul heavy-duty vehicles and high-speed ferries are challenging to electrify with batteries. There are mainly two options for decarbonization of these two transport segments; biofuels and hydrogen. Biofuels are a limited resource in Norway [51], and only used in market segments and transport modes with few, or no other options.

In the IND scenario, we observe that biofuels are used as a transient fuel, as it is easier, and also cost efficient, to achieve emission reduction by switching from fossil fuels to biofuels. Biofuels are limited, and the bio resources have many possible applications (such as industrial raw material, building material, furniture, pulp and paper, heating, transport fuel). An assumption in the analysis is that to obtain a sustainable energy system, Norway will not use more bio energy than the domestic bio energy potential. Norwegian bio resources are mainly from forestry. However, in the future bio energy may also be harvested from marine resources. This future, and uncertain, marine bio energy potential is not included in the analysis. The total domestic amount of bio resources is almost 50 TWh annually, based on timber [51]. In addition, there is a biogas potential of 3 TWh annually. The annual use of bio resources is approx. 34 TWh (including biofuels and biomass), which implies there is a potential to increase the use of bioenergy with almost 50%. In 2030 the analysis gives a significant share of biofuels, however a considerable reduction in the use of biofuel is observed towards 2050. When hydrogen technologies are available, and hydrogen technology costs are reduced towards 2050, it is cost efficient to use hydrogen in both land-based freight and in air and sea transport.

Economic effects

The REMES analysis assumes in the IND scenario that hydrogen is produced on a large scale by both electrolysis and the reforming of natural gas with CCS. The main market demand for hydrogen is the Norwegian transport sector and exports to the rest of Europe. More precisely, the volume of exports together with its utilization in the transport industry cover approximately half of the economic value added that was provided by the Oil & Gas sector in 2007. For the transport sector, we assume that the large-scale investment in

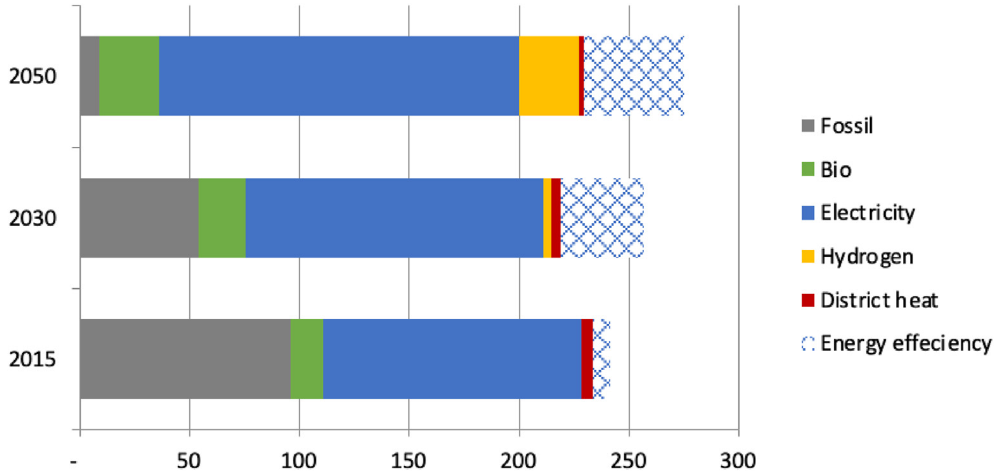

Fig. 1 – Use of energy in the IND scenario, divided on energy carriers, 2015, 2030 and 2050. TWh/year.

