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A hybrid perspective on energy transition pathways: Is hydrogen the key for Norway?

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ABSTRACT

Hydrogen may play a significant part in sustainable energy transition. This paper discusses the sociotechnical interactions that are driving and hindering development of hydrogen value chains in Norway. The study is based on a combination of qualitative and quantitative methods. A multi-level perspective (MLP) is deployed to discuss how exogenous trends and uncertainties interact with processes and strategies in the national energy system, and how this influences the transition potential associated with Norwegian hydrogen production. We explore different transition pathways towards a low-emission society in 2050 and find that Norwegian hydrogen production and its deployment for decarbonization of maritime and heavy-duty transport, decarbonisation of industry and flexibility services may play a crucial role. Currently, the development is at a branching point where national coordination is crucial to unlock the potential. The hybrid approach provides new knowledge on underlying system dynamics and contributes to the discourse on pathways in transition studies.

1. Introduction

To meet the climate targets, radical changes to the energy system are required. Considering the complex interlocking social, economic and technological processes this involves, the notion of sustainability transition pathways is gaining relevance. Recent studies suggest that more effort should be made to explore how different pathway approaches may be linked, to provide new insights into transition challenges [1–3].

This paper presents findings from an interdisciplinary project, where mixed methods were used to discuss overarching energy transition pathways towards 2050. We focus on the role hydrogen could take in wider system change, as a “missing link”, allowing sector coupling and decarbonisation of sectors that are difficult to transition via electrification alone [4–6]. The transition potential of hydrogen is recognised by the EU, which aims to provide up to 10 million tons of renewable hydrogen by 2030 [7]. In an initial phase, the EU expects to import hydrogen from neighbouring countries. Japan [8] and South Korea [9], also include large-scale import in their hydrogen strategies.

Norway is fully integrated into EU’s internal energy market, as a supplier of energy. Its power sector is 93.4% renewable [10] and may get the highest power surplus in Europe in 2050 [11]. Beside abundant hydropower, significant on- and offshore wind resources provide a good starting point for renewable hydrogen production. On the other hand, the economy is heavily dependent on oil and gas, and it will be challenging to transition to a low-emission society without adverse impacts on economic growth. Norway’s natural gas may also play an important role in the decarbonisation of Europe, on its own or through hydrogen production with carbon capture and storage (CCS). Strategic decisions taken now may thus have wide ramifications.

We consider the development as at a critical branching point [12,13], where multiple choices create a window of opportunities for hydrogen energy solutions. The paper aims to shed new light on the socio-technical dynamics which have opened this situation and may lead to different trajectories for hydrogen in Norway’s energy transition. We explore the potential and barriers to large-scale production and deployment, based on a mapping of existing initiatives and interviews with key stakeholders. Furthermore, we discuss the role hydrogen may take in different pathways towards a zero-emission society in Norway in 2050. In so doing, we take a “hybrid” perspective, linking qualitative socio-technical analysis and quantitative modelling [14].

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A bottom-up optimisation model for the national energy system (TIMES-Norway) is applied, together with the top-down general equilibrium model REMES, assessing interactions in the wider economy. The multi-level perspective (MLP) on socio-technical system transitions is used to analyse the present complex and still open innovation trajectory for hydrogen, and discuss the feasibility of the model-based scenario results concerning hydrogen. We suggest that the combination of a socio-technical perspective and quantitative modelling can be particularly useful at critical branching points, where several complex pathways and solutions are considered.

The following section presents previous research on sustainability transition pathways, hydrogen and Norwegian energy policy that our analysis relates to. Section 3 describes the research design and methods employed. Section 4 presents our qualitative findings, while Section 5 contains the modelling results. Section 6 is a discussion of alternative transition pathways and their feasibility. Lastly, we conclude and provide some pointers for future research.

2. Background

2.1. Perspectives on sustainability transition pathways

Current discourse on sustainability transitions includes at least three different conceptions of pathways: a) biophysical – centred on long-term, macro-level human-climate interactions, b) techno-economic – focused on techno-economic adjustments linking current sector configurations to low-carbon futures, and c) socio-technical – considering pathways as unfolding socio-technical patterns of change [2,3]. Biophysical and techno-economic pathways tend to emphasize rational economic factors, modelled to show the impacts of different courses of action under specified preconditions and assumptions [3]. Socio-technical pathways focus on a wider array of social and material interactions and how system configurations shift from one arrangement to another over time by attending to coevolutionary patterns [15].

The multi-level perspective (MLP), prominent in socio-technical transitions research, views transitions as non-linear processes resulting from an interplay of actors, institutions and technologies [16]. It draws particular attention to the tension between stability and change, represented by interactions at three analytical levels: 1) niche developments, in terms of stakeholder interaction with radical innovations; 2) socio-technical regimes, representing the stable *meso*-level of institutional structuring of existing systems; and 3) exogenous socio-technical landscape developments [16]. One strand in MLP has focused on developing pathway typologies with regard to the overarching multi-level patterns (e.g. substitution, transformation, reconfiguration, de- and realignment) that may characterize transitions [12,17,18]. These highlight path dependency and lock-ins, which may explain the persistence of existing systems but also set preconditions for development of new pathways [19–21]. However, they also shed light on processes of path creation, or tendencies towards more radical change. While MLP tends to adopt a broad sociological frame, actor expectations are crucial [22,1], and individual projects may reveal aspects of transitions that otherwise remain invisible [1]. Including concrete initiatives in their empirical foundation may therefore also strengthen MLP analyses.

How actors can change the orientation of pathways at critical stages is highlighted in several studies focusing on branching points, or potential openings in established trajectories where multiple choices are available [12,13]. Branching points can be constituted by social as well as material pressures. In an early study on hydrogen pathways [14], the concept is applied to discuss critical thresholds and crossroads at sub-system level, pertaining to technology, user practices, business strategies and government policies. A study on the UK electricity system [12] uses it to pinpoint the challenges alternative pathways imply for different actors. A more recent study focuses on the dynamics that create, contest and define branching points for decarbonisation in Canada [13]. While the latter stops at discussing how actors might shape alternative trajectories, we examine alternative trajectories in more detail, in terms of their interactions and implications for the national economy, and their socio-technical feasibility [3].

Different pathway conceptions can be mobilised separately or jointly [1–3]. During the last decade, a strand of research aiming to link quantitative models and socio-technical transition frameworks has emerged [23–26]. Recent reviews [15,26] identify three methodological linking strategies:

- Iterating – defining the narrative of a transition and translating it into a set of assumptions serving as inputs for a model
- Merging – bringing storylines and models together to form a model incorporating socio-technical elements
- Bridging – storylines and models are run in parallel and interact only at certain defined points, for example via shared concepts

It is argued that to support transformative change, there is the need to a) pluralise pathways, broadening the scope of search, b) consider their temporal ordering (e.g. branching points, interim steps, etc.) and c) attend more to the conditions for pathways realisation [3]. Considering recent arguments for more focus on multi-sector interactions [27] and "whole systems" (considering both generation, distribution and use) in energy transitions research [28], this may be particularly important. This paper contributes by providing an empirical study where multiple pathway conceptions and their conditionality are discussed.

2.2. Scope for hydrogen in sustainable energy transition

Internationally, a range of studies propose overarching transition pathways, towards the EU target of 95% reduction of climate gas emissions by 2050 [11,29,30], a 100% renewable power system [31,32], a temperature rise below 2 °C [33,34], or "the best estimate" [35]. These depend largely on electrification, with big investments in power generation and grid capacity. Estimates for the share of wind and solar power vary from 46% [34] to 90% [36]. Extensive wind power development is, however, controversial [37], and projections indicate that it is not possible to reach a 100% renewable energy system by 2050 without exceeding the limit for sustainable utilization of biomass resources [38]. This underscores the need for alternative solutions.

Several studies quantify the future role of hydrogen [39,40,41]. Estimates of the global demand in 2050 vary greatly, from 67 [33] to 650 million tons per year [42]. For Norway, a market from 250 000 tons [6] to around 450 000 tons per year [43] is estimated for 2030. At the same time, it is argued that some of the prevailing hydrogen scenarios involve degrees of optimism which are difficult to justify [44]. The hydrogen society agenda is seen to exploit socio-technical imaginaries, or "collectively imagined forms of social life and social order reflected in the design and fulfilment of nation-specific scientific and/or technological projects" [45] p. 120, to confront the multiple obstacles that still hinder uptake of hydrogen [46]. A recent study shows that whereas formal roadmaps tend to elide social and policy uncertainties, individual stakeholder expectations highlight their conditionality [47]. The consulted stakeholders emphasized the need for technological, social and institutional co-evolution, to realise hydrogen's potential as a sustainable energy carrier. Non-economic barriers, including 1) complex legal-administrative procedures, 2) lack of information guidelines and standards, 3) lack of public knowledge and awareness, 4) limited acceptance, and 5) lack of government initiatives to provide infrastructure, still prevail [48].

