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Exploring the complexity of hydrogen perception and acceptance among key stakeholders in Norway

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HIGHLIGHTS

- We address a need for whole system and societal dimensions approaches in hydrogen research.
- We apply a novel combination of multi-level empirical account and whole system modeling.
- We provide new empirical insights from a Norwegian context and whole system perspective.

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ABSTRACT

This article explores the complexity of factors or mechanisms that can influence hydrogen stakeholder perception and acceptance in Norway. We systematically analyze 16 semi-structured in-depth interviews with industry stakeholders at local, municipal, regional, and national levels of interest and authority in Norway. Four empirical dimensions are identified that highlight the need for whole system approaches in hydrogen technology research: (1) several challenges, incentives, and synergy effects influence the hydrogen transition; (2) transport preferences are influenced by combined needs and limitations; (3) levels of knowledge and societal trust determinant to perceptions of risk and acceptance; and (4) national and international hydrogen stakeholders are crucial to building incentives and securing commitment among key actors. Our findings imply that project management, planners, engineers, and policymakers need to apply a whole system perspective and work across local, regional, and national levels before proceeding with large-scale development and implementation of the hydrogen supply chain.

Introduction

The need for new energy solutions is evident on many levels. Climate change calls for low-emission energy solutions, as energy supply is crucial for producing and transporting essential goods. At the time of writing Europe faces military conflict, which significantly displays the interdependency in a global market. The current situation has led to reductions in gas delivery and higher energy prices, which increases the production costs for fertilizer and raises food prices.

The Energy roadmap 2050 aims for an 80–95% reduction in greenhouse gases, with further figures being a 31% reduction since 1990 and an aim of a 55% reduction by 2030 [1,2]. Due to its suitable climate and topography, Norway is already a large producer and exporter of clean electricity. At the same time, Norway is one of the world's largest producers of oil and gas, which challenges the ability to achieve national climate goals.

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With a history of rapid technological development over the last five decades, there is an expressed political desire to take the lead in low-emission technology [3]. Hydrogen and hydrogen-based fuels have been identified as one of the key pillars to decarbonization of the global energy system [4]. Nationally, the hydrogen technology transition receives a significant focus, including via funding of research projects estimated to be around a total of NOK 500 million for the 2010–2020 decade [5].

Hydrogen technologies maintain a niche existence due to a lack of policy and regulatory support, as well as a vague public profile where factual information on the hydrogen chain as a whole is missing including concrete everyday life benefits [6–8]. A review by Griffiths et al. [9] finds "the absence of comprehensive, national and international policy and regulatory frameworks for hydrogen adoption in industrial systems" to be a main barrier against the development of the hydrogen sociotechnical system. Within hydrogen perception and acceptance research, the study scope has been limited to geography and applications [10], and some studies are becoming outdated given the rapid advancements in the field [8,11]. Two papers from a Norwegian study – Tarigan and Bayer [12] and Tarigan et al. [13] – also applied a limited focus on hydrogen vehicles and are dated some years back; nevertheless, they might provide relevant insight about acceptance: They found that the higher the knowledge the higher the attitude to support a sustainable environment and hydrogen energy (pro-environment attitudes levels), which can increase public acceptance of hydrogen vehicles and refueling stations as well as willingness to pay for hydrogen fuel. Recently, a Norwegian survey experiment by Bentsen et al. [14] revealed low public literacy regarding hydrogen as well as acceptance of liquid hydrogen in maritime transport being dependent on the production method presented to the participant. Acceptance in this study was higher for "green" hydrogen production than for "blue" and "grey." The literature further indicates that the public acceptance of hydrogen technologies depends on environmental awareness and benefits, with the latter being dependent on the availability of hydrogen infrastructures, compatible domestic and industrial heat appliances, fuel pricing levels/willingness to pay as well as media coverage and support for the hydrogen market [6,8,15].

The provision of goods and services in modern societies is based on socio-technical systems, embedding the required technological change needed to accelerate zero-carbon energy transitions into a wider field of social, institutional, and economic change. The stability needed for a socio-technical system to operate efficiently may be a hinder to deploying novel technologies and new energy solutions leading to unambitious incrementalism and lock-in [16–18]. Societal factors, such as political guidelines, regulation, environment, and public acceptance, may thus both enable and hamper technological development [19]. Moreover, current literature reveals a need for multi-sector interactions, multi-level perspectives (MLP), and overall whole system (considering generation, distribution, and use) approaches including modeling in energy transitions research [20–24]. A whole system approach also accounts for the socio-technical system (STS) viewpoint that organizations, humans, and technology are embedded in an external environment of financial/economic circumstances, regulatory frameworks, and stakeholders [25–27]. Specifically, Dammen et al. [22] applied a hybrid socio-technical analysis and modeling approach in exploring the dynamics driving and hindering the development of hydrogen value chains, finding that exogenous trends and uncertainties interact with processes and strategies in the national energy system. In general, there is a gap between technological development and focus on social science in the hydrogen transition, which calls for a better understanding of societies and an investigation of the societal effects of hydrogen industry development [10].

Addressing the identified need for whole system approaches within hydrogen technology research, including the need to account for societal dimensions, our study aimed to explore the complexity of factors or mechanisms that can influence private and public stakeholders' hydrogen acceptance in Norway, such as alternate green fuel sources, technology maturity, and risk perceptions.

Methods

Data collection

This article is based on an interview case study conducted as part of the project "Liquide hydrogen to decarbonize maritime transport in Norway" (PILOT-E) funded by the Research Council of Norway (RCN). The study includes 16 semi-structured in-depth, personal interviews with hydrogen industry stakeholders at local, municipal, regional, and national levels of interest and authority in Norway (Table 1). These interviews constitute Case 1 and Case 2 in the study and were conducted between January and September 2021. A third case (individual level) was interviewed in the Winter of 2021 but is not included in this paper. Geographically, the 16 Informants represent three counties in the Western part of Norway, which are characterized by a long coastline and many fjord crossing points for transportation purposes (bridges, ferries, and undersea tunnels). At municipal, regional, and national levels, informants were recruited through direct contact,

Table 1 – Stakeholders interviewed.

Interview	Case	Interview category	Interview sub-category
#1	#1	National level	Regulatory authority 1
#2	#1	County level	County politician 1
#3	#1		County politician 2
#4	#1		County politician 3
#5	#1	Municipal level	Mayor 1
#6	#1		Mayor 2
#7	#1	Port level	Port authority 1
#8	#1		Port authority 2
#9	#2	Local level	Enterprise 1
#10	#2		Enterprise 2
#11	#2		Enterprise 3
#12	#2		Enterprise 4
#13	#2		Enterprise 5
#14	#2		Enterprise 6
#15	#2		Enterprise 7
#16	#2		Enterprise 8

either by e-mail, phone, or both. These informants (Case 1) had interests and/or formal responsibilities related to the facilitation or regulation of maritime transportation, industry development, or securing public transportation needs in coastal areas. At the local level (Case 2), informants were recruited through their workplace, which was in an existing high-energy industry area that could potentially also be a future hydrogen production and/or filling site. A list of enterprises was given by the industry area management, and the head managers of a randomly selected sample of enterprises were approached with a request for participation from one of their employees. Some managers chose to participate themselves. Topics in the interview guide included a) role in and process of the hydrogen development/implementation (Case 1 only), b) hydrogen knowledge and perception of technology maturity, c) hydrogen risk perception, and d) reflections on the future energy situation (on different levels and for different transportation purposes).