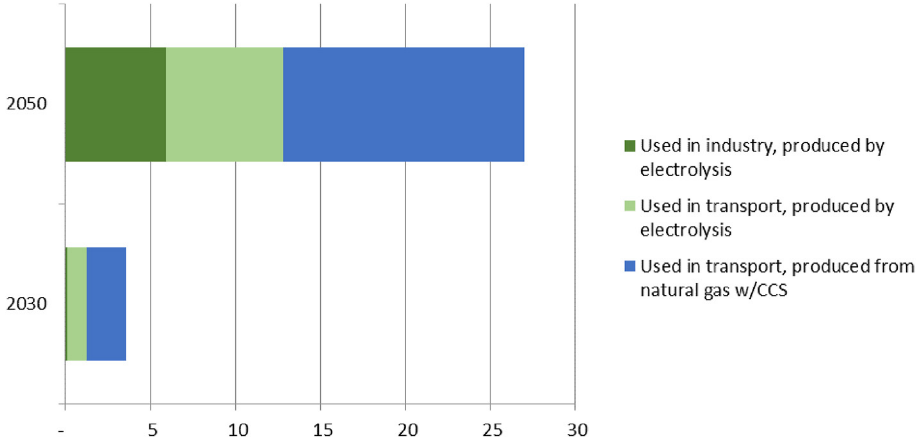

Fig. 2 — **Use of hydrogen in the IND scenario in Norwegian industry and transport (TWh/year).**

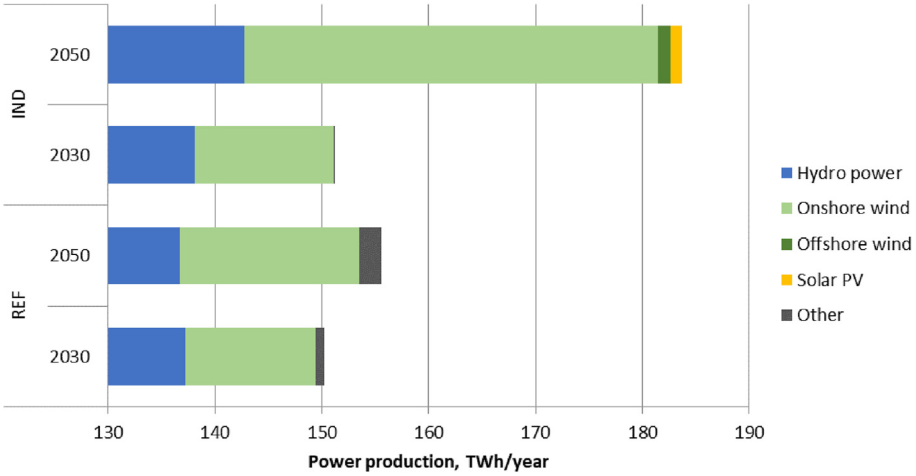

Fig. 3 — **Norwegian power production both REF and IND scenario (TWh/year).**

hydrogen is reflected in the fact that hydrogen is an important fuel both for maritime, for heavy-duty transport and for passenger car transport outside urban areas, while BEV is strongly present in urban traffic.

The economic model has been designed to apply a set of shocks over a time interval spanning between 2007 and 2050. These shocks are modelled as a system of progressive taxation which gradually changes over time and leads the target sectors to reduce their activity level, to phase out the exports of oil and gas and to discourage the utilization of gas without the complementary CCS. The objective is to reduce the production of fossil fuels by over 90% from 2007 and completely phase out the exports of oil and gas. Moreover, other fossil fuels such as coal extraction will be forced to stay below the activity levels of 2007. Finally, we assume a demographic growth set slightly below 1% per year to 2050 [52].

The most known indicator resulting from such analysis is the GDP, displayed in Fig. 5. The analysis shows that the GDP growth falls short of the projection provided by the SSB main alternative [52]. In fact, according to the SSB projection the country's real GDP should follow the same growth pattern of the population, reaching round 358 Billion Euros, whereas the implemented green transition will reduce the growth rate leading the real GDP to settle at 307 Billion Euros.

The main reason of the growth reduction led by the green transition can be identified in the restrictions placed on fossil fuels and the impact on available energy products such as electricity. We assume that industry has substitution possibilities between different existing energy carriers, such as biofuels and electricity, while transport sectors will accommodate for the utilization of hydrogen.