For Norway specifically, limited understanding of the global challenges and unclear energy policies are considered as a challenge [48]. This is related to the country's abundant renewable energy and small-state political economy [49]. Norway was an early climate pioneer [50], and its success with electrification, especially for decarbonising transport, has been highlighted [51]. However, governments have increasingly struggled to reconcile the petroleum-based economy and an ambitious mitigation policy [50,52]. While climate policy should both promote new low-carbon solutions and constrain existing polluting industries [53], Norwaýs has been more ambitious in transport than in the energy sector, where niche support and disruptive policies remain weak [49].

At the same time, the corporatist orientation [49] may be conducive to hydrogen. When Norway began R&D on hydrogen energy, the prospect of using natural gas for electric power was an important reason [54]. Substantial innovation activity from 1990 to the early 2000 s was linked to two different technological trajectories: Statoil (now Equinor) seeking new applications for natural gas, and Norsk Hydro focusing on electrolysis to produce hydrogen from hydroelectric power [54]. Whereas the latter, called “green” hydrogen, is a zero-emission alternative, hydrogen from natural gas reforming demands CCS to be classified as low-carbon, so-called “blue” hydrogen [55]. In the Norwegian context, main arguments for the former are scalability and availability to exploit stranded power today, whereas “blue” hydrogen is associated with larger volumes and lower future costs, and there has, at times, been a rhetoric of competition. Put together, these observations suggest that the discussion of hydrogen’s role in energy transition pathways may be enriched by perspectives that take both techno-economic and socio-technical interactions into account.

3. Research design and methods

3.1. Research design

Our “hybrid” approach is rooted in an applied science project (2016–2020), where social scientists, energy experts and economists worked in consultation with seven user partners from the energy sector (see Annex 1) to develop an “energy roadmap” for Norway towards 2050. We define it as bridging, in that model-based scenarios and socio-technical analysis were iteratively compared, contrasted, and combined to address the focal challenge [1]. In terms of the eight-step bridging procedure since proposed by Geels et al. [56], the country in this case was given. The user partners were involved from the beginning, when a reference scenario based on existing projections and trends was established. The third step, conceptual exploration of alternative scenarios or pathways [56], was also participatory, with an initial desk study followed by two partner workshops. Different policy choices and trajectories for technology, market and industrial development were considered. However, socio-technical pathway typologies were not explicitly mobilised. In line with [56] alternative pathways were modelled, and we did a qualitative MLP study on hydrogen, identified as the most crucial innovation in this case. In step six, the quantitative scenarios were confronted with the qualitative study. Then, for an integrated perspective on pathways and their implications (step seven and eight in [56]), socio-technical typologies [17,18] were applied in two workshop discussions with the user partners.

In this paper we foreground the case-study, which investigated the scope for hydrogen as an energy carrier, with a focus on technology, market, actors, and institutional dynamics. This is connected with the quantitative scenario assessments exploring long-term strategies for the whole energy system, as illustrated below (Fig. 1).

The overarching problem formulation was elaborated through the initial study of policy and pre-existing scenarios, highlighting the challenges linked to oil and gas and need for radical innovations to decarbonise transport and industry. This informed the definition of the quantitative scenarios and focus of the case-study. The case-study assesses the ongoing trajectory and socio-technical interactions influencing the scope for hydrogen, starting from concrete initiatives. Hence, it is complementary and also provided inputs (e.g. data on costs, expected price developments) to the quantitative modelling, which explores future needs, potentials and impacts in a national perspective. As indicated (Fig. 1), the concept of a critical branching point is considered as the focal bridge [1,15]. However, goal-setting, momentum, depth and scope of change [1] are also used to discuss and findings from the two threads of investigation. The final discussion of sustainability transition pathways is guided by the broad understanding of feasibility and evaluation frame proposed by Turnheim and Nykvist [3], considering pathways as representations, in terms of their envisioning of transition potentials, and the conditions for their realisation. On the right-hand side of Fig. 1 the vertical order is shifted, to illustrate that in a future-oriented perspective the models provide more specific results, whereas the socio-technical analysis helps relate these to historical processes and emergent properties in system change [1]. The specific methods are presented below.

3.2. Qualitative case-study on hydrogen

The case-study combined three methods: 1) An exploratory document study including previous research, grey literature, public documents and news reports, to get an overview of current perspectives on the status, drivers and barriers to hydrogen as an energy carrier. 2) Semi-structured interviews. Since adequate supply is crucial to develop hydrogen value chains but deployment has been most in focus, we used six large-scale (>5 MW) production initiatives as empirical starting point. These were selected in consultation with the national hydrogen association, as the most promising in 2018. Key actors were interviewed and publicly available information was used to map the actor networks, motivations and goal ambitions, technology, resources and market opportunities for each initiative. Based on snowballing, a broader set of stakeholders were interviewed, on their activities, plans and perceptions of the transition potential of hydrogen in a long-term perspective. The interviews were carried out as 1–1.5 h physical or video meetings, with notes systematically coded and compared in Excel. The categories and number of interviewees are presented below (Table 1).

3) As an entry to the dialogue between actors and key stakeholders, participant observation at four national and three international workshops was carried out. 30–180 actors from different parts of the value chain, as well as other stakeholders, participated in each. The authors participated as organizer (1), presenter (2) and regular attendants (4), and recorded observations systematically. For further information on

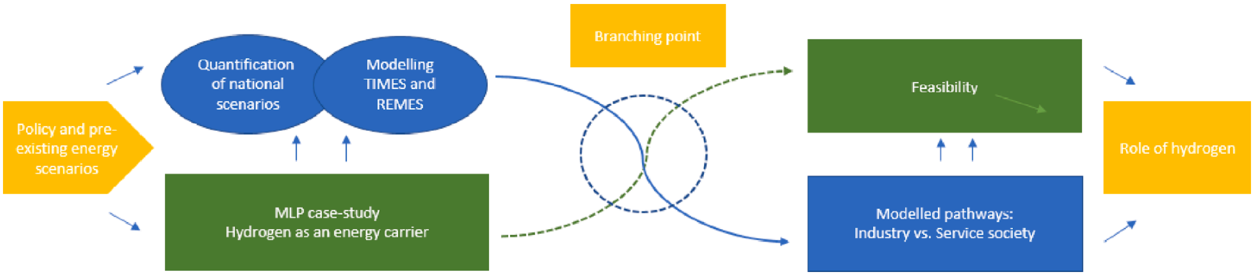

Fig. 1. Overarching research design. Quantitative elements coloured blue, qualitative socio-technical elements green, and connecting, integrated parts of the process represented in yellow.

Table 1
Categories of stakeholders interviewed for the case study.

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, energy and climate	2
Total sample	26

the interviewees and workshops, see Annex 1.

Following the MLP, the qualitative data were analysed in terms of three levels: niche developments (hydrogen innovations; emerging solutions, actors, networks), socio-technical regime (the established practices and rules that stabilize the existing energy system and may either hinder or facilitate uptake of hydrogen), and the socio-technical landscape (wider trends and developments, beyond the actors' influence) influencing the scope for hydrogen in energy transition [16].

3.3. Scenario development

For the scenario development, the framework from e-Highway2050 [57] was used to discuss alternative scenarios with technological, economic/financial, socio-political and R&D dimensions. These were held up against the reference scenario. After several iterations with the user partners, two simplified scenarios were selected for quantification: The "Industry Society", where the petroleum sector is reduced and converted to natural gas reforming with CCS, and the "Service Society" where petroleum is shut down completely, but the service sector grows to replace its contribution to the national income and behaviour change, energy efficiency and utilization of bioenergy come in more strongly. In the "Industry Society" the relative share of activity (and energy use) between the industry and the service sector is kept as in 2018. In the Service Society, the service sector is assumed to grow while the industry sector remains at a stable level, continuing the trend before 2018 up to 2050.

For both scenarios, population growth is assumed to be in accordance with Statistics Norway's middle scenario (+29% to 2050) [25], and the future of the European power system is based on the X-7 scenario of eHighway2050, where wind and solar energy cover 61% of annual power use [58]. The two scenarios were quantified for use in the mathematical model analyses, as outlined in Table 2.

3.4. Modelling

TIMES and REMES were selected to provide quantitative analysis including a detailed representation of the complete energy system, stochastic aspects of renewable generation in the power system, the technical aspects of the power grid and regional aspects of the overall economy. Previous energy scenarios for Norway towards 2050 focus on the energy or power sector separately and do not include impacts on other sectors nor provide results with a spatial resolution for Norway.

TIMES is a modelling framework providing a detailed techno-economic description of resources, energy carriers, conversion technologies, energy transmission and demand. **TIMES-Norway** [59] is an optimisation model of the energy system considering Norway in terms of five geographical regions. It provides operational and investment decisions for seven periods from 2015 to 2050. The total energy system cost includes investment in supply and demand technologies, operation and maintenance costs, income from electricity export and costs of electricity import from foreign countries. The model is driven by exogenous demand for energy services, industry, buildings and transport. Each demand category can be met by existing and new technologies such as electricity, bioenergy, 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 costs, efficiencies, lifetime and learning curves. For this study, electricity trade prices were provided from the power market model EMPS [60].