Due to Covid 19 restrictions, all interviews in the study were performed using phone or video (Teams app) and audio-recorded. The length of the interviews varied from 20 min up to 2 h, where Case 1 interviews typically had a longer duration than in Case 2. Audio files were fully transcribed into text and anonymized (removal of names, affiliations, and other sensitive information), and audio files were thereafter deleted. The transcribed material comprised a total of 218 A4 pages. Information handling in this study has been approved by the NSD (Norwegian Center for Research Data).

Data analysis

The empirical data were systematically analyzed using the computer-assisted qualitative data analysis software (CAQDAS) QSR NVivo 11 (QSR International, Melbourne, Australia). A main feature of CAQDAS is that it increases our ability to gain an overview of and map emerging patterns and relationships in the data material, in this case, related to our research aim to explore contextual factors such as alternate green fuel sources, technology maturity, and risk perceptions on hydrogen acceptance among key stakeholders in Norway [28]. Thus, CAQDAS enables the researcher to achieve systematic operation at the research design level, specifically the analysis process, which improves reliability [29]. CAQDAS also enables “creative management of multiple data sources and enables researchers to make visible their methodological processes for a more ‘trustworthy’ study” [[30]:p159], which highlights the importance of precisely accounting for the research steps undertaken during the analysis process [31], as outlined next. We specifically applied a “meaning unit-category-theme” coding strategy to identify underlying themes in the data [32–38]. Meaning units are text segments that convey a stand-alone meaning, which in this paper connects to the exploration of hydrogen acceptance complexity. Related meaning units form larger patterns of meaning (categories), while related categories form the largest patterns of meaning (themes). In the language of the NVivo coding program, and as shown in Tables 2–5, lower-level nodes represent meaning units and higher-level nodes categories.

Aimed at identifying key stakeholders' knowledge, insights, and perceptions related to hydrogen technology acceptance, Author 1 performed a systematic content analysis of the transcribed session material using QSR NVivo. Specifically, Author 1 imported into NVivo the 16 transcribed interviews (see Table 1), labeled as document sources by the program. Author 1 then read each source document to identify and condense into nodes text segments that conveyed a standalone meaning regarding hydrogen perception and acceptance. Nodes represent themes, places, people, and other areas of interest, i.e., the nodes have a coding function. This produced 69 lower-level nodes, 9 higher-level nodes combining related nodes, and at the largest abstraction level 4 theme nodes combining the higher-level nodes. Author 1 presented the result of the coding process at an internal workshop with all authors present. Specifically, Authors 2 and 3, having performed several of the interviews and previously reviewed and preliminary coded the data, found that the coding reflected their own impressions and coding. Thus, the workshop facilitated comparison across researchers, i.e., analytical triangulation, which contributed to validating the coding process [39,40]. The workshop also facilitated consensus among the authors, by resolving discrepancies and disagreements related to the coding process [41,42]. The outcome of the coding process is presented in the results section next.

Results

In this section, we present the outcome of our data coding, following the logic of identifying and combining text segments that convey a standalone meaning, ranging from lower-level nodes and higher-level nodes to themes (highest abstraction level). Each of the four themes is presented in table format (Tables 2–5) for transparency and overview, followed by quotations illustrative of the specific theme. Documenting the number of sources and references supportive of each higher-level node improves the transparency and validity of the results. Of note, lower-level nodes that are closely related have been combined, with the number of sources and references provided (multiple sources node support are highlighted in bold text).

Theme I is about green shift opportunities and barriers related to hydrogen, where the challenges include alternate/competing clean technology energy carriers or transportation solutions, the need for speed and infrastructure, the risk and cost pictures, and so forth. The opportunities converge on larger green transformation ambitions related to industrial areas and harbors including incentives arrangements and the offering of a range of green fuel sources as well as synergy effects. The following excerpts are illustrative of Theme I:

In any case, I see opportunities to produce hydrogen on a much larger scale than we have done so far [...] It is whether we can get a [industrial area with] biogas plant, next door to the hydrogen factory, which can exchange energy for the different needs. Then we are suddenly an eternity machine of another world. In addition, there is a huge value in the fact that we can extract the gas from land and solve a problem that at least some people experience very strongly, namely methane. Then you understand that I have a “king's idea” that we should establish something in this industrial area. Where we can transition from being a hydrogen producer to becoming something more. Namely, to become a green premise supplier for almost everything that is of energy here in our area. […] The whole idea behind the hydrogen hub is based on local value creation, local jobs and the development of a technology that may lead to skilled jobs in a very… not business-poor area, but perhaps in a slightly too narrow business area – *Mayor 2*.

In my world, shipping is the greenest thing you can do in relation to trucks at least, at long distances. I see a very positive attitude. If you look at the offshore segment first, then. Those who invest in LNG […] have gone in zero-calculation. It has not really paid off to invest in new forms of operations. So new technology costs money […] You get an even bigger greener lift when you also have a better perception that it is the best alternative. I notice this in the attitude within shipping, that this is the way it goes. They invest in it. There are costs, yes, but in the long run, there is great positivity around it. I am a little less concerned with the mainland road, given that we want a win-win situation with the local actors. This implies that when we get more goods and more logistics by sea, the local truck operators win. It is “hand in glove”. They cover the smaller traveling distances for goods. So, we work together to get the long-distance trucks away – *Port authority 1*.

If you only advertise zero emissions [tenders], then you will not really be able to deliver. Although we have players [that] can deliver speedboats at a slightly lower speed. We are talking about… well, one knot is exceptionally much more expensive, right. There is quite a lot more energy consumption. At the same time, we have people that say that speed is the most important thing. To be honest, it's a pretty difficult situation to be an ambitious zero-emission politician right now, because there are so many things being pitted against each other, instead of maybe looking at a trial scheme – *County politician 1*.

Theme II concerns multiple factors including combined needs and considerations, maturity levels, and limitations determining transportation preferences. Combined needs and considerations include the suitability of hydrogen and other clean technologies as well as fossil energy carriers to specific transportation needs or requirements (capacity, regularity, flexibility, speed, distance, pricing, and so forth), the “greenness” of clean technologies including production, the combination of hybrid and clean technologies, and more. Hydrogen infrastructure limitations concern bottlenecks related to the present power grid capacity and the amount of energy lost during hydrogen production, which in turn relates to a lack of technological maturity for hydrogen. The following excerpts are illustrative of Theme II:

But then there is the challenge we have in Western Norway, capacity on the power grid. This makes production a challenge in relation to the fact that it takes a lot of power to produce, if you are going to turn it into green hydrogen […] If you want to expand all watercourses and everything that is agreed upon, it may well be that you get enough for Norway's needs, so to speak. But at the same time, you take the energy (which is then electricity) and turn it into hydrogen, and you get an efficiency of 70%. This is also an “issue” that you must in a way address. This is a challenge – *County politician 3*.

Technology has evolved. What we did not think was possible five years ago is suddenly possible now. We see this in the development of electric cars. I think that for part of the ship fleet, hybrid solutions with batteries and traditional but much more environmentally friendly diesel engines with low sulfur in diesel, are very relevant. I think that is the case for large parts of the fleet. For other parts of the fleet, a pure electric operation may be relevant on shorter travel distances. Speedboats are an example of that. Everything is about how fast you want to sail and how much energy you should use […] Our risk is that ships arrive with LNG, with hydrogen, with ammonia, and with electricity, right. So, everyone has different needs. It will cost a lot for us ports to facilitate everything. Then you may end up with several inferior solutions and expensive solutions – *Port authority 2*.