Analysing the various parts composing the overall GDP in Fig. 5 (where we display the oil sector and the gas sector together), we notice that the phase out of oil does not completely lead the value added of the Oil & Gas sector to zero because natural gas can still be used together with CCS. Natural gas is mainly used to produce hydrogen, whose value added partly replaces the decrease of the value added for the Oil & Gas sector. The use of CCS technology requires input of electricity and steam in large amounts, which increases the value added for power sector and low temperature heating due to the increased demand for CCS.

The exports levels needed to ensure a growth in value added in the hydrogen sector capable of replacing half of the value added provided by the Oil & Gas sector in 2007 are reported in

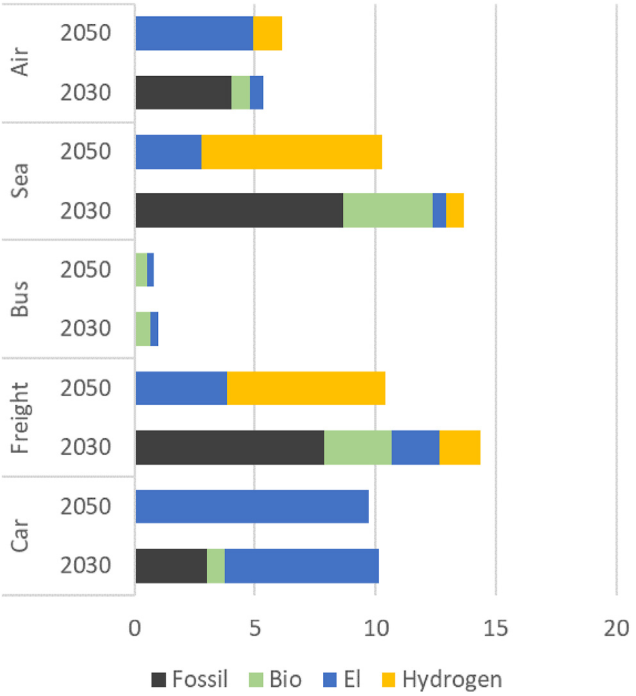

Fig. 4 – Use of different fuels in transport sector in 2030 and 2050 in the IND scenario (TWh/year).

Fig. 6, which displays a monetary value of exports of about 64 Billion Euros in 2050. Assuming a price of around 8 Euro per kg of hydrogen in 2020 and considering the evolution of inflation-adjusted prices computed in the economic model, the amount of hydrogen exports in 2050 is around 5.6 Million tons.

Ongoing initiatives, drivers and barriers

In the 1940–1950s, Norway had the world's largest electrolysis plants. When natural gas reformation became more affordable, these plants were replaced, but local know-how remained. Research on hydrogen as an energy carrier started early [53], with several ambitious projects, including a “hydrogen highway”. Five hydrogen refuelling stations were built, but the 2008 financial crisis slowed down investments. The electrification of transport accelerated, and hydrogen car manufacturers prioritized other markets. Since 2014 a new momentum has been building. Table 3 shows the main characteristics of six (>5 MW) production initiatives considered most promising in 2018.

The ambitions stated for these initiatives suggest a substantial annual production may be realised within few years. Some actors, such as NEL, Greenstat and SINTEF are involved in several cases. Large incumbents are central in three initiatives, and public stakeholders are important in all. Maritime transport and industry are the main target users, and in three cases export is part of the business vision. The main actor at Jelsa went bankrupt in 2019, but others have emerged, e.g. in connection with an existing windfarm at Smøla, and at Kollsnes, where a gas reforming plant including CCS is planned for 2021. Two recent public-private partnerships take a whole value chain approach. BKK, Equinor and Air Liquide are at the centre of one, aiming to produce 20–30 tons of liquefied hydrogen daily from 2024. The other, Hellesylt Hydrogen Hub, will provide 2370 tons annually from 2023.