REMES is a forward-looking computable general equilibrium model, representing the Norwegian economy focusing on the energy system [61]. It distinguishes between the same five regions as TIMES-Norway. The input data is from Statistics Norway and the CREEA project [62], while the values for the sectoral elasticities of substitution are based on [63]. Eleven energy commodities concur in the development of final energy, with hydrogen and CCS as backstop technologies. REMES models the long-term dynamics of the overall economy by defining the behaviour of the production sectors, the consumption preferences of the final consumers, as well as the international trade balance and internal and international monetary transfers. The behaviour of each (profit

Table 2
Assumptions for the quantitative scenarios.

Assumption	Reference scenario	Industry society	Service society
CO2 restrictions	No	Yes	Yes
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	Both the oil and gas sectors are reduced to zero.
Industry	Energy demand as in 2015	Energy demand increase with the same rate as GDP (+51% to 2050)	Energy demand as in 2015
Service sector	Energy service demand increases with the same rate as population (+29% to 2050)	Energy service demand increase with the same rate as GDP (+51% to 2050)	Sharp increase in energy service demand (+68% to 2050)
Transport	As in national transport plan - cars increase 37% to 2050 - - road freight increasing 74% to 2050	As in national transport plan - cars increase 32% to 2050 - road freight increasing 85% to 2050	- Person and freight transport kilometres as in 2015-Increased use of public transport
Households	Energy service demand increases with 13% to 2050 (increased population, more efficient new dwellings)	Energy service demand increases with 13% to 2050 (increased population, more efficient new dwellings)	Lower energy service demand, due to increased awareness, reduced consumption, and increased urbanization (−7% in 2050)
CCS	No	Yes	No
Building Integrated PV	No	No	Yes (7 TWh in 2050)
Hydrogen Technology learning	Moderate	High	Low
Biofuels	Follows today's trend, unlimited access, 25% price increase 2040	Restricted access, double price 2050	Unlimited access, no price increase
Energy efficiency	Limited to heat pumps and more energy effective vehicles	Energy efficiency measures included in all sectors	Energy efficiency measures included in all sectors

maximizing) sector is modelled by defining the level of cross-substitutability of each input factor as the relative prices of these factors change. The behaviour of the (utility maximizing) final consumers is defined via their propensity to exchange a commodity with another as the relative prices change.

Whereas TIMES suggests optimal energy investments, REMES adds insight on how high-impact policies such as the phase-out of the oil and gas sector and/or emergence of a large-scale market for hydrogen may influence the wider economy. The latter is highly relevant, considering the call for more attention to multi-sector interactions in transitions research [27]. Below, main findings from the case-study (section 4) and scenario assessments (section 5) are presented, before we turn to a discussion of transition pathways.

4. Qualitative findings

4.1. Exogenous drivers and uncertainties

To limit global warming to 1.5 °C, a significant upscaling of investments in a wide portfolio of mitigation options is needed [64]. Between 2010 and 2019 the cost of solar photovoltaics (PV) declined 82%, followed by concentrating solar power (CSP) at 47%, onshore wind at 40% and offshore wind at 29% [33]. This has clearly influenced Norwegian players. Large multinationals such as Equinor and Statkraft engage heavily in new renewables and consider hydrogen as a promising business area. Most of the interviewed stakeholders saw decreasing renewables costs as an important driver, but some also noted that the pace of development could limit the scope for “blue” hydrogen.

On the other hand, energy investment as a share of global GDP has been decreasing since 2014, and investment in renewable projects for 2020 was expected to fall by around 10% due to Covid-19 [65], which also brings uncertainty about future trends. There is rising awareness and activism [66,67], but also resistance to measures such as onshore wind power [37,66]. The latter is increasing in Norway, where 2020 saw harsh debates and a share of sceptics increasing from 25% to 34% [68].

The Paris Agreement was also upheld as a key driver. While international support for the agreement has been variable, the re-commitment by the US gives cause for optimism. EU’s Climate Action and European Green Deal [69] provide direction, and the Clean energy for all Europeans [70] aims to adapt the market to a system with more variable renewable energy. Still, a lack of climate commitment remains in some member states [71]. Renewable electricity may soon become consistently cheaper than natural gas [72], but the gas community is developing a new decarbonisation narrative, and there are studies favouring the combination of electrification and gas [73]. Norway has a joint climate commitment with the EU, and to what extent the different measures are embraced will influence the scope for “blue” as well as “green” hydrogen.

Moreover, the understanding of environmental challenges is shifting, from individual issues, towards systems and systemic causes [74]. This is reflected in national hydrogen strategies, such as those of Japan, South Korea, China, Germany and France, which increasingly take a holistic approach [40]. Only 14 member states have so far included hydrogen in their plans for alternative fuels infrastructure [75], but EU’s hydrogen strategy sets specific targets for 2024 and 2030 [7]. Hydrogen is also presented as critical for recovery from the Covid-19 crisis by creating sustainable growth [7]. These factors increase the pressure on Norwegian decision-makers, to contribute to sustainable hydrogen development and maintain competitiveness for Norwegian technology providers.

4.2. Priorities and tensions in the national context

The Norwegian government wants to cut climate gas emissions 55% by 2030 and 90–95% by 2050. Reducing emissions from transport and industry, enabling CCS, strengthening Norway’s role as supplier of renewable energy, and low emission shipping are key priority areas [76]. The White paper on energy defines a market-based approach, with focus on hydropower and electrification. It also promises support for R&D on hydrogen [77]. The integrated hydrogen strategy, of 2020, confirms this commitment [78]. However, it does not include specific targets and has been criticised for not signalling clearly that public agencies should prioritize development of hydrogen value chains [79].

National climate policy considers hydrogen as one of multiple solutions for the longer term, especially for long-haul transport [80]. Of the total national support for climate measures in 2020 (around 700 million euro), a large part was dedicated to R&D and demonstration of zero-emission solutions, under a principle of technology neutrality. Carbon tax has been the key control policy [49]. In 2019, a 5% increase for all sectors was announced, and the government foresees annual increases of this order up to 2025. Most of the interviewees emphasized the importance of the CO_2 tax, and many argued for a CO_2 fund to stimulate the uptake of hydrogen and other zero-emission solutions.

As noted above, the current policy relates to a consensus-driven form of governance [49]. In line with [81], interviewees pointed to two dominant and partially conflicting interests in Norwegian energy politics: One linked to the power sector and the other to the petroleum-based industry. Norway’s role as early mover in LNG for ships and persistent efforts to establish a full-scale value chain for CCS may, according to some, be related to lock-ins in the form of network externalities and institutional learning effects linked to fossil fuels. The world-leading test centre and ambition to establish full-scale CCS at Mongstad oil refinery in the early 2000 s spurred the vision of a hydrogen society with hydrogen as “the new oil”. A “hydrogen highway” with five refuelling stations between Oslo and Stavanger was launched. However, the financial crisis in 2008 slowed down investments. Battery-electric cars took off from 2010, and public funding for hydrogen became centered on small-scale “green” projects. On the other hand, the power sector claims “the future is electric” and some stakeholders suggested that the strong focus on electrification has detracted attention from the need for wider system change, in line with [48].

The National plan for infrastructure for alternative fuels in transport [82] prioritizes electrification, with biofuels as a supplement. Incentives for fuel cell vehicles are among the best in Europe [83]. The support for hydrogen refuelling stations has been variable and will in future depend on the increase in vehicles. However, Norway will take a special responsibility for hydrogen bunkering solutions [82], and green public procurement is used to promote low-emission transport both on land and sea, where exploring hydrogen has been encouraged for high-speed passenger vessels [83]. This may be related to the maritime sector’s importance in Norway and its ambition to be a frontrunner in green solutions [83,84]. Heavy investments in battery-electric solutions and charging infrastructure may, however, create new lock-ins, as technologies are costly, long-lived and requiring substantial grid investments. Furthermore, an observation from our interviews, as well as sector roadmaps [85], is that end-user acceptance may be higher for biofuels, which do not require new infrastructure and change of user practices.

In the industry sector, some actors are willing to experiment, but large parts of the industry have an energy and capital-intensive structure, where hydrogen solutions will require risky and costly process change [86,87]. Due to the high share of flexible hydropower, there has been less focus on hydrogen for stationary power in Norway. Producing hydrogen in periods with excess supply may limit the need for grid investments [88], but this has so far received limited attention from policy-makers.

Whereas national authorities aim for a market-based development, counties and municipalities have been active as facilitators. This was emphasized by many stakeholders, in line with previous research [66,89]. Possible reasons for this may be required climate plans and growing focus on innovative, green public procurement, as well as regional imaginaries linking hydrogen and new growth in the maritime industry and/or exploitation of stranded power. The interviewed actors noted that with limited engagement from large public institutions, the willingness to invest in relatively immature technologies will be lower. There are also legal-administrative barriers, most pressing for maritime applications [90]. Many of these relate to hydrogen's risk profile as a low-flashpoint fuel.