Some hydrogen equipment has had standards for many years, in a way, such as filling stations for hydrogen. At least there have been technical specifications for its construction. At the same time, for other equipment, there are perhaps major shortcomings. So, it is a bit both yes and no in relation to the maturity of the technology then, but hydrogen has been used in the industry as well, for a long time. There are experiences out there on the use of hydrogen. So, I think I must answer: A little both yes and no, to put it simply. In some areas, there are standards and experiences, while in other areas you may have to develop new solutions to be able to do what you want with hydrogen – *Regulatory authority 1*.

Theme III concerns perceptions of hydrogen knowledge, risks, and trust among stakeholders. Hydrogen knowledge appears as either of a niche character, slightly above average, or lacking at local/port, municipality, and county levels as well as among the public. Consequently, the stakeholders call for making publicly available insight into several facets of hydrogen including value chain, color classification, hydrogen handling and risks, alternate energy carriers, and associated recyclability considerations. In addition, concerns regarding hydrogen risks are described. Nevertheless, the stakeholders express confidence and trust in hydrogen risks being under control and that social acceptance can be reached. The following excerpts are illustrative of Theme III:

First and foremost, people in general and perhaps also people who sit in both the municipality and the county municipality, they lack knowledge about hydrogen. There is probably still a fear of hydrogen, i.e., the danger of explosion. An uncertainty. If it is not a fear, then there is at least an uncertainty associated with the treatment of hydrogen. […] But I have of course received questions both on the street and in conversations with people, where they express a little fear of what hydrogen is in the short term. Everyone is probably concerned about one thing, and that is that hydrogen-based solutions will come in one form or another, also on the road. But they are insecure, and they want more knowledge and experience before they eventually land that discussion. So, as I said, it is about us being out very early. Not necessarily technologically, but in relation to the knowledge of hydrogen and its possibilities, and to that extent also dangers in the use of it – *Mayor 2*.

Yes, again, I have the confidence that as long as we have a regulated market or a market ... that is, good public approval schemes for the products that are used both at sea and on land, I have confidence that good schemes are being developed in various ways. What shall I say? That they minimize the risk of using hydrogen, to put it simply […] So I am a technology optimist when it comes to the fact that we manage to keep the risk down and that what becomes commercial has a low risk […] I think that if we do this right – because with the foundation we have in Norway, the Norwegian population generally has reasonably high confidence in both the business community and political authorities – If we do it right and are good at the stories and pedagogy along the way, then I think there are chances for it to go well. At least we cannot afford not to consider it anymore, and we must work to achieve social acceptance – *County politician 2*.

But if we start from [anonymous city] center, space is scarce. That is one thing. If this were to be one hundred percent harmless, it would still be a challenge because we have a shortage of space. We have electricity, true. We have a lot of electricity in our quays which means that we can deliver to cruises over 40 MW at the same time. An insane amount of power. But establishing a factory almost in the middle of the city center, we would have problems getting it done. Both because we do not have space and of course because it is explosive, so to speak. So, you have to have security. So, establishing such a factory at our facilities in [anonymous city] today, it is not going to happen – *Port authority 2*.

Theme IV is about the roles and responsibilities of central hydrogen stakeholders nationally and internationally. Specifically, the county level currently carries an unsustainable hydrogen innovation and financing burden, and there is consequently a need for central authorities to properly commit to hydrogen technologies including by means of improving current regulations and requirements. In combination, leading international actors in transportation and shipping also need to invest in hydrogen technologies. The following excerpts are illustrative of Theme IV:

Feedback from us politically, both from experiences with ferries and speedboats, is that it is the county and the regions that bear all the responsibility and all the credit, but you kind of feel that at the national level ... there is no contribution nationally to achieve this […] At the moment, we have not seen any national investment, neither in electrification or hydrogen. We have to be honest about that. Of course, that means that we in the county are a bit between the bark and the wood. We feel a little squeezed. Because if we go for this [hydrogen ferries], there will be additional expenses. We have not gotten close to what we should have had for the ferries [investment]. – *County politician 1*.

To start hydrogen as a form of energy, you are dependent on some of the major players investing in it, so that you can start large-scale production of hydrogen and large-scale distribution. This is necessary. […] Internationally, you are dependent on these large shipping companies that operate goods, such as Maersk and the like, acting. They do, of course, but as I understand it, Maersk invests in ammonia and not hydrogen. So, the question is how much is coming [implied: of hydrogen investments]. – *Port authority 2*.

[We are] a party that in a way has had our own thoughts and we applaud all technological development. We believe that Norwegian knowledge can be used in a good way to develop new and good solutions in relation to securing a zero-emission society […] At the same time, we must land on what we believe can be the future and that makes us invest in it. We are really at a small crossroads in relation to the zero-emission society and such […] We must be open to the fact that what will be the future has not actually been created yet. – *County politician 3*.

Discussion

The global need for new and green energy calls for rapid energy transitions. However, focusing on technological development alone is inadequate and the inclusion of societal perspectives is crucial to fulfilling the ambitions [10]. Contextual differences and barriers need to be considered including technological potential, national regulations, acceptance levels, and economic possibilities to enable an energy transition and create sustainable socio-technical systems [6,9,10,22]. This article explores the perceptions of hydrogen stakeholders on different levels, to understand how the Norwegian society – being heavily dependent on oil and gas production and export – can and should move forward to develop a hydrogen value chain in balance with societal considerations. Our analysis of the resulting empirical data sheds light on this challenge and revealed four dimensions of hydrogen perception and acceptance (see Fig. 1, lower part) reflecting the themes identified in the results section (see Tables 2–5).

Extending the first author's previous holistic modeling developments [37,43][1] to other research domains and concepts, Fig. 1 presents a conceptualization of the interrelated, many-dimensioned, and contextual nature of the hydrogen perception and acceptance phenomenon. The conceptualization is informed by the literature findings in the introduction section (see Fig. 1, upper part) as well as the identified themes in the results section (see Fig. 1, lower part). The conceptualization is aimed at establishing a base for testing and extension in further research and exploration endeavors applying whole system approaches.

Literature findings on hydrogen perception and acceptance, as identified in the introduction section, support an "environmental awareness" dimension (see Fig. 1, upper part). This includes higher individual hydrogen knowledge producing higher pro-environment attitudes and public acceptance as well as hydrogen acceptance being dependent on environmentally related awareness, benefits, and production methods [6,8,12–15]. Another literature-informed dimension is "infrastructural conditions" (see Fig. 1, upper part), comprised of structural and market-oriented elements such as availability of hydrogen infrastructures, compatible domestic and industrial heat appliances, fuel pricing levels/

[1] Previous developments include a study of patient safety and safe work practices in surgical operations [43] and an exploration of the societal safety and security concepts [37], both conducted in Norway.