Currently, there are around 20 ongoing pilots in the maritime sector. Most interviewees discussed a “chicken or the egg dilemma” as regards supply and demand. In addition, Yara has a program to decarbonize its fertilizer production from 2025, via green hydrogen. The possibilities for replacing coal-fired power plants in Svalbard with hydrogen or ammonia from wind in Finnmark are investigated [54]. Furthermore, there are efforts to produce hydrogen from offshore wind, to provide stable renewable power for offshore installations and shipping. Hydrogen for stationary power is not very relevant in the Norwegian context. However, hydrogen for flexibility services may limit the need for grid investments associated with largescale electrification [55].

MLP provides a system perspective on the factors and interactions shaping t energy transitions. At a wider ***landscape*** level, where most actors have little influence, the decreasing

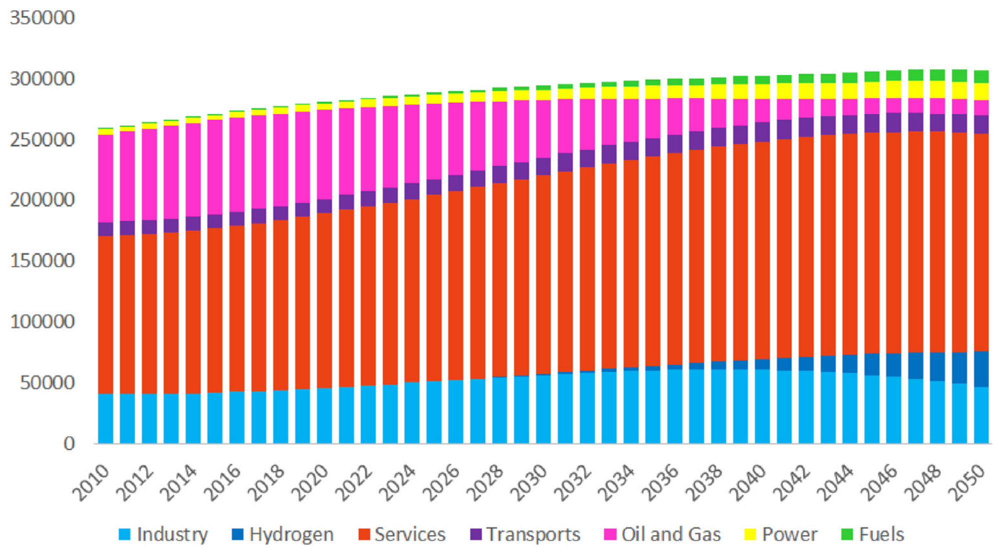

Fig. 5 – Dynamics of the GDP over time with sectoral allocation in the IND scenario.

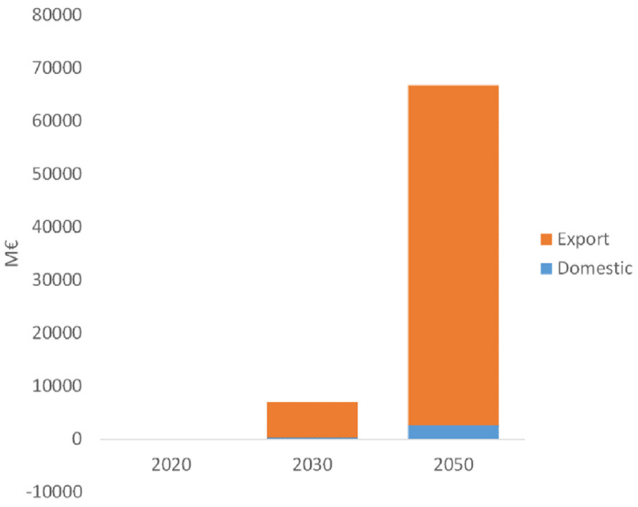

Fig. 6 – Allocation of hydrogen consumption in the IND scenario.