Following the failed “hydrogen highway” and demise of grand visions also elsewhere in the world, there has been a tendency to construct hydrogen as a “hype” [91]. Some interviewees felt that this still influences public perceptions, suggesting that socio-technical imaginaries also can have adverse impacts, when they fail or change. Changing framework conditions for LNG and biogas have created uncertainty about the long-term commitment to specific solutions. Moreover, some expressed scepticism about the overall sustainability of hydrogen, with a view to energy efficiency, land use and uncertainty regarding CCS. The plans for full-scale CCS at Mongstad were scrapped in 2013, and the business case remains uncertain. However, in 2020 the Norwegian government decided to support the realisation of a full-scale CCS chain linked to cement production, which also may enable "blue" hydrogen chains.

Thus, multiple lock-ins and tensions are at work. Beside energy markets and change in technologies, these are linked to policy and political action [23]. Diverging sector interests have so far resulted in a compromise and, some say, unclear mix of energy and climate policies. They are also associated with different technological trajectories for hydrogen. As noted by [13], pathways not only involve multi-level patterns, but are just as fundamentally (re)produced through sequences of critical choices at branching points. In this case, actor interactions surrounding CCS represent one such point. Prioritisation of land use for wind power generation, biomass production or other purposes is another. Likewise, prioritising between battery-electric transport and charging infrastructure and enabling hydrogen and other low-emission solutions is a crucial decision. A main, underlying question concerns the transformation of the petroleum sector. At the same time, there is a tension between two institutional logics [12], a market logic and a governance logic, surrounding hydrogen, as illustrated in Fig. 2:

This is apparent in national policy as well as between administrative levels, with local authorities focusing on local synergies which may favour either “blue” and/or “green” hydrogen. Moreover, socio-technical imaginaries have been constructed differently at different points in time, working both for and against uptake of hydrogen solutions.

4.3. Building momentum for hydrogen

In 2006, the Norwegian hydrogen sector was weak, dominated by a few large incumbents [92]. From 2014, with the sharp decline in solar power prices, a profiled investor brought in substantial capital, and the Norwegian hydrogen industry had increasing international success [93]. The first hydrogen cars came, and some counties and municipalities got a renewed interest in hydrogen for transport. Several interviewees emphasized that liberal politician and former Minister for energy and the environment, Ola Elvestuen, was a crucial advocate. Thus, not only corporate actions, but decisions and roles taken by individuals were highlighted.

By August 2020, the Norwegian Hydrogen Association counted 45 companies. In line with [43] at least 23 additional companies were mentioned in the interviews. Incumbent actors still play a central role, but there are also multiple specialised entrants and early users promoting hydrogen solutions. While Norway currently has only 145 fuel cell electric vehicles [94] there are more than 20 ongoing pilots in maritime transport. Since ships require substantial volumes and transport costs are high, securing adequate supply of hydrogen has become a concern. Key stakeholders described a *“chicken or the egg dilemma”*, where uncertainty about supply is hindering deployment, whereas large-scale production requires committed users. The production initiatives we assessed are dispersed along the Norwegian coast (Fig. 3).

As the figure shows, one initiative is linked to “blue” hydrogen, another to electrolysis from wind power, and the rest to electrolysis based on surplus hydropower. Three focus on alkaline electrolysis (AE) while two relate to proton exchange membrane (PEM) electrolysis, which requires less space and works at high current density, which may reduce operating costs. In Glomfjord and Jelsa, facilities from discontinued industry are available. At Tjeldbergodden, 15 t/day of excess hydrogen from methanol production may be used to kick-start “blue” hydrogen production via pressure swing adsorption (PSA), and Equinor is a key partner, working with the whole value chain. In Tyssedal, the ambition is to replace coal and coke in titanium and ilmenite production. The plan in Kvinnherad also includes liquefaction. At Jelsa, large-scale production for export was projected by a German-led consortium, but the local subsidiary went bankrupt in 2019 and the status is unclear.

The expected capacity for the six initiatives over the next years is 10–60 MW, or 2–20 tons per day. Maritime transport and industry are the main target groups, and export is envisaged as a future option also at Tjeldbergodden and Raggovidda. In line with [87], large incumbents are central in three of the initiatives. Some actors, including NEL Hydrogen and consultants Greenstat and SINTEF, are involved in several cases, and regional authorities and development companies are important in all. All the initiatives have received some level of public support, mostly regional, but also R&D funding from the national and EU level.

While high costs remain a barrier, most actors expected cost reductions towards 2030. Some anticipated that increasing carbon taxes and demand for zero-emission alternatives will make large-scale green production profitable within few years. In one case, the actors estimate to reach production costs of around 3–5 euro per kg from 2024 [95]. International studies also expect a drastic lowering of costs of hydrogen from electrolysis in a 2050 perspective [32,96]. Other interviewees suggested that support to reach industrial-scale production for methods such as PEM, anion exchange membrane (AEM) and solid oxide (SOE) electrolysis may be appropriate.

Since this research commenced more initiatives have emerged, e.g. at a windfarm in Smøla [95], at Kollsnes, where a 20 MW gas reforming plant including CCS is planned by 2023, and at Mongstad, where Equinor, Air Liquide and regional power company BKK aim to provide liquid hydrogen for offshore supply ships by 2024 (also marked in Fig. 3). Yara works to decarbonise its fertilizer production from 2025, via “green” hydrogen. The possibilities for replacing coal-fired power in Svalbard with hydrogen from Northern Norway and hydrogen for power in remote communities are also investigated [97,98]. Mixed roles for hydrogen are explored in local and regional energy hubs in Western Norway [99,100]. Furthermore, there are efforts to convert offshore wind to hydrogen and store it on the seabed, to provide stable renewable power for offshore installations and shipping [101]. H21 North of England highlights the potential for export of natural gas and “blue” hydrogen to eliminate emissions from industry and 37 million homes in the UK [102], and similar opportunities are explored in Germany and France.

There are two national R&D centres on hydrogen and fuel cells, and mission-type funding has been provided for selected hydrogen projects since 2016 [103]. Still, most interviewees saw a need for further research and market stimulation. Technological challenges remain, and implementation requires large infrastructure investments. Liquefaction is a key to storage and distribution across larger distances, which remains a major cost challenge. While the operation costs are coming down [104], a liquefier is a huge investment. At the same time, ammonia and Liquid Hydrogen Organic Carriers (LHOCs) are gaining interest [105]. This can influence the acceptance for hydrogen, both positively, by providing more options, and perhaps negatively, by increasing “fuzziness” and fear of lock-ins. Also, several stakeholders at the attended workshops considered the business case for CCS uncertain. Thus, the transition potential of hydrogen, especially hydrogen based on natural gas, is contingent [66] on complementary technologies.

In line with [66], several interviewees noted a divide between actors

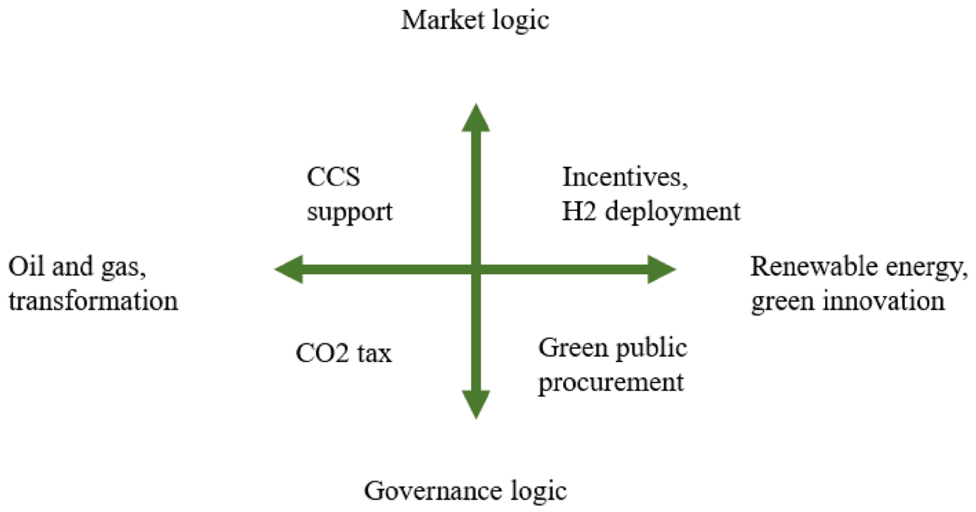

Fig. 2. Tensions in the prevailing socio-technical regime.