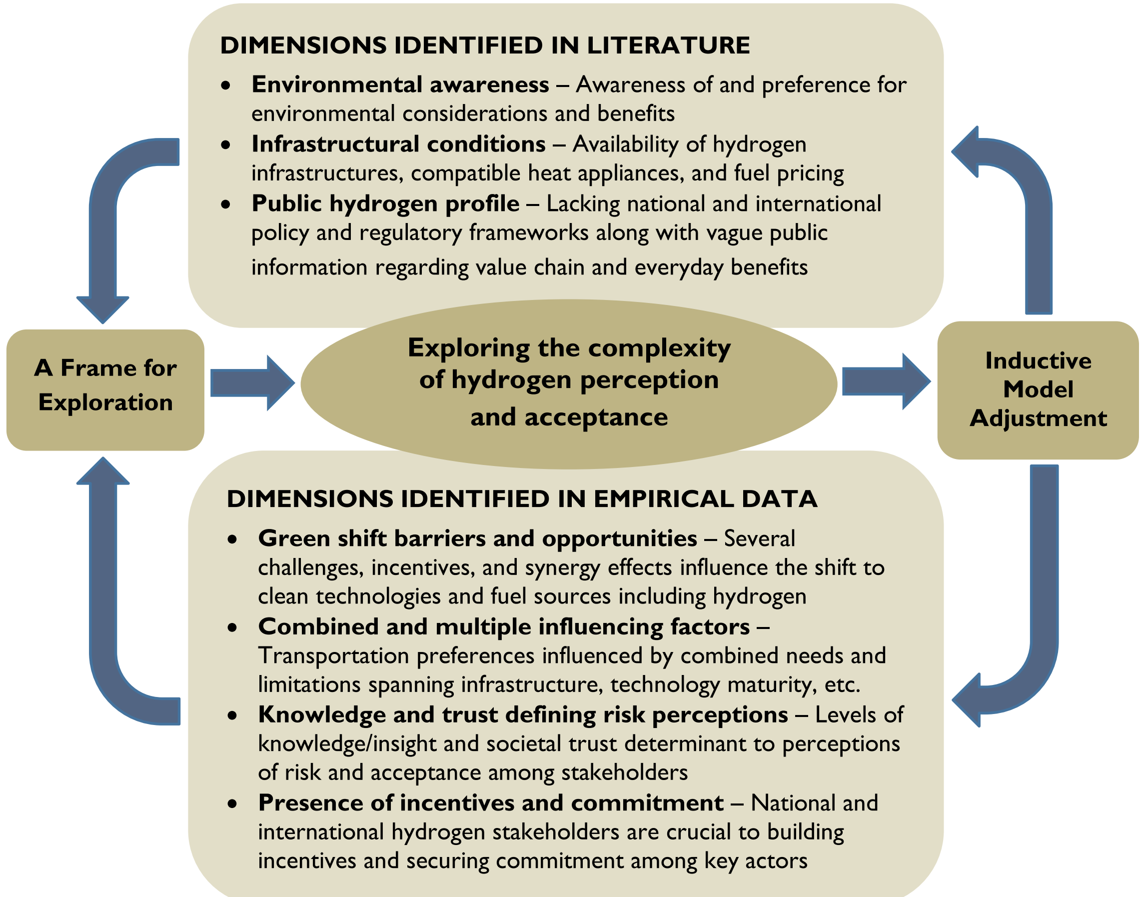

Fig. 1 – Figure logic/dynamics: Throughout the PILOT-E project period, various dimensions inform the understanding of the hydrogen perception and acceptance phenomenon, which provides a rudimentary orientation for empirical exploration of the phenomenon ("A Frame for Exploration"). The emergent findings resulting from an analysis of new empirical data, in addition to reviews of literature conducted during the project period, refine the understanding of the phenomenon, as indicated by the arrow from the circle towards the right center rectangle and by the arrows pointing to the upper and lower rectangles ("Inductive Model Adjustment").

willingness to pay, and media coverage and support for the hydrogen market [6,8,15]. Current studies also support a "public hydrogen profile" dimension (see Fig. 1, upper part), characterized by an absence of comprehensive national and international policy and regulatory frameworks along with vague public information regarding the hydrogen value chain and associated everyday benefits [6,7,9].

Combining both a whole system view and hydrogen acceptance focus, the clean technology study by Leiren et al. [44] serves as a comparison to the empirical dimensions identified in our study (see Fig. 1, lower part). Leiren et al. [44] presented a whole system view of factors influencing the acceptance of onshore wind energy development including technical characteristics of the project, impacts on the environment, economy, and society, contextual factors, and individual characteristics. Under contextual factors, they listed the market, planning and permitting process, governance and regulatory framework, and trust in key actors. The trust element features strongly among stakeholders in Leiren et al. [44] and is specifically related to actors (national decision-makers, regional/local decision-makers, and investors) as well as planning and permitting processes (as in, degree of process participation, transparency, and trust). Our findings related to the "knowledge and trust defining risk perceptions" dimension (Fig. 1, lower part) underscore the relevance of trust in technology acceptance and add nuances and depth to this understanding. We find that aspects of knowledge/insight and societal trust are closely intertwined and determinants of risk perceptions and acceptance among stakeholders. Specifically, based on lacking, niche, varied, average, or slightly above knowledge about hydrogen (Table 4, N35–N46), the stakeholders are confident [read: trust] that hydrogen risks are controllable and covered by safety assessments, regulations, storage, bunkering, and fueling measures (Table 4, N47).

In terms of the market acceptance factors and specifically energy demand identified in Leiren et al. [44], our findings related to the "combined and multiple influencing factors" dimension (Fig. 1, lower part) resonate and add nuances and depth to this understanding. We found that transportation preferences are influenced by combined needs and limitations, where both the battery and hydrogen markets require better solutions and generally higher maturity levels before

Table 2 – The outcome of the coding process; Theme I.

Theme I: Green shift opportunities and barriers related to hydrogen *(Sources: 10; References: 30)*		
Higher-level nodes (A1-X)	Lower-level nodes (N1-X)	Actors
H1: The challenges of achieving a green shift *(Sources: 6; References: 13)*	**N1:** A commitment to zero-emission express ferries is challenged by several factors including demand for speed, cost levels, risk picture, infrastructure needs, technology immaturity, and climate reduction rewards ***(Sources: 4; References: 11)***	County politician 1; Mayor 2; enterprise 1 & 8
	N2: Current transportation infrastructure needs to transit from ferries to bridges that are more environmentally friendly; tonnage transport at sea is still necessary *(Sources: 1; References: 1)*	Mayor 1
	N3: Foresee high future potential for biogas given the negative emission of this fuel source, though limited production has been an issue *(Sources: 1; References: 1)*	County politician 1
H2: The green shift drive, incentives, and synergy effects *(Sources: 7; References: 17)*	**N4:** As a harbor, positive to hydrogen as well as other future energy carriers and concerned with offering a range of green fuel sources to land logistics including the truck industry *(Sources: 1; References: 1)*	Port authority 1
	N5: Believes that a pilot project is highly visible, e.g., in terms of testing hydrogen features and demonstrating regularity, and thus represents an important national tool to turn or sway a critical public opinion ***(Sources: 2; References: 2)***	County politicians 1 & 2
	N6: Both maritime and road transport sectors are very positive, and even though offshore LNG has been costly the potential long-run payoffs of green technologies are what counts including synergies across industries ***(Sources: 3; References: 4)***	Port authority 1; county politician 2; regulatory authority 1
	N7: Emphasizes the importance of hydrogen combining the greenest production and best use of renewable energy like water with a competitive price *(Sources: 1; References: 1)*	County politician 3
	N8: Relying on a zero-emission vision including harbor logistics, the overall goal is to become the greenest harbor and city in Norway *(Sources: 1; References: 1)*	Port authority 2
	N9: The green focus is a product of national and regional political drive towards zero-emission combined with cornerstone green investor interest and municipal administrative drive *(Sources: 1; References: 3)*	Mayor 2
	N10: The harbor is focused on exploring and adapting to new and green energy technologies, and has developed incentive arrangements to push the market in the greener direction *(Sources: 1; References: 2)*	Port authority 2
	N11: The municipality embraces future green value chains including local jobs and competency building and focusing on fish farms utilizing byproducts of hydrogen production and achieving a colocation and symbiosis between hydrogen and biogas production *(Sources: 1; References: 3)*	Mayor 2

becoming commercially viable (Table 3, N26; N30; N34), though certain markets of transportation such as a maritime and air transportation including larger/heavy volumes hold higher hydrogen implementation potential (Table 3, N23; N32). Stakeholders also emphasize how infrastructural limitations and the varying needs of markets (land, sea, air, passenger, cargo transport, etc.) including regularity, flexibility, and pricing dictate the suitability of clean technologies including pure or hybrid battery, hydrogen, and LNG solutions (Table 3, N12; N13; N15; N18; N20; N22; N25, N27; N29).