cost of renewables and international climate collaboration have increased the pressure for radical energy innovations. On the other hand, increasing popular resistance to e.g. wind power [56] brings uncertainty. The *Clean energy for all Europeans* aims to adapt the market to a system with more variable renewable energy, but most member states have so far adopted capacity mechanisms with a national focus, and the level of climate commitment is variable [57,58]. Some studies suggest that renewable electricity will become consistently cheaper than fossil gas before 2030 [59], but others favour the combination of electrification and gas [60,61]. Beside EU's hydrogen strategy, national strategies increasingly take an integrated approach, where multiple roles for hydrogen are envisaged [1,62]. This has expanded the “window of opportunities” for hydrogen. Of recent, another uncertainty has been added: The covid-19 crisis may both reduce the ability to invest and increase the focus on green job creation.

At the ***regime*** level, prevailing set of rules and practices that uphold and reinforce the existing system, one finds two dominant and partially conflicting interests in Norwegian energy politics: One linked to the power sector and electrification, and the other to the petroleum-based industry [63]. These are associated with institutional lock-ins [64]. Norway's current effort to establish a full-scale value chain for CCS may be related to network externalities and institutional learning effects linked to fossil fuels. The national energy policy and action plan for infrastructure for alternative fuels have a strong emphasis on electrification, while presenting hydrogen as a longer-term solution. While future support for hydrogen refuelling stations will depend on the increase in vehicles, hydrogen represents opportunities for the maritime industry, and Norway will take a special responsibility to facilitate development in this area. However, already heavy investments in battery-electric solutions and charging infrastructure may create new lock-ins. Furthermore, end-user acceptance in shipping and heavy-duty transport may be higher for biofuels, which do not require costly infrastructure changes. For most of the energy-intensive industry, hydrogen will also require radical and costly process change. Especially for maritime applications there are remaining legal-administrative barriers, related to hydrogen's risk profile as a low-flashpoint fuel [65]. Some interviewees had reservations with a view to safety. Others noted that social acceptance is limited due to the past construction of hydrogen as a “hype”, and some expressed scepticism about its overall sustainability, especially when produced from natural gas reforming with CCS.

In Norway, carbon tax has been the key control policy. This has been related to the form of governance, in a small state with consensus-driven policymaking [47]. Most of the consulted stakeholders underscored the importance of the CO2 tax, and many argued for a CO2 fund to stimulate uptake of hydrogen solutions. Whereas the national authorities aim for a market-based development, municipalities and counties have been active as facilitators, due to co-benefits such as regional development and reduced local pollution. All the studied production initiatives have benefited from public support. On the demand side, Norway has one of the best incentive schemes for hydrogen cars [66]. Public funding for R&D, demonstrations and public-private partnership to stimulate uptake of hydrogen solutions has increased significantly, and green procurement is used actively to enable transition in public tendered transport [67]. Still, the national hydrogen strategy has been criticised, for not signalling clearly that public agency should prioritize industrialisation and development of hydrogen value chains. The crucial role of CCS and the need for public-private partnership to facilitate maritime and industry applications were emphasized by most interviewees. Main tensions and lock-ins are summarized in Table 4.

In Foxon's terms, we find a tension between two institutional logics, a market logic and a governance logic surrounding hydrogen [68]. We also see a tension between industry networks oriented towards renewables and natural gas, green and blue hydrogen, which seems to have contributed to the “chicken or the egg dilemma”. The observed lock-ins are associated with barriers. However, some may also work in favour of hydrogen. Competences in incumbent industries and strength of public R&D actors were important for the early experiments with hydrogen. Economies of scope, due to specialisation in key elements, and the beneficial interrelatedness with gas related technologies, have also been emphasized in previous research [64]. Similar interactions are found in the studied production initiatives, where incumbents play central roles, while lead technology providers and consultancies are important intermediaries. In addition, local networks and synergies are important in all cases (see Table 3).