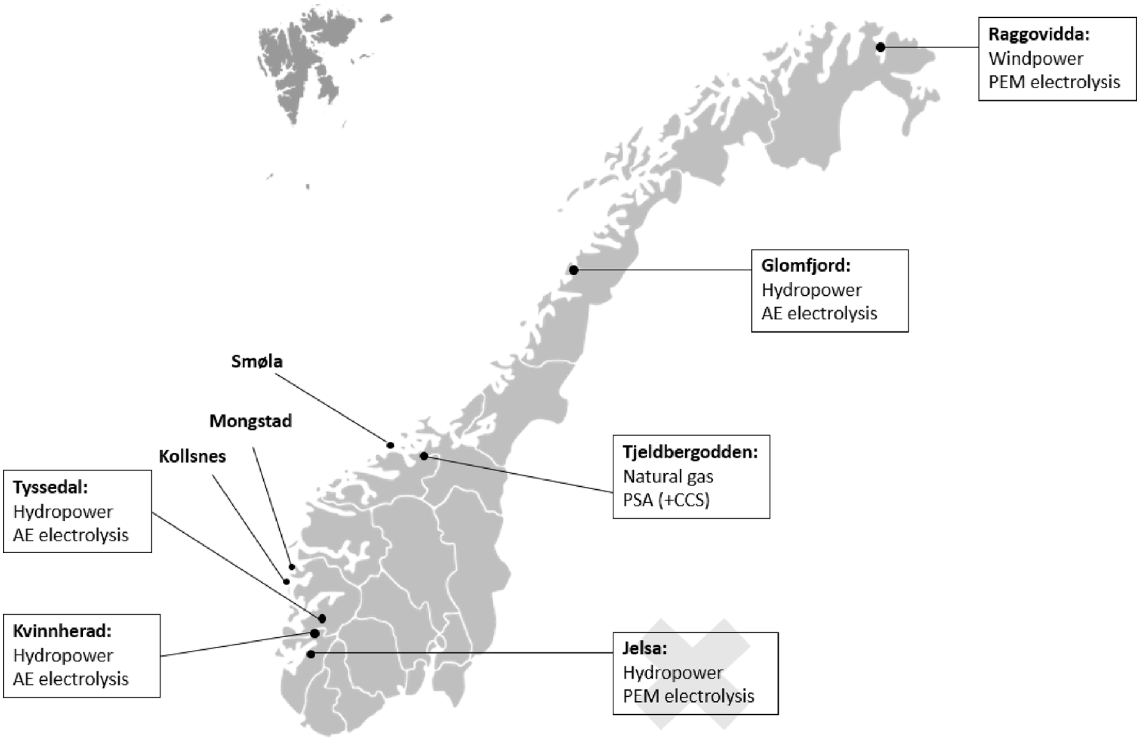

Fig. 3. Overview of studied hydrogen production initiatives.

in “green” and “blue” hydrogen. In two of the observed workshops, a rhetoric of competition was a stated concern. On the other hand, the market is small and transparent. Several actors advocated for joint efforts to develop a larger *“showcase”*. The Norwegian Hydrogen Association has increased capacity, and niche actors take part in national and international standardization committees. As we have seen, there are symbiotic relations with other emerging technologies, such as wind power and CCS.

Thus, according to established proxies [18,87], there are many signs of niche maturation. The explosion of a hydrogen refuelling station near Oslo 2019 caused a set-back in public acceptance. Currently, only one refuelling station is open. However, there are several public–private initiatives to introduce hydrogen for fleet vehicles. As noted, there is a strong momentum in the maritime, and a growing interest in hydrogen for energy storage, transfer and flexibility services. As one actor stated; *“we are nearly there”*, but there is the need for more coordination and cross-sectoral collaboration to unleash a market. Thus, it may be argued that the development at niche level is near a critical threshold or branching point [12,13], where the onward development depends on technological, social and institutional co-evolution, in line with [23,47].

5. Modelling results

The modelling addressed the possibilities and challenges associated with a) shutting down Norwegian oil and gas production and replacing it with full electrification and more extensive use of bio resources, or b) maintaining and transforming the natural gas sector with CCS. These strategic alternatives reflect the two networks of interests and technology underlying Norwegian energy and climate policy and the critical branching point identified in the previous section.

5.1. Future energy use

Both for the “Industry Society” and the “Service Society”, the modelling suggests that the national hydrogen consumption will be relatively low in 2030 but become significant by 2050. Fig. 4 shows the TIMES-Norway results for hydrogen production for domestic supply in both scenarios by 2030 and 2050.

In the “Industry Society” for 2050, a total of 21 TWh (630 000 tons)[1] of hydrogen is produced for domestic use (export being out of scope for TIMES-Norway). When natural gas reforming with CCS is made available at a price of 1 NOK/kWh, about half of the hydrogen production will be by natural gas reforming and half by electrolysis. Without CCS, the total hydrogen supply will be at the same level but provided solely from electrolysis, with a significant increase in power consumption. In the “Service Society”, 3 TWh (92 000 tons) of hydrogen from electrolysis will be used for industrial purposes by 2050, if there are no restraints on bioenergy. With a restriction on imports of bioenergy, electrolysis will produce 17 TWh (507 000 tons) of hydrogen; 15 TWh (446 000 tons) for the transport sector and 2 TWh (61 000 tons) for use in industry, resulting in a sharply increasing power consumption also in this scenario.

As illustrated in Fig. 5, hydrogen consumption in the “Industry Society” will increase significantly in the transport and industry sectors from 2030 to 2050, when hydrogen respectively accounts for 64 and 73% of the market shares in heavy-duty and maritime transport. The estimated amounts for freight are 2 TWh (51 000 tons) in 2030 and 7 TWh (200 000 tons) by 2050, for sea transport 1 TWh (23 000 tons) in 2030 and 8 TWh (226 000 tons) by 2050, for aviation 1 TWh (23 000 tons) by 2050, and industry (energy), 6 TWh (167 000 tons) by 2050. For cars and buses, battery-electric solutions and biofuels will dominate.

5.2. Sectoral dynamics

The REMES results suggest that phasing out oil and gas production and fossil fuels will slow economic growth, due to revenue losses and reduced availability of important input factors for other sectors. Several sectors will also be affected by higher power and bio-resource prices. While per capita GDP (Gross Domestic Product) growth relative to 2007 is 0% by 2050 in Statistics Norway’s reference scenario, it will be −0.43% per capita under the “Service Society” scenario and −0.34% per capita in the “Industry Society”, where hydrogen will contribute importantly to exports and induce spillover effects towards connected sectors. The sectoral dynamics in the “Industry Society” are displayed in Fig. 6.

The same effects under the “Service Society” are displayed in Fig. 7.

Looking at value creation in the “Industry Society” (Fig. 6), the contribution by the hydrogen industry will increase gradually towards 2050. Natural gas is mainly used to produce hydrogen, whose value added partly replaces the decrease in value added for production of oil and gas. The usage of CCS requires electricity and steam in large amounts, which increases the value added for power and steam supply (placed under the sector of fuels). Demand from the hydrogen sector increases the electricity price, which impairs the growth of energy intensive industries. Leaving services as the main drivers of the economy, as in the “Service Society” (Fig. 7), has a much smaller impact on spillover effects and energy prices, and results in a scenario that is less performing growth-wise. While hydrogen may play a less significant role in the economy, it is crucial to reduce emissions from transport, also in the “Service Society”.

6. A “hybrid” perspective on transition pathways

Different pathway conceptions can complement each other as a) representations of ongoing transitions, b) in terms of how they envision transition potentials, and c) how they engage with real-world conditions for pathway realisation [3]. Our discussion is therefore structured along these dimensions.

6.1. Representing ongoing transition

The modelled pathways are presented as strategic options, subject to a rational decision-maker outside the analyses. The socio-technical analysis sees technologies and markets co-evolving with political processes, shedding light on transition challenges or bottlenecks [56] that either are excluded or included as assumptions in the quantitative modelling, such as the uncertainties linked to expansion of onshore wind power, lack of hydrogen infrastructure, legal-administrative barriers, uncertain business case for CCS, social acceptance and remaining technological challenges linked to storage and transportation of hydrogen.

In line with [23,47], we find that institutional change, by way of policy development, network building and standardization, has been and remains important to enable uptake of hydrogen. Including assessment of specific production initiatives as well as deployment provides a “whole system” perspective [28] that sheds light on system barriers, such as the *“chicken or the egg dilemma”*, and the tensions over “green” and “blue” hydrogen. Over the years, there have been twists and turns related to international market trends, the development of other low-emission technologies, and fluctuations in public funding. Lock-ins linked to existing processes and practices create inertia, and there are tensions between different institutional logics [12] and sector interests which have been associated with fractions but of recent seem to be conjoining. Interestingly, the interviews also highlight the role of individual entrepreneurs and socio-technical imaginaries [46].