As for governance and regulatory framework factors and specifically “national/regional/local policies: financial support schemes” identified by Leiren et al. [44], the “presence of incentives and commitment” dimension in Fig. 1 (lower part) provides insight. We find that both national and international partners need to invest in and signal a commitment to hydrogen technology and establish the associated regulations, requirements, and incentives to push in this direction (Table 5, N62; N63; N65–N67; N69). According to the stakeholders, while the national authorities have shown some/indirect support (Table 2, N9; Table 5, N69), the actual technology push/drive and responsibility is mainly located at a regional and local level (Table 2, N4; N10; N11; Table 5, N62; N65; N67). Further nuancing the understanding of financial and regulatory support schemes as strongly regionally anchored, several stakeholders in our study suggested that the county has strived to remain technology-neutral to navigate strong advocates for both hydrogen and battery technologies, which through tenders has inspired strong regional research and innovation (Table 5, N64).

When it comes to further nuances and similarities across literature and empirical data pattern, the dimensions “public hydrogen profile” and “knowledge and trust defining risk perceptions” in Fig. 1 are closely linked in the sense of hydrogen knowledge being essential to technology acceptance including associated risks as well as assessment of everyday benefits. Similarly, the dimensions “infrastructural conditions” and “combined and multiple influencing factors”

Table 3 – The outcome of the coding process; Theme II.

Theme II: Multiple factors including combined needs and considerations, maturity, and limitations determining transportation preferences *(Sources: 14; References: 43)*

Higher-level nodes (A1-X)	Lower-level nodes (N1-X)	Actors
H3: Limitations of hydrogen infrastructure and energy supply and associated implications *(Sources: 4; References: 6)*	**N12:** Green hydrogen production requires an electric energy supply which is in limited supply particularly in Western Norway; in addition, process residue or lost energy needs to be properly used ***(Sources: 2; References: 2)***	County politician 3; enterprise 2
	N13: High level of hydrogen adoption will put a considerable strain on the electric energy supply with the rise in people's energy prices and associated negative hydrogen reputation, making hybrid solutions more viable *(Sources: 1; References: 1)*	County politician 3
	N14: Previously electricity production was wasted or lowered due lack of power lines, which in combination with key business actor dialog triggered the idea of hydrogen production to utilize unused energy *(Sources: 1; References: 2)*	Mayor 2
	N15: Rural or district Norway lacks the capacity to transport renewable energy *(Sources: 1; References: 1)*	Mayor 1
H4: Transportation preference governed by combined needs and considerations *(Sources: 13; References: 23)*	**N16:** Respondent believes in a combination of hydrogen and battery solutions supported by waterpower as environmentally- friendly and future proof; access to cobalt for battery in limited supply reducing long-term viability of battery ***(Sources: 3; References: 4)***	Enterprise 3, 5 & 6
	N17: Respondent believes in every fuel source except battery; expresses skepticism about the minerals required to make batteries and whether one can dispose of these environmentally-friendly *(Sources: 1; References: 1)*	Enterprise 4
	N18: Respondent believes in a future with dedicated and hybrid battery and hydrogen solutions suitable to different transport applications on land and sea ***(Sources: 2; References: 2)***	County politician 2; enterprise 7
	N19: Concerned about making the greenest production, having enough storage, and weighing the benefits and disadvantages including partners and public perceptions of the process *(Sources: 1; References: 1)*	Port authority 1
	N20: Emphasizes hybrid for cars due to lack of full-fledged alternatives and also for supply boats where you need power, while LNG is more suitable for the cruise industry and also the purest fuel for large transports *(Sources: 1; References: 1)*	Port authority 1
	N21: Emphasizes the importance of existing and strong El-ferry regularity, on the flipside power supply and charging stations are very costly and hydrogen preferable *(Sources: 1; References: 2)*	County politician 1
	N22: Ferry transportation regularity and capacity is of the highest importance, the technology itself subordinate ***(Sources: 2; References: 2)***	Mayor 1; enterprise 5
	N23: Foresee battery power in a shorter-term future horizon given technology safety and simplicity but high-cost levels and hydrogen in the long run due to its potential for heavy transport and volumes *(Sources: 1; References: 1)*	Mayor 2
	N24: Foresee hydrogen use on distances prioritized by the authorities, further limited by technology immaturity across industries and the authorities' ability to support the green shift *(Sources: 1; References: 1)*	Mayor 2
	N25: Perceives maritime and air transportation sectors as most interested and invested in hydrogen transition including hybrid variations; battery technology is preferred for land transport, but hydrogen is also adopted by some ***(Sources: 3; References: 3)***	County politician 1 & 2; regulatory authority 1
	N26: Perceives that the choice of pure electrical or hydrogen power, hybrid solutions, or traditional but greener fossil fuel solutions depends on transport distance, prices, and future developments *(Sources: 1; References: 1)*	Port authority 2
	N27: Solid transportation solutions require both regularity and travel distance capacity to achieve passenger travel flexibility, making hybrid solutions ideal and cost-effective *(Sources: 1; References: 1)*	County politician 3
	N28: Strongly emphasizes the need for new energy carriers in the harbor that can connect land infrastructure and sea, and the need to consider associated public perceptions *(Sources: 1; References: 2)*	Port authority 1
	N29: Transport and shipping actors have different needs and may invest in LNG, hydrogen, ammonia, etc. making it too costly for the harbor to accommodate all needs, that is a risk *(Sources: 1; References: 1)*	Port authority 2

(*continued on next page*)

Table 3 – (*continued*)

Theme II: Multiple factors including combined needs and considerations, maturity, and limitations determining transportation preferences *(Sources: 14; References: 43)*		
Higher-level nodes (A1-X)	Lower-level nodes (N1-X)	Actors
H5: Transportation preference governed by maturity levels *(Sources: 8; References: 14)*	**N30:** Current battery and hydrogen technologies need more maturity before broader commercial implementation and application ***(Sources: 6; References: 7)***	County politicians 1 & 2; enterprise 2, 3, 5 & 6
	N31: Hydrogen production needs to convert lost energy to make the production process sustainable, or use biomass and waste in the production *(Sources: 1; References: 1)*	Mayor 1
	N32: Maritime transportation is ideal for hydrogen fuel given the weight of the hydrogen engine; however, dead weight might be reduced over time and developments and make road transport feasible ***(Sources: 2; References: 3)***	Mayor 1; enterprise 2
	N33: Perceives a mix of fuel solutions for different types of transportation and travel distances as the future, not least given the fast technological developments *(Sources: 1; References: 2)*	County politician 1
	N34: The maturity of hydrogen technology varies, with experiences and standards in place in some areas but others require the development of new solutions *(Sources: 1; References: 1)*	Regulatory authority 1

Table 4 – The outcome of the coding process; Theme III.