Considering the ***niche*** level, an OECD report in 2006 found the Norwegian hydrogen sector weak, dominated by a few large incumbents [69]. By 2020 the Norwegian Hydrogen Association counted 45 members, and our interviewees mentioned at least 23 additional companies with important roles. Hydrogen is the focus of two national research and innovation centres, and the actors are active in national and international standardization committees. Most of the interviewed stakeholders emphasized that cost reductions are expected towards 2030, as noted in recent studies [70,71]. Due

Table 3 – Overview of the studied hydrogen production initiatives and their characteristics.

Initiative/location	Source/Technology	Actors, networks	Goals, ambitions	Scales, levels	Resources	Public support
Raggo-vidda	Windpower Electrolysis, PEM (polymer electrolyte membrane)	VarangerKraft Hydrogen, power company, Hydrogenics, Statkraft, Statnett	Pilot: 2,5 MW Fullscale: 1080 kg/day	Region (transport, industry, flexibility) Svalbard	Front-end research and development, national interest	EU project (Haeolus)
Glomfjord	Hydropower electrolysis (alkaline)	Glomfjord Hydrogen, Greenstat, Meløy Energi, NEL, municipality, Yara	6t/day	Region (transport, industry)	Existing facilities, industry tradition, local support	Innovation Norway, regional development
Tjeldberg-odden	Natural gas Pressure Swing Adsorbtion (PSA)+CCS	Hydrogen Mem-Tech, Equinor RENE, Tjeldberg-odden development company)	Ongoing PSA pilot, methanol plant with capacity for 15 tons H2 pr day	Region Largescale export	Global industry world-leading competence	National CCS research program, research council, state enterprise for CCS
Tyssedal	Hydropower Electrolysis (alkaline)	Tizir (iron ilmenite plant), Greenstat, Sunnhordland power company, Statkraft	30t/day (50 MW) Replace 100 000t of coal at Tizir (5–10 years)	Region (industry)	Consultants vs. well-established actor, national company with multinational owners	State enterprise, support for zero-emission energy solutions
Kvinnherad	Hydropower, Electrolysis Liquefaction	Sunnhordland power company, Gasnor (Shell) NEL, Kvinnherad Energi, Greenstat	10-20t/day (30–60 MW)	Region (transport) Export	Early days, Letter of Intent	County, municipality, Norwegian Environment Agency
Jelsa	Hydropower electrolysis (PEM)	Norsk H2, HY2GEN, EU investors, local entrepreneur, ITM Power	2020: 100 t/month 10 MW Up to 1500 t/month	Region (transport) Export	Private capital, existing facilities, competence from Germany	Innovation Norway

Table 4 – Summary of main lock-ins and tensions influencing the scope for hydrogen production in Norway.

Lock-ins	Tensions
• Economies of scale in petroleum and hydropower • Network externalities – fossil transport and industry regimes hindering hydrogen infrastructure • Learning effects - competences in incumbent industries and public R&D facilitating early experiments with hydrogen • Economies of scope - specialisation in key • elements for deploying hydrogen Informational increasing returns – wide acceptance of battery-electric solutions • Technological interrelatedness – with gas • Collective action – renewables electrification seen as clean & safe	• Interests linked to petroleum vs. power sector • Market vs. governance logic • Protect established industry vs. develop renewable business • National priorities vs. regional interests • Uncertain business case vs. potential of CCS • Debates over wind power, land use • Hype vs. 'hypertech' • Green vs. blue hydrogen • Centralised vs. distributed energy system

to the large share of flexible hydropower, power prices are relatively stable in Norway, and the power surplus is expected to increase significantly from 2018 to 2030 [72].

Still, technological challenges remain. Liquefaction is a key to storage and distribution across larger distances. While costs are coming down [73], a liquefier is a major investment. At the attended workshops, several stakeholders emphasized that the business case for CCS remains uncertain. The emergence of ammonia and Liquid Hydrogen Organic Carriers (LHOCs) is generating interest, but more alternatives may also create uncertainty and delay the uptake of hydrogen solutions.