This underscores that transition pathways are far from linear [16–18]. Previous decisions, such as abandoning “the hydrogen highway” and putting full-scale CCS at Mongstad on ice, have pulled in different directions. Still, an overall impression from the case-study is that hydrogen has shifted from a predevelopment phase, when relatively immature technologies were explored by incumbents, to a take-off phase where various technological options coexist, some mature and some early stage. As illustrated below (Fig. 8), this is the result of increasing landscape pressures, including interactions between political developments, hydrogen strategies in frontrunner countries, global market trends, and increasing knowledge and awareness.

The trends at landscape level cause tensions in the established energy regime, linked to different actor-networks, technological trajectories and imaginaries, as well as regional concerns and ambitions. At niche level, the initial phase with R&D dominated by incumbents was followed by a period with multiple, more distributed and partly competing initiatives. Currently, there is a tendency towards convergence. As the figure illustrates, we seem to approach a critical branching point [12,13], both in terms of mounting regime tensions linked to oil and gas transition (hydrogen as “the new oil”) and climate change mitigation linked to new renewables (“future is electric”), and in terms of hydrogen niche development, where the need for national coordination is emphasised.

While the socio-technical analysis sheds light on historical patterns and contemporary interactions, the “Industry Society” and the “Service Society” provide techno-economic representations of the future system configurations that may result from alternative strategies, as illustrated below (Fig. 9).

Based on existing sectors and a set of pre-defined assumptions, the models provide easy-to-grasp and seemingly objective accounts of how hydrogen will be produced and applied, and how this will influence the value creation in different sectors. Since current sectors and resource flows can be modelled quite accurately and assumptions are traceable

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[1] Conversion factor 33.33 kWh per kg hydrogen (Source: Norwegian Water Resources and Energy Directorate).

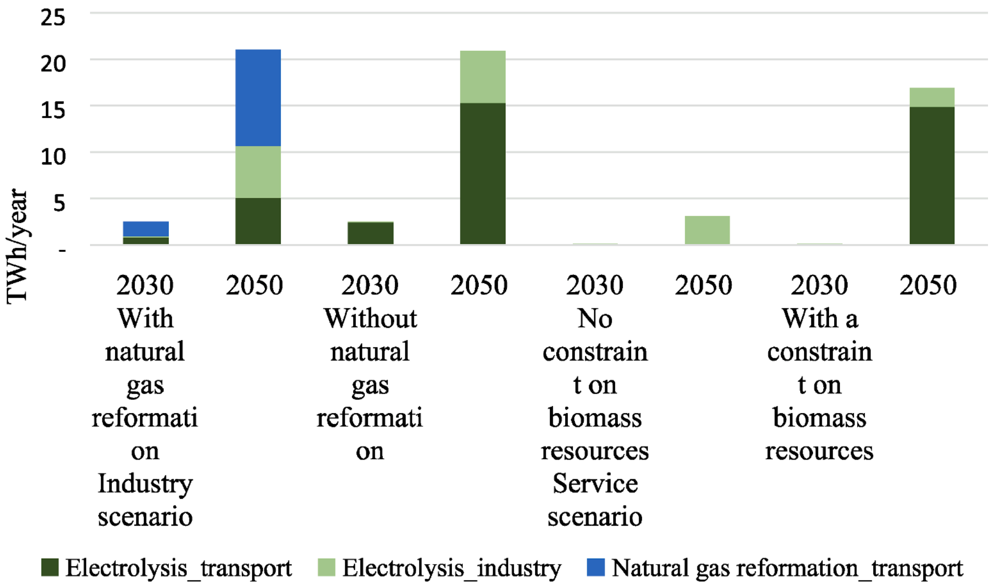

Fig. 4. The distribution of green and blue hydrogen for domestic supply in the different scenarios.

and transparent, this provides valuable knowledge on how multi-sectoral interactions [27,28] may play out in a long term perspective, towards 2050. In the "Industry Society" hydrogen may play a crucial role, both in terms of energy use, emission reductions, and national value creation. The sources and technologies for hydrogen production will depend on the outcome of another branching point, relating to CCS. In the "Service Society" hydrogen has less influence on the economy, but when the limited availability of bioresources is taken into account, "green" hydrogen becomes necessary for the decarbonisation of transport.

Thus, linking the techno-economic and socio-technical pathway perspectives expand the scope of analysis, both in time, where historical, contemporary and future interactions are included, and in scale, where both national and local/regional scale, as well as that multi-technology and multi-sector interactions are taken into account.

6.2. *Envisioning transition potentials*

In terms of the above-mentioned pathway typologies [17,18], the "Industry Society" can be considered as a substitution pathway, where strong landscape pressure and regime tensions open a window of opportunities for hydrogen. This occurs through incremental institutional change and improving price/performance characteristics. The "Service Society" may be understood as dealignment and realignment pathway [18]. The oil and gas sectors are decommissioned, but there is no single, stable niche innovation filling the gap. Instead, a substantial level of behaviour change is assumed. This implies that co-evolution processes occur alongside technological changes, in line with the most recent definition of this pathway type [18].

The pattern emerging from the qualitative case-study may be characterized as a sequence of transition pathways, linked to landscape pressures that continue to build and gradually become more disruptive [18]. Currently, we see the contours of a reconfiguration path [18]. Pressures to restrict petroleum production and increase new renewables are conducive. Hydrogen solutions are promoted strongly in regions where there are considerable synergies and co-benefits. New hydrogen carriers, such as ammonia and LOHCs, are explored. In line with increasing electrification, the need for flexibility services is increasing, and energy hubs with smart integration of multiple energy carriers, new roles and responsibilities are being tested. In terms of goal-setting [1] stakeholders express ambitions and perspectives in line with the techno-economic scenarios. However, we also find a third perspective on Norway's energy transition, where both "green" and "blue" hydrogen develop as part of a wider energy mix and come to fill multiple functions in an increasingly complex and distributed system. We see 'new combinations' between multiple innovations, as well as second-order learning and unintended consequences, which give this transition pathway an open-ended character [18].

Considering momentum [1], the findings from the modelling and socio-technical analyses are well aligned. Hydrogen is supported in national energy and climate policy, the hydrogen industry is growing, and there are multiple demonstration and pilot projects targeting full-scale implementation in transport and industry, before 2030. The recent development surrounding CCS may be conducive, and the ambitions among the studied production initiatives are in line with the amounts and uses proposed for the "Industry Society" by 2030.

As to depth of change [1], the "Industry Society" involves radical technological change (substitution of natural gas by hydrogen), but leaves other system elements mostly intact. The "Service Society" involves more transformative change, with altered behaviour, consumption and land use patterns. Still, despite their different preconditions, the overarching sectoral dynamics in the "Industry Society" and "Service Society", do not exhibit any radical change, as illustrated by the relative similarity of Figs. 6 and 7. The qualitative study suggests that more profound structural changes may take place, linked to the growth and decline of specific energy technologies.

In terms of scope (number of dimensions that change), the "Industry Society" involves technological and market change across existing sectors. The "Service Society" includes complete shutdown of oil and gas, and a radical expansion of the service sector, as well as changing settlement and transport patterns. The third perspective, foreseeing a more distributed energy system with new sector couplings and a broader mix of energy solutions involves a wider and deeper restructuring, which the quantitative models cannot account for.

Thus, our bridging approach helped broaden the scope and range of trajectories considered. This may be particularly important at critical branching points; As noted by [3] pluralising pathways may be fruitful, especially in contexts of high uncertainty and openness. And although incommensurable, they can be related and discussed using established pathway typologies.

6.3. *Addressing conditions for pathway realisation*

Conditions for pathway realisation may be considered in terms of the

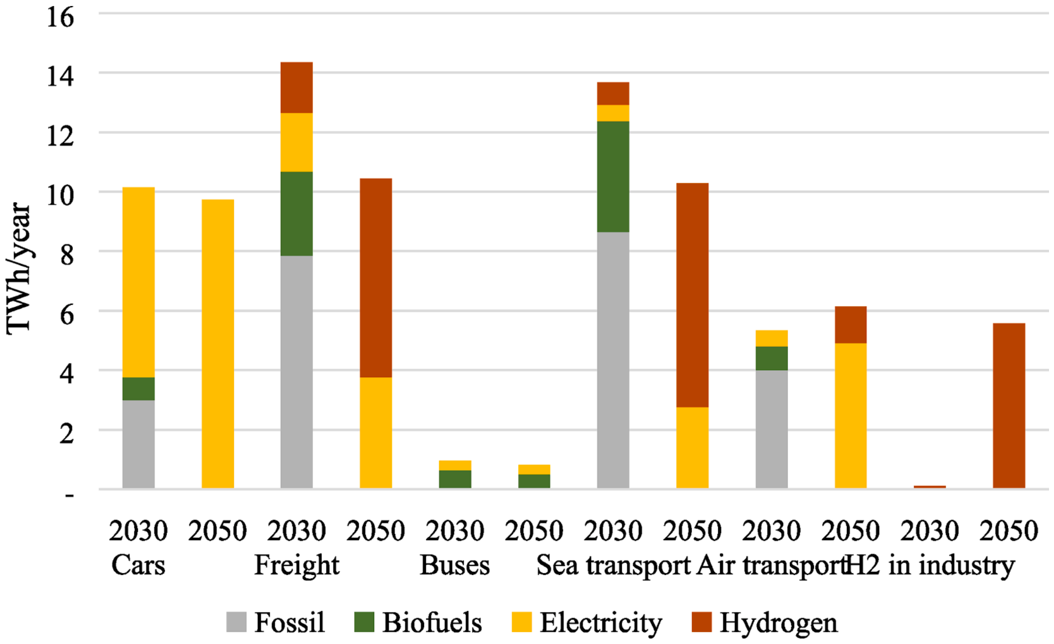

Fig. 5. Distribution of fuels in transport and hydrogen consumption in the industry sector in the "Industry Society" scenario by 2030 and 2050.