Theme III: Perceptions of hydrogen knowledge, risks, and trust among stakeholders *(Sources: 16; References: 79)*		
Higher-level nodes (A1-X)	Lower-level nodes (N1-X)	Actors
H6: Hydrogen knowledge levels and risk associations *(Sources: 15; References: 39)*	**N35:** Battery production without energy lost and recyclability would be superior to hydrogen production; knowledge about this should be made publicly available *(Sources: 1; References: 1)*	Mayor 1
	N36: Hydrogen knowledge and business potential gained through consortium partnership and dialogues with shipping companies and actors involved in tenders *(Sources: 1; References: 2)*	Port authority 2
	N37: Knowledgeable about hydrogen from a business perspective and relies on internal dedicated technical expertise and milieu for in-depth assessments *(Sources: 1; References: 1)*	Port authority 1
	N38: Limited knowledge about hydrogen, derived from informal channels and various news sources including debates and incident coverages ***(Sources: 4; References: 5)***	Enterprise 3–5, 7
	N39: Mainly people in general but also at both municipality and county levels lack hydrogen knowledge and express fear or uncertainty related to hydrogen handling and general risks including explosion *(Sources: 1; References: 4)*	Mayor 2
	N40: People, in general, lack knowledge about hydrogen; more discussions, information, and practical demos are needed for the technology to catch interest and consideration ***(Sources: 2; References: 4)***	Enterprise 6 & 8
	N41: Perceives battery technology as riskier than hydrogen due to the dangerous gasses resulting from battery fires, a large challenge in confined spaces such as garages that require new equipment and knowledge *(Sources: 1; References: 3)*	Enterprise 1
	N42: Perceives hydrogen knowledge level as average or slightly above, gained via job experiences, meetings, conferences, actors, and media; emphasizes the importance of critical thinking and seeing the whole picture ***(Sources: 6; References: 9)***	Mayor 1; county politician 1 & 3; enterprise 1, 6 & 8
	N43: Perceives that hydrogen is known but less so internally and that it is important to increase knowledge level among maritime actors *(Sources: 1; References: 1)*	Port authority 1
	N44: Perceives variance in hydrogen knowledge level among municipalities including planning departments and associated fire departments *(Sources: 1; References: 2)*	Regulatory authority 1
	N45: The public perception of hydrogen is often based on highly visible incidents and limited and unvarnished knowledge; hydrogen reputation needs to be improved *(Sources: 1; References: 1)*	Port authority 2
	N46: While hydrogen technology is known and ready for application, politicians and the public lacks and desires insight into the hydrogen value chain, color classifications, and general overview ***(Sources: 3; References: 6)***	County politician 1 & 2; regulatory authority 1

Table 4 – (*continued*)

Theme III: Perceptions of hydrogen knowledge, risks, and trust among stakeholders *(Sources: 16; References: 79)*		
Higher-level nodes (A1-X)	Lower-level nodes (N1-X)	Actors
H7: Perceptions of risks associated with hydrogen, and societal trust levels *(Sources: 15; References: 40)*	**N47:** Confident that hydrogen risks are or will be under control and similar to other energy carriers, and that proper precautions in terms of safety assessments, regulations, storage, bunkering, and fueling will be taken ***(Sources: 11; References: 15)***	County politicians 1–3; port authorities 1 & 2; mayor 2; enterprise 1, 3, 5 & 7
	N48: Given people's H-bomb associations and skepticism, believe that solid communication and perception of safety is really important combined with implementation on the large and heavy medium and long transport distance units nationally and internationally *(Sources: 1; References: 5)*	County politician 3
	N49: Given the high level of trust in Norwegian society and given that we communicate the right stories, social acceptance of hydrogen technology can be reached *(Sources: 1; References: 1)*	County politician 2
	N50: Hydrogen risks are perceived as similar to gas-fueled cars or gas tanks, with rare accidents; trust the technology and that risks are under control and something we get used to ***(Sources: 2; References: 3)***	Mayor 1; Enterprise 4
	N51: Information and communication about risks associated with hydrogen should be improved in relation to actors in the municipality and associated partners *(Sources: 1; References: 1)*	Mayor 1
	N52: Internal preparedness and specifically risk and vulnerability analyses factor in neighboring hydrogen refinery *(Sources: 1; References: 2)*	Enterprise 1
	N53: Overall hydrogen risks including across sea and land are hard to assess given that risks of the substance itself might be higher than others but better contained by equipment and thus potentially equal in risk level *(Sources: 1; References: 2)*	Regulatory authority 1
	N54: Perceives hydrogen as riskier for the private compared to the commercial market including sea transport, due to the number of private car accidents and explosiveness of hydrogen ***(Sources: 2; References: 2)***	Enterprise 2 & 7
	N55: Perceives hydrogen to be safer at sea due to the ability to contain the fuel in a shell, general ease of constructing a safe system around the fuel, and less traffic density ***(Sources: 2; References: 2)***	Enterprise 3 & 4
	N56: Perceives the reputational risks of hydrogen incidents at sea as far less impactful compared with incidents on land *(Sources: 1; References: 1)*	County politician 3
	N57: Perceives the risks of hydrogen and battery technology as similar, each with distinct risks such as explosiveness of hydrogen and difficulty of putting out electric fires *(Sources: 1; References: 1)*	Enterprise 6
	N58: Prefers a ship-based container or tank solution for bunkering that contains all risks to the ship rather than the harbor and makes hydrogen distribution easier *(Sources: 1; References: 2)*	Port authority 2
	N59: The combination of limited city development areas and safety considerations makes a bunkering facility near the city center unlikely and unwanted, but this option is still being explored *(Sources: 1; References: 2)*	Port authority 2
	N60: The general public fears that they must pay the bill for the hydrogen transition; the county emphasizes the lower running costs and thus ticket prices of non-fossil fuel technology *(Sources: 1; References: 1)*	County politician 1

connect in terms of technological and infrastructural limitations. Finally, the dimension “environmental awareness” identified in the literature resonates with the dimension “green shift barriers and opportunities” in our data, specifically the notion that the green shift implies concerns for production and emission profiles, synergy effects of green value chains, and associated requirements.

It should be noted that our results regarding trust may be contextually influenced, as the population in Nordic countries seems to have more social trust than in other countries [45]. Furthermore, during its early years, the Norwegian (and UK) petroleum industry suffered from a range of safety incidents, as well as large accidents. This led to the development of a thorough safety regime for the entire Norwegian petroleum industry, which is based on trust, founded on a three-party collaboration (the tripartite), and has received international recognition [46,47]. Results regarding hydrogen safety and risk management may in our study be colored by a certain public level of trust in risk regulation.

Study limitations and strengths

Our findings represent a qualitative snapshot in time, from a Norwegian context. Thus, while extrapolation and generalizability of the resulting findings can be problematic and a limitation of our study [48,49], our empirical account covers multiple stakeholder levels as well as methods (in-depth interviews, electronic coding, analytical triangulation) to deepen and widen the understanding of the multi-faceted, complex nature of hydrogen perception and acceptance from a whole system perspective [39,40,50,51]. We consider the combination of in-depth descriptions and whole system

Table 5 – The outcome of the coding process; Theme IV.