The overarching visions have also shifted: From a "hydrogen economy" linked to fuel cell electric vehicles, to one where hydrogen may play several roles in a wider energy mix, both internationally and in Norway. In two of the attended workshops, a rhetoric of competition between proponents of blue and green hydrogen was a stated concern. However, complementarity and common interests, especially in the maritime, are, also increasingly emphasized. Thus, there are many signs of maturation [74]. However, there are also limitations when it comes to market formation, and for some applications learning processes have not stabilized. The positive trends and remaining challenges at niche level are summarized in Table 5.

Table 5 – Summary of positive trends and challenges observed for hydrogen as an emerging niche innovation in Norway.

Positive trends	Challenges
• More and stronger large-scale production initiatives • Cost reductions, expected to continue • Technologies maturing fast • Norway leading in maritime applications • Increasing capacity and coordination • From competitive to collaborative rhetoric • Recent public-private partnerships • Increasing orientation towards 'energy mix'	• Chicken or the egg dilemma • Liquefaction, storage and transport costly • Remaining safety issues • Regulatory gaps • Risk, uncertain framework conditions • Social acceptance • Blue hydrogen contingent on CCS • Multiplexity and 'fuzziness' (H2, Ammonia, LHOCs, etc.)

Discussion

Hydrogen may play a central role in decarbonization of the Norwegian society, both because bio resources are limited, and not sufficient to cover the energy demand in sectors like transport and industry, and because hydrogen is a potential source of sustained income from natural gas resources and new income from renewables. Hydrogen is needed to meet the 2050 objectives unless substantial new technological breakthroughs happen in other areas. Further improvements will in any case be needed in both battery technologies, hydrogen technologies and biofuels production to meet the 2050 low carbon objectives. Fossil fuels will gradually be phased out from the transport sector. This transition will need planning and building of new infrastructure for refuelling and charging of zero emission vehicles and vessels. Building new infrastructure is both costly and time consuming, thus it is necessary to base investment decisions on detailed analysis of the future demand for hydrogen. With a too optimistic view on learning rates for hydrogen technologies, there is a possibility of building more hydrogen infrastructure than needed, however, with too pessimistic assumptions, a delay in building new infrastructure can also make it difficult to reach 2050 targets.

The analysis shows that when hydrogen technologies are made available, and the technology learning rates give reduced investment costs for hydrogen technologies towards 2050, hydrogen is utilized in both in industry and transport (land-based road freight, air and sea transport). The domestic demand for hydrogen increases to 27 TWh in 2050, of which approximately 50% is produced by renewable electricity using electrolysis and 50% from natural gas using steam methane reforming with CCS. Almost 80% of the hydrogen produced is used in the transportation sector, while the remaining 20% is used in the processing industry. According to the qualitative case study, there are ongoing initiatives in production, industry and transport in Norway in line with the results from the energy system analysis.

The linkage between the long-term energy system model TIMES-Norway and the power market model EMPS is described in Ref. [38]. The qualitative energy system results in this paper are based on several iterations between TIMES-Norway and EMPS, such that the long-term energy system investment strategies consider the operational complexity of the power sector. This is a strength when modelling of renewable power generation and import/export electricity prices in the energy system model, and it provides consistent assumptions concerning Norwegian electricity demand and capacity in the power market model. Developments in one sector have major impacts in other sectors, e.g. the production of hydrogen increases renewable electricity production, but can also increase the electricity price. The analysis shows that Norwegian energy resources can cover the increased demand for electricity and hydrogen in a decarbonised energy system. However, further work is needed to encompass other variables such as clean feedstock, technical feasibility, and performance of a renewable hydrogen supply chain.

In future work interlinked analysis of the economy, the energy system and detailed transport sector models can provide new insight in policy measures suitable for supporting the transition to a zero-emission transport sector.

Major structural changes are needed in the Norwegian economy to maintain economic growth when petroleum exports are phased out. Continued economic growth requires export of hydrogen, or similar high-volume services or commodities. Phasing out fossil industries can slow the economic growth, both because of the direct effects of phasing out the oil industry and because the reduced availability of industrial input and fuels will trigger a rise in price for substitute commodities.