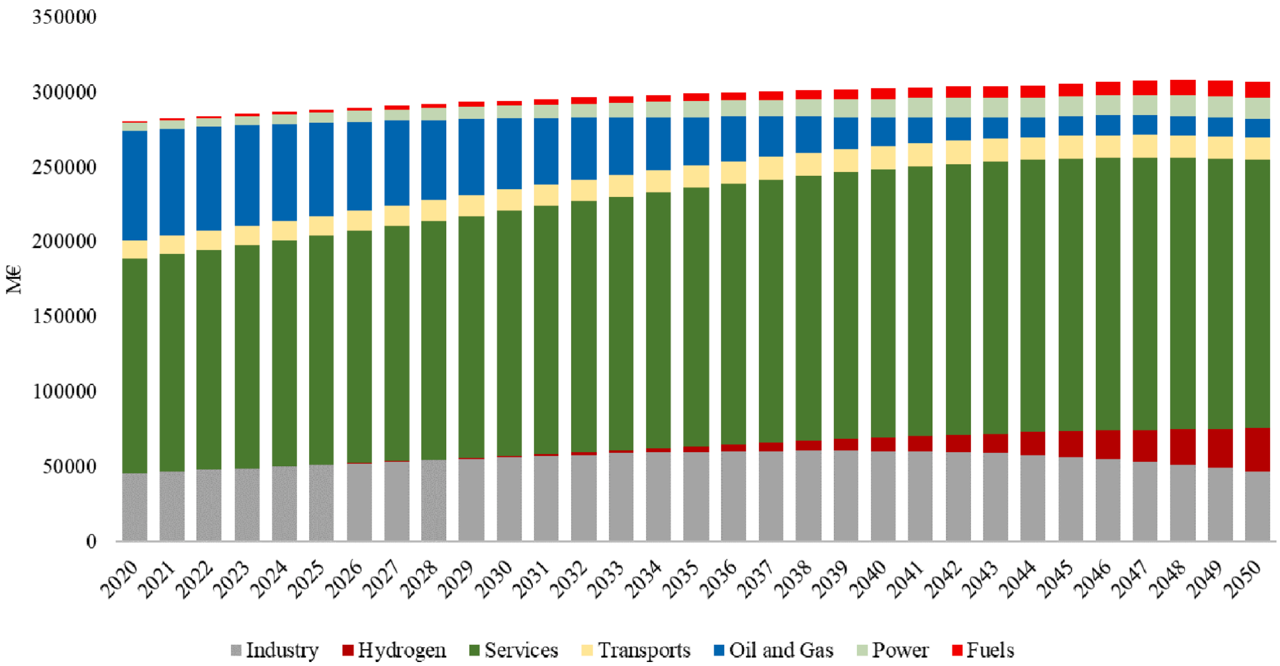

Fig. 6. Dynamics of the sectoral value-added development under the Industry Society scenario (1000 Euros).

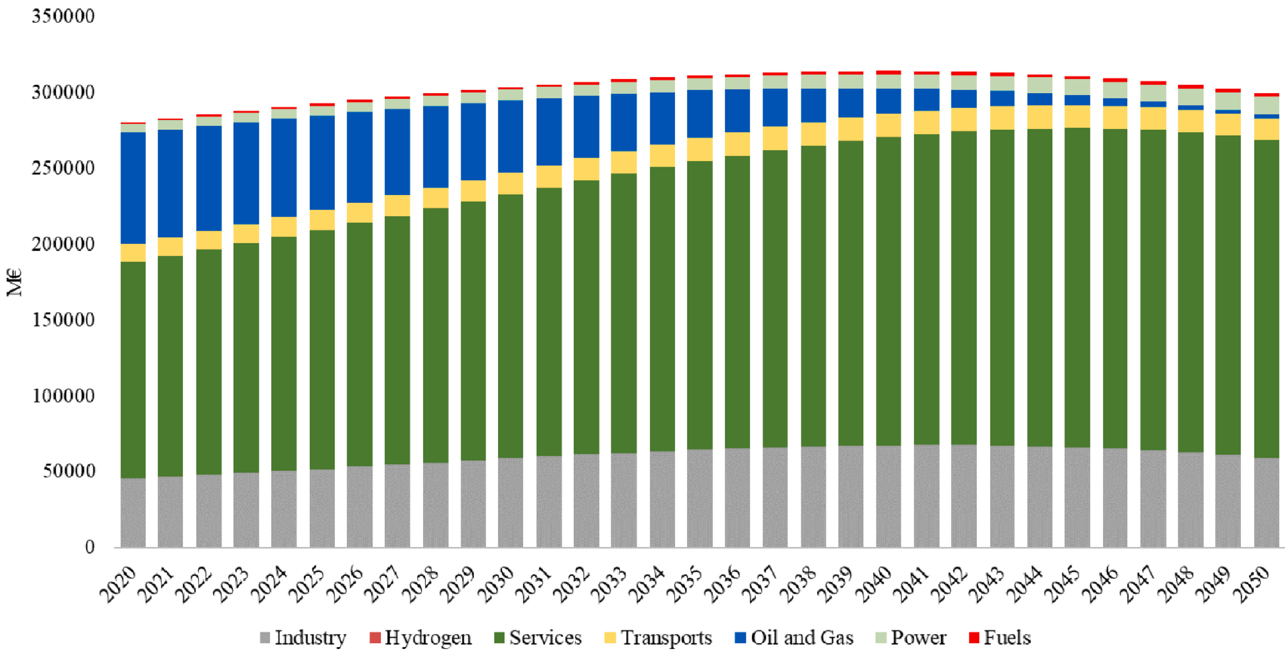

Fig. 7. Dynamics of the sectoral value-added development under the Service society scenario (1000 Euros).

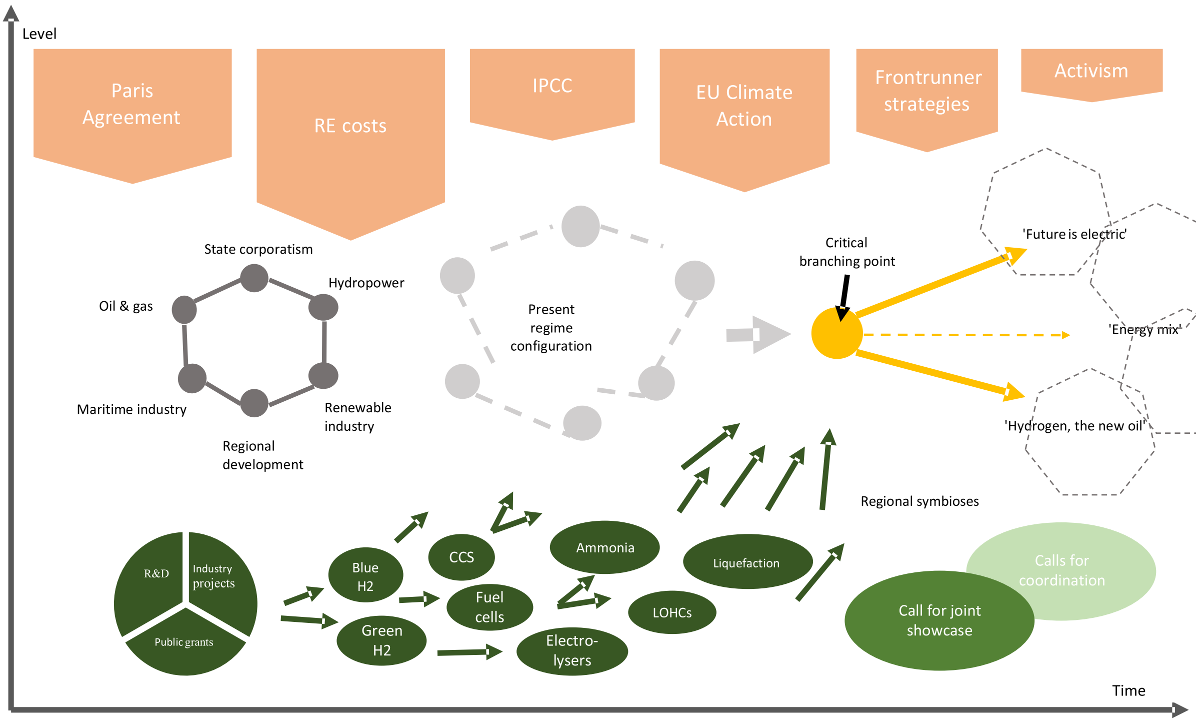

Fig. 8. Multilevel perspective on the emergence of hydrogen as energy carrier in Norway.