Theme IV: Roles and responsibilities of central hydrogen stakeholders *(Sources: 6; References: 22)*		
Higher-level nodes (H1-X)	Lower-level nodes (N1-X)	Actors
H8: The county's role in relation to hydrogen and central authorities *(Sources: 3; References: 13)*	**N61:** Communicates zero-emission strategies via annual reports and the climate plan and not directly to the public or citizens *(Sources: 1; References: 1)*	County politician 3
	N62: County input to national authorities including hydrogen strategies has not resulted in national support for the hydrogen transition *(Sources: 1; References: 1)*	County politician 1
	N63: The county cannot be the pilot and test object for all new and costly technology, the budget is not there and will compromise on for instance educational offerings; the national authorities need to take responsibility for the process *(Sources: 1; References: 5)*	County politician 3
	N64: The county has strived to remain technology-neutral to navigate strong advocates for both hydrogen and battery technologies and in the process through tenders inspired strong regional research and innovation ***(Sources: 3; References: 6)***	County politicians 1-3
H9: The role and responsibilities of central national and international transportation actors including authorities *(Sources: 5; References: 9)*	**N65:** For hydrogen to gain hold both central national and international players in transportation and shipping need to invest in the technology *(Sources: 2; References: 3)*	Port authority 2; county politician 3
	N66: The authorities need to raise the requirements for transportation, given that actors operating old boats or fleets do not voluntarily transition to hydrogen due to costs *(Sources: 1; References: 1)*	Mayor 1
	N67: The county and local regions have all the responsibility, costs, and glory for hydrogen implementation while the national authorities do not contribute *(Sources: 1; References: 1)*	County politician 1
	N68: The municipality and local enterprise determine responsibility for preparedness including resource commitment in relation to the neighboring hydrogen refinery *(Sources: 1; References: 2)*	Enterprise 1
	N69: There was pressure from higher authorities to implement hydrogen ferries at the municipality level, neither desired nor influenced by the municipality itself *(Sources: 1; References: 2)*	Mayor 1

contextualization of a multi-level empirical account as a main strength and contribution of our study to existing research on hydrogen perception and acceptance. As suggested in the introduction section, our contribution aligns with the need for further research on whole system perspectives that accounts for hydrogen technologies as part of the overall energy system, and hereunder specifically the currently limited understanding of societal dimensions and underlying larger contextual mechanisms [6,10,52]. In our study and of specific relevance to this journal, these mechanisms are linked to production and emission, risk perceptions, societal trust, regional and national regulation and support, and more. The current knowledge base on stakeholder hydrogen perception and acceptance, and more broadly technology acceptance, can be improved by future studies applying in-depth and whole system perspectives in different contexts [44]. The resulting contextual insights and variations can be applied to validate and extend existing dimensions and understandings from a whole system perspective (as in, Fig. 1).

Regarding the length of our transcribed interview material, comprising 218 A4 pages, this study applies a qualitative method approach using in-depth interviews with respondents. These interviews can span very short (20 min) to medium and long interviews (1–2 h), as was the case in our study. The textual size of the data material is reflected in verbatim interview transcripts, which can be very short (a couple of pages) or medium to long (20–30 pages). However, within qualitative research, the more transcribed data material you have the better is your ability to identify patterns in the data, i.e., the validity of your results increases. Thus, transcription size equals quality in qualitative research.

Conclusion

In this article, we targeted an identified need for further explorations into the complexity of factors or mechanisms that can influence hydrogen perception and acceptance in society. Our study contributes to addressing this need in two novel ways; theoretically, by establishing a whole system modeling and contextualization of a multi-level empirical account combined with literature insights (Fig. 1), and empirically by validating and extending current knowledge on hydrogen perception and acceptance to a Norwegian context via detailed in-depth insight and identification of emergent patterns and dimensions. The implication for future research is to adopt whole system and detailed approaches to explorations of the hydrogen perception and acceptance phenomenon in different world regions, specifically accounting for societal perspectives and dimensions, contextual variations and nuances, and associated modeling such as Fig. 1 in our study. Consequently, a practical implication lies in the need for project management, planners, engineers, and so forth, to consider the larger contextual picture (multiple interconnected dimensions on local, regional, and national levels) before proceeding with larger-scale development and implementation of a hydrogen supply chain including production, processing, transportation, and storage [53].

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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REFERENCES

[1] EU European Council. Sustainable development in the European Union — 2022 monitoring report on progress towards the SDGs in an EU context. Luxembourg: Publications Office of the European Union; 2022 May. Available from: https://ec.europa.eu/eurostat/web/products-statistical-books/-/ks-09-22-019.

[2] EU European Council. Energy roadmap 2050. Luxembourg: Publications Office of the European Union; 2012. Available from: https://energy.ec.europa.eu/documents_en.

[3] Eckersley R. National identities, international roles, and the legitimation of climate leadership: Germany and Norway compared. Env Polit 2015;25:1–22. https://doi.org/10.1080/09644016.2015.1076278.

[4] IEA. Energy system overview. Paris. 2022 September. Available from: https://www.iea.org/reports/energy-system-overview.

[5] NMCE Norwegian Ministry of Climate and NMPE Environment & Ministry of Petroleum and Energy. The Norwegian Government's hydrogen strategy – toward a low emission society. Oslo: The Norwegian Government; 2020. Available from: https://www.regjeringen.no/en/dokumenter/the-norwegian-governments-hydrogen-strategy/id2704860/.

[6] Edwards RL, Font-Palma C, Howe K. The status of hydrogen technologies in the UK: a multi-disciplinary review. Sustain Energy Technol Assessments 2021;43:100901. https://doi.org/10.1016/j.seta.2020.100901.

[7] Schmidt A, Donsbach W. Acceptance factors of hydrogen and their use by relevant stakeholders and the media. Int J Hydrogen Energy 2016;41(8):4509–20. https://doi.org/10.1016/j.ijhydene.2016.01.058.

[8] Ricci M, Bellaby P, Flynn R. What do we know about public perceptions and acceptance of hydrogen? A critical review and new case study evidence. Int J Hydrogen Energy 2008;33(21):5868–80. https://doi.org/10.1016/j.ijhydene.2008.07.106.

[9] Griffiths S, Sovacool BK, Kim J, Bazilian M, Uratani JM. Industrial decarbonization via hydrogen: a critical and systematic review of developments, socio-technical systems and policy options. Energy Res Social Sci 2021;80. https://doi.org/10.1016/j.erss.2021.102208.

[10] Hanusch F, Schad M. Hydrogen research: technology first, society second? GAIA 2021;30(2):82–6. https://doi.org/10.14512/gaia.30.2.5.

[11] Schulte I, Hart D, van der Vorst R. Issues affecting the acceptance of hydrogen fuel. Int J Hydrogen Energy 2004;29(7):677–85. https://doi.org/10.1016/j.ijhydene.2003.09.006.

[12] Tarigan AKM, Bayer SB. Temporal change analysis of public attitude, knowledge and acceptance of hydrogen vehicles in Greater Stavanger, 2006–2009. Renew Sustain Energy Rev 2012;16(8):5535–44. https://doi.org/10.1016/j.rser.2012.05.045.

[13] Tarigan AKM, Bayer SB, Langhelle O, Thesen G. Estimating determinants of public acceptance of hydrogen vehicles and refuelling stations in greater Stavanger. Int J Hydrogen Energy 2012;37(7):6063–73. https://doi.org/10.1016/j.ijhydene.2011.12.138.

[14] Bentsen HL, Skiple JK, Gregersen K, Derempouka E, Skjold T. In the green? Public perceptions towards methods of hydrogen production. Energy Res Soc Sci, in revision 2022.

[15] Apostolou D, Welcher SN. Prospects of the hydrogen-based mobility in the private vehicle market. A social perspective in Denmark. Int J Hydrogen Energy 2021;46(9):6885–900. https://doi.org/10.1016/j.ijhydene.2020.11.167.

[16] Geels F. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and case study. Res Pol 2002;31(8–9):1257–74. https://doi.org/10.1016/S0048-7333(02)00062-8.

[17] Geels FW, Sovacool BK, Schwanen T, Sorrell S. The socio-technical dynamics of low-carbon transitions. Joule 2017;1(3):463–79. https://doi.org/10.1016/j.joule.2017.09.018.

[18] Smith A, Stirling A, Berkhout F. The governance of sustainable socio-technical transitions. Res Pol 2005;34(10):1491–510. https://doi.org/10.1016/j.respol.2005.07.005.

[19] Geerdink T, Sprenkeling M, Slob A, Puts H. Guideline societal embeddedness assessment DigiMon. Final report of the ACT DigiMon project. The Netherlands: TNO; 2020.