The development of a large-scale hydrogen industry, capable of exporting large amounts of hydrogen that can partly replace the lost value from the petroleum sector, is strictly connected to the availability of large amounts of renewable power production. While it is easy to see why this is true in the case of production by electrolysis it is nevertheless true also if hydrogen will be produced using steam methane reforming. In this latter case, the process involves burning of natural gas, implying CO_2 emissions as by-product. This negative externality needs to be controlled by CCS. The storage of CO_2 requires a large consumption of electricity; thus, the electricity price will rise. It is therefore important to expand and strengthen the power sector and secure a clean supply of electricity.

The economic analysis assumes that the large amount of available natural resources will allow Norway to produce hydrogen at a lower cost compared to other countries. The extent of export of hydrogen, depend on the capability of other countries of developing an infrastructure for hydrogen. If the demand for hydrogen in Europe increases, Norway may become one of the important players in the European production of this energy carrier. The extent in which this production will not harm the internal activities due to an increase in power prices depends, on the availability of large amounts of renewable electricity.

The strength of current projects and initiatives supports the model findings, that hydrogen may play a crucial role in Norway's transition to a low-carbon society. The increasing pressure for alternative solutions and tensions in the existing sociotechnical regime, combined with the increasing momentum of the hydrogen industry, suggest that the innovation uptake is near a tipping point, where a true market may be unleashed. While political acceptance is increasing, market acceptance is limited by lack of infrastructure, uncertainty regarding future framework conditions, and the “chicken or the egg dilemma”. Hydrogen's complexity as energy solution and the focus on electrification of transport further influence social acceptance. Still, while further technology development is required, the long-term transition potential of hydrogen is increasingly recognized. To move towards the modelled scenario, key stakeholders suggest that more support, cross-sector collaboration and specific national targets for hydrogen production and deployment will be needed.

While quantitative systems modelling allows for structured exploration of specific assumptions and constraints, the inclusion of a socio-technical perspective sheds light on system interactions at multiple levels and addresses dimensions of transition that are not included in techno-economic model assessments [75]. Our qualitative study sheds light on non-economic barriers and areas of uncertainty emphasized in previous research. It draws attention to path dependency and lock-ins linked to existing technologies and institutions. It also provides new knowledge on the state of development of the Norwegian hydrogen industry and the governance arrangements that may be required to depart from the current trajectory.

Conclusions

While the study takes as a starting point the transition away from a petroleum-based economy in Norway, it raises several questions that may be of interest for other regions. When it comes to the key insights from the analysis, they are related to what type of changes are needed in the economy and in the energy system to achieve two sometimes conflicting objectives: reducing or removing climate gas emissions and maintaining economic growth. Some of the key insights that we find are general and can be of interest for any country that will transition towards climate neutrality.

Hydrogen will play a central role in decarbonization of the Norwegian society, both because the available bio resources are limited, and not sufficient to cover the energy demand in sectors like transport and industry, and because hydrogen is a potential source for sustained income from natural gas and new income from renewables.

Hydrogen as an energy carrier is linked to several uncertainties, including international climate and energy policies, technological development, social acceptance and the ability to build markets for use of hydrogen in the transport and in the industry sector. To succeed with the volumes indicated in our study, national and European coordination is needed.

Wind power is needed to provide substantial amounts of renewable power – both onshore and offshore. Wind power is used for hydrogen production by electrolysis and as input factor for implementing the storage of CO2 and therefore facilitating the production of hydrogen using steam reforming.

As the percentage of solar and wind generation in Europe increase, the variations in Norwegian power prices increases both in the short-term, and between seasons and between years, adding value to flexible hydropower resources.

The analysis shows that availability of clean energy is the fundament of continued economic growth.

Combining multiple models as well as qualitative socio-technical research enables a holistic perspective that provides new knowledge on system interactions and should be further explored.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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