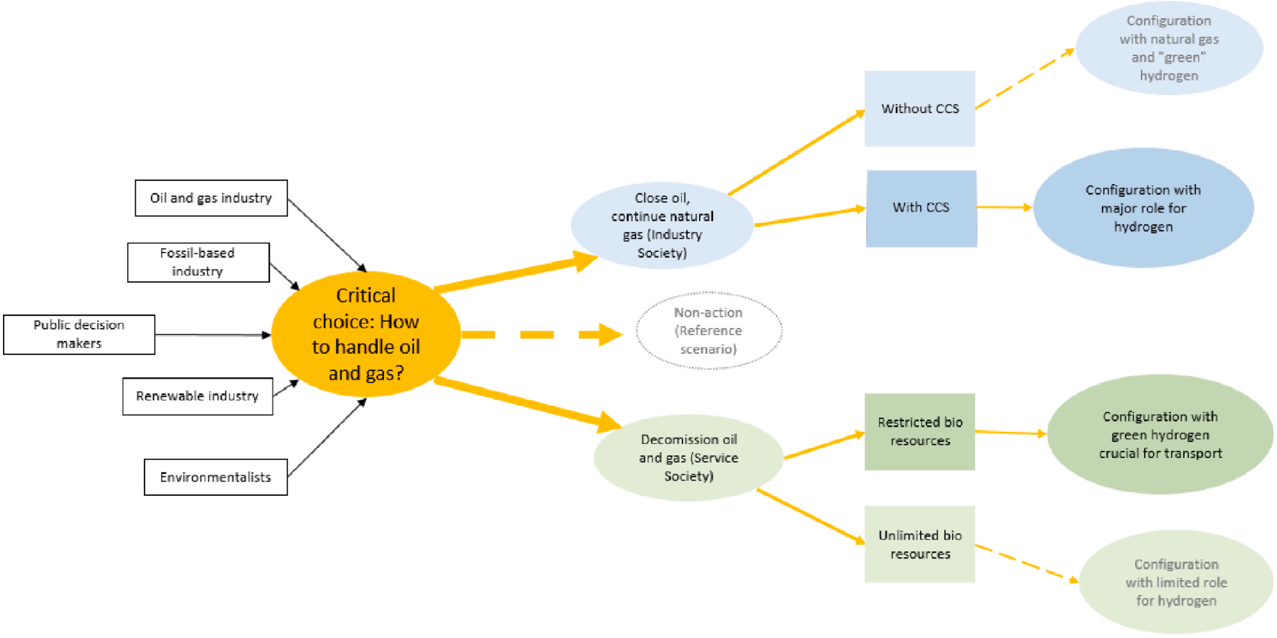

Fig. 9. Critical branching point and scope for hydrogen in quantitative scenarios for Norway's transition to a low-emission society by 2050.

maturity of options (i.e. technological or social innovations), system integration and infrastructure, societal acceptability, and political feasibility [3]. In our case, the "Industry Society" assumes a high level of technology learning. The socio-technical case-study confirms that there are multiple initiatives and potential for large-scale production of hydrogen already by 2030. However, some hydrogen technologies are still relatively immature, and there are challenges linked to transportation, storage and CCS. Required infrastructure is not yet in place and there are no firm plans for its development. While public acceptance may be variable, the political acceptance of this pathway is high, considering the noted small-state corporatism [71], local synergies and concern to maintain economic growth.

In the "Service Society", all hydrogen is from electrolysis, which is mature and scalable. Charging infrastructure and grid investments linked to large-scale electrification will be a challenge, but the models do not foresee a role for hydrogen in flexibility, contrary to the potential noted in the case-study. The use of hydrogen in 2030 is limited, but by 2050 the share of hydrogen in transport may increase significantly, unless unprecedented leaps in biomass production or battery technology are seen. The socio-technical study shows that the focus on renewables and electrification remains very strong in Norway. To move towards the "Service Society" would, however, require a stronger element of "creative destruction" [24] and more behaviour change. While there is increasing awareness and arguments for this alternative are gaining ground, maintaining jobs and economic growth loom high on the political agenda. Growing scepticism towards wind power expansion [37,68] may also work against the "Service Society". On the other hand, Covid-19 has altered behaviours significantly. While most of this may be temporary, behaviour change in some areas may accelerate due to the pandemic and the long-term impacts of the virus are still unknown.

The tendency towards reconfiguration and wider system change apparent from the qualitative study has so far received limited attention in Norway [48]. Many of the most promising solutions and concepts are still early stage. They challenge established understandings and sector boundaries, underscoring the need for systems thinking and integrated approaches, by policymakers as well as business actors.

While MLP illuminates socio-technical complexity and can be used to address the conditions for realising alternative pathways, the quantitative modelling sheds light on the economic implications of transitioning towards a low-emission society. Although hydrogen may be a key enabler, both the "Industry Society" and the "Service Society" suggest transitioning to a low-emission society by 2050 will have a negative impact on GDP growth per capita. The qualitative case-study, indicates that a larger system reconfiguration is ongoing. In this perspective hydrogen will also be important, but the trajectory is open-ended and the economic implications are difficult to foresee.

Combining techno-economic and socio-technical perspectives may also be fruitful in the dialogue with key stakeholders. Numbers speak louder than words, and techno-economic pathways provide powerful visions for change. On the other hand, they are rather abstract. The socio-technical analysis provides insight on how transition is embedded in existing structures and enacted by individual and corporate actors, shedding light on practical conditions and stakeholder perspectives on how transition may be realised. Thus, a bridging approach to sustainability transition pathways may provide more "actionable" knowledge [2,3].

7. Concluding remarks

This paper has applied a bridging approach [1,56], where quantitative modelling of the complete energy system and its interactions with the overall economy was compared, contrasted and combined with a socio-technical case-study on the scope for hydrogen energy solutions. The combination of methods sheds new light on how multi-sector interactions may play out in different energy transition pathways for Norway towards 2050. The qualitative case-study used MLP as framework, but considered specific production and deployment initiatives, as well as stakeholder perspectives on policies and interests as part of the wider system interactions. This provided an empirically rich account of historical and contemporary socio-technical dynamics influencing the transition potential of hydrogen.

Globally, there is an increasing pressure for alternative energy solutions, linked to increasing awareness and manifestations of climate change. Norway holds a joint commitment with the EU, with ambitious climate targets. The case-study drew attention to divergent interests, linked to the petroleum-based industry and the renewable power sector. These have been associated with unclear energy policies, as well as different trajectories and imaginaries for hydrogen. While the national transition is at a critical branching point concerning oil and gas, regional and sector synergies are adding momentum for hydrogen, and there are multiple large-scale production and deployment initiatives, suggesting that full-scale value chains can be in place by 2030.

The quantitative modelling explored two alternative pathways towards a low emission society in 2050. In the "Industry Society", hydrogen will become an important value creator and export good. In the "Service Society", where both the oil and gas sectors are shut down, hydrogen will be less significant for the economy, but still crucial for decarbonisation of transport. The socio-technical analysis provides a third pathway, where hydrogen develops as part of a more radical reconfiguration of the energy system.

Thus, bridging broadened the perspective on possible trajectories, as well as the overall scope of analysis. It also provides new knowledge on the feasibility [3] of alternative pathways. The quantitative assessments provide specific results on how the "Industry Society" and the "Service Society" will influence the economy. While political acceptance for the "Industry Society" seems high, the case-study highlights remaining transition bottlenecks [56], including lack of infrastructure, uncertainty linked to CCS, legal-administrative barriers, social acceptance and remaining technological challenges. The "Service Society" requires a stronger element of "creative destruction" [53] and behaviour change, and uncertainty concerning wind power is a critical factor. The multiple new solutions and roles for hydrogen and tendency towards reconfiguration observed in the qualitative study has so far received limited attention, and many solutions and concepts are early stage. Moreover, the "whole system" [28] perspective sheds light on system challenges such as "the chicken or the egg dilemma" and tensions over "blue" and "green" hydrogen, suggesting that new types of interventions and forms of collaboration are needed. The combination of envisioning long-term impacts and addressing contemporary challenges may be particularly useful at critical branching points [13].

Our study was grounded in a collaborative project, influenced by prevailing pathway conceptions and partner priorities. A more systematic integration might have provided more common reference points and better analyses. More research on how socio-technical analysis can help refine quantitative modelling and on how quantitative scenarios can be used to elaborate and develop more forward-looking socio-technical pathway perspectives may be useful to build more "actionable" [2,3] knowledge for sustainability transitions.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2021.102116.

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