[20] Wang C, Lv T, Cai R, Xu J, Wang L. Bibliometric analysis of multi-level perspective on sustainability transition research. Sustainability 2022;14(7):4145. https://doi.org/10.3390/su14074145.

[21] Kanger L. Rethinking the multi-level perspective for energy transitions: from regime lifecycle to explanatory typology of transition pathways. Energy Res Social Sci 2021;71:1–12. https://doi.org/10.1016/j.erss.2020.101829. a101829.

[22] Damman S, Sandberg E, Rosenberg E, Pisciella P, Graabak I. A hybrid perspective on energy transition pathways: is hydrogen the key for Norway? Energy Res Social Sci 2021;78:102116. https://doi.org/10.1016/j.erss.2021.102116.

[23] Andersen AD, Steen M, Mäkitie T, Hanson J, Thune TM, Soppe B. The role of inter-sectoral dynamics in sustainability transitions: a comment on the transitions research agenda. Environ Innov Soc Transit 2020;34:348–51. https://doi.org/10.1016/j.eist.2019.11.009.

[24] McMeekin A, Geels FW, Hodson M. Mapping the winds of whole system reconfiguration: analysing low-carbon transformations across production, distribution and consumption in the UK electricity system (1990–2016). Res Pol 2019;48:1216–31. https://doi.org/10.1016/j.respol.2018.12.007.

[25] Sony M, Naik S. Industry 4.0 integration with socio-technical systems theory: a systematic review and proposed

theoretical model. Technol Soc 2020;61:101248. https://doi.org/10.1016/j.techsoc.2020.101248.
[26] Davis MC, Challenger R, Jayewardene DNW, Clegg CW. Advancing socio-technical systems thinking: a call for bravery. Appl Ergon 2014;45(2):171–80. https://10.1016/j.apergo.2013.02.009.
[27] Hendrick HW, Kleiner BM. Macroergonomics: theory, methods, and applications. Mahwah, NJ, London: Lawrence Erlbaum Associates; 2002.
[28] Talanquer V. Using qualitative analysis software to facilitate qualitative data analysis. In: Bunce DM, Cole RS, editors. Tools of chemistry education research. Washington, DC: American Chemical Society, ACS Symposium Series; 2014. https://doi.org/10.1021/bk-2014-1166.ch005.
[29] de Ruyter K, Scholl N. Positioning qualitative market research: reflections from theory and practice. Qual Mark Res 1998;1:7–14. https://doi.org/10.1108/13522759810197550.
[30] Ryan ME. Making visible the coding process: using qualitative data software in a post-structural study. Issues Educ Res 2009;19(2):142–61.
[31] Kapoulas A, Mitic M. Understanding challenges of qualitative research: rhetorical issues and reality traps. Qual Mark Res 2012;15:354–68. https://doi.org/10.1108/13522751211257051.
[32] Høyland SA, Gressgård LJ, Hansen K, Holte KA. Exploring multiple working arrangements in Norwegian engineering, procurement, and construction industry from a middle manager and supervisor perspective – a socio-technical system perspective. Appl Ergon 2019;76:73–81. https://doi.org/10.1016/j.apergo.2018.12.005.
[33] Høyland S, Skotnes RØ, Holte KA. An empirical exploration of the presence of HRO safety principles across the health care sector and construction industry in Norway. Saf Sci 2017;107:161–72. https://doi.org/10.1016/j.ssci.2017.07.003.
[34] Høyland S, Hagen JM, Skotnes RØ. Exploring the benefits of cloud services and accountability tools from a competitiveness and return on investment perspective. Int J Inf Technol Manag 2017;16:215. https://doi.org/10.1504/ijitm.2017.10005170.
[35] Høyland S, Haugen AS, Thomassen Ø. Perceptions of time spent on safety tasks in surgical operations: a focus group study. Saf Sci 2014;70:70–9. https://doi.org/10.1016/j.ssci.2014.05.009.
[36] Høyland SA. A contribution to empirical revitalization of the samfunnssikkerhet concept. Saf Now 2018;4(3). https://doi.org/10.3390/safety4030032. Article 32.
[37] Høyland SA. Exploring and modelling the societal safety and societal security concepts – a systematic review, empirical study and key implications. Saf Sci 2018;110:7–22. https://doi.org/10.1016/j.ssci.2017.10.019.
[38] Leech NL, Onwuegbuzie AJ. An array of qualitative data analysis tools: a call for data analysis triangulation. Sch Psychol Q 2007;22:557–84. https://doi.org/10.1037/1045-3830.22.4.557.
[39] Denzin NK. Sociological methods. New York: McGraw-Hill; 1978.
[40] Patton MQ. Qualitative evaluation and research methods. Newbury Park, CA: Sage Publications; 1990.
[41] Bradley EH, Curry LA, Devers KJ. Qualitative data analysis for health services research: developing taxonomy, themes, and theory. Health Serv Res 2007;42:1758–72.
[42] Hruschka DJ, Schwartz D, StJohn DC, Picone-Decaro E, Jenkins RA, Carey JW. Reliability in coding open-ended data: lessons learned from HIV behavioral research. Field Methods 2004;16:307–31. https://doi.org/10.1177/1525822X04266540.
[43] Høyland S. Developing and validating a scientific model for exploring safe work practices in interdisciplinary teams. Saf Sci 2012;50:316–25. https://doi.org/10.1016/j.ssci.2011.09.008.
[44] Leiren MD, Aakre S, Linnerud K, Julsrud TE, Di Nucci M-R, Krug M. Community acceptance of wind energy developments: experience from wind energy scarce regions in Europe. Sustainability 2020;12(5):1754. https://doi.org/10.3390/su12051754.
[45] Delhey J, Newton K. Predicting cross-national patterns of social trust: global pattern or Nordic exceptionalism? Eur Sociol rev 2005;21(4):311–27. https://doi.org/10.1093/esr/jci022.
[46] Engen OA, Lindøe P, Hansen K. Power, trust and robustness – the politicization of HSE in the Norwegian petroleum regime. Pol Pract Health Saf 2017;15(2):145–59. https://doi.org/10.1080/14773996.2017.1318458.
[47] Kaasen K. Safety regulation on the Norwegian continental shelf. In: Lindøe P, Baram M, Renn O, editors. Risk governance of offshore oil and gas operations. New York: Cambridge University Press; 2014.
[48] Erlandson DA, Harris EL, Skipper BL, Allen SD. Doing naturalistic inquiry: a guide to methods. Newbury Park, CA: Sage; 1993.
[49] Lincoln YS, Guba EG. Naturalistic inquiry. Newbury Park, CA: Sage Publications; 1985.
[50] Moran-Ellis J, Alexander VD, Cronin A, Dickinson M, Fielding J, Sleney J, Thomas H. Triangulation and integration: processes, claims and implications. Qual Res 2006;6:45–59. https://doi.org/10.1177/1468794106058870.
[51] Olsen WK. Triangulation in social research: qualitative and quantitative methods can really be mixed. In: Haralambos M, Holborn M, editors. Developments in sociology. Ormskirk: Causeway Press; 2004.
[52] Roche MR, Mourato S, Fischedick M, Pietzner K, Viebahn P. Public attitudes towards and demand for hydrogen and fuel cell vehicles: a review of the evidence and methodological implications. Energy Pol 2010;38(10):5301–10. https://doi.org/10.1016/j.enpol.2009.03.029.
[53] Stöckl F, Schill WP, Zerrahn A. Optimal supply chains and power sector benefits of green hydrogen. Sci Rep 2021;11(1):14191. https://doi.org/10.1038/s41598-021-92511-6.