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In the green? Perceptions of hydrogen production methods among the Norwegian public

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A R T I C L E I N F O

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A B S T R A C T

This article presents findings from a representative survey, fielded through the Norwegian Citizen Panel, examining public perceptions of hydrogen fuel and its different production methods. Although several countries, including Norway, have strategies to increase the production of hydrogen fuel, our results indicate that hydrogen as an energy carrier, and its different production methods, are still unknown to a large part of the public. A common misunderstanding seems to be confusing 'hydrogen fuel' in general with environmentally friendly 'green hydrogen'. Results from a survey experiment ($N = 1906$) show that production method is important for public acceptance. On a five-point acceptance scale, respondents score on average 3.9 for 'green' hydrogen, which is produced from renewable energy sources. The level of acceptance is significantly lower for 'blue' (3.2) and 'grey' (2.3) hydrogen when respondents are informed that these are produced from coal, oil, or natural gas. Public support for hydrogen fuel in general, as well as the different production methods, is also related to their level of worry about climate change, gender, and political affiliation. Widespread misunderstandings regarding 'green' hydrogen production could potentially fuel public resistance as new 'blue' or 'grey' projects develop. Our results indicate a need for clearer communication from the government and developers regarding production methods to avoid distrust and potential public backfire.

1. Introduction

Are citizens' perceptions of the use of hydrogen as a fuel affected by how the hydrogen is produced? Countries around the world are increasingly committing to and investing in hydrogen as a potential solution to decarbonize industries and meet the goals of carbon dioxide reductions. Several countries, including France, Japan, Australia, Norway, Germany, the United Kingdom, Portugal, Spain, Chile, and Finland, as well as the European Union (EU), have published strategies for increasing the production of hydrogen. In the hydrogen strategy from the EU, hydrogen is seen as "essential to support the EU's commitment to reach carbon neutrality by 2050 and for the global effort to implement the Paris Agreement while working towards zero pollution" ([1], p. 1).

As the interest in hydrogen as an alternative to fossil fuels has grown, natural and social scientists have shown increased interest in the public's opinion of using hydrogen as an energy carrier. When democratic societies seek to restructure their energy infrastructure, there is a need for public acceptance. Without public acceptance, the process of developing energy technologies can be greatly impeded or even halt [2]. Understanding public perception of, and responses to, new energy technologies can help facilitate communication between policymakers and the public, as well as provide critical information for anticipating potential public reactions to new technologies [3,4].

As a way of simplifying complex processes and technologies related to hydrogen fuel production, different methods of producing hydrogen are commonly communicated to the public using colour labels (see supplementary material part B for examples of colour labelling in hydrogen strategies). Three common colour labels used to describe

Abbreviations: CCS, Carbon capture and storage; HET, Hydrogen energy tehnologies.

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Table 1
Treatments.

Treatment	Value
1A	So-called “grey” hydrogen uses coal, oil, or natural gas, which means that the process of producing the hydrogen produces large CO_2 emissions.
1B	So-called “blue” hydrogen uses coal, oil, or natural gas, but the CO_2 gas is separated from the hydrogen and returned to where it came from. In Norway, it involves storing CO_2 under the seabed on the continental shelf.
1C	So-called “green” hydrogen is produced from electricity and then preferably from renewable energy, which in principle does not involve any emissions of CO_2.

hydrogen production are “grey”, “blue”, and “green”. So-called grey hydrogen is produced from coal, oil, or natural gas, which typically involves large emissions of carbon dioxide (CO_2). Blue hydrogen is also produced from coal, oil, or natural gas, but the carbon is separated from the hydrogen and permanently stored to prevent emissions to the atmosphere, for example by technologies such as carbon capture and storage (CCS). Finally, green hydrogen is produced from renewable energy sources, such as solar, wind, or tide, which in principle does not involve any emissions of CO_2.

As these colour labels communicate the extent to which hydrogen can have a positive impact on reducing carbon dioxide emissions, they offer ‘cues’ to citizens about the environmental aspects of using hydrogen as an energy carrier. By examining how colour cues influence public support for hydrogen, we get a better understanding of the degree to which environmental concerns drive public support. A recent study reviewing the literature on public acceptance of hydrogen energy technologies (HET) concluded that, while there is some evidence to suggest that people are in favour of renewable hydrogen, the extent to which people value the attributes of each production method and how this influences acceptance is not clear [5]. The study called for research investigating “the extent to which the acceptance of downstream HET applications is determined by the production method and under what conditions one production method may be preferred over another” ([5], p. 10454).

Based on existing knowledge, we can assume that the public’s positive perception of hydrogen is, at least partly, driven by the impression that hydrogen is a climate-friendly fuel compared to existing alternatives. In the eyes of the public, hydrogen might be associated with a sustainable energy transition that is necessary to counter climate change. To the extent that citizens at the onset perceive hydrogen as a green technology, we should expect support for hydrogen to remain high when citizens are exposed to colour labels communicating that hydrogen is produced in ways that minimize CO_2 emissions. On the other side, support can be expected to plummet if hydrogen fuel production is presented as a cause of CO_2 emissions.

In this study, we use an original survey experiment to examine the public acceptance of the use of grey, blue, and green hydrogen for maritime traffic along the Norwegian coastline. We aim to gain a better understanding of whether and to what extent hydrogen production methods influence public acceptance of the use of hydrogen as an energy carrier. In addition, we examine the extent to which these views are contingent upon citizens’ concerns about climate change and their party preferences. The results of the survey experiment are further compared to responses to a separate survey question asking citizens about their perceptions of the use of hydrogen as a fuel for ferries and passenger ships without specifying the production method. This comparison is important as it enables us to examine with greater confidence whether citizens’ opinion of hydrogen as an alternative fuel is linked to perceptions of hydrogen as a climate-friendly fuel.

The remainder of this paper is organized as follows. In Section 2, we situate the analysis within the wider literature on public support for energy technologies. We also review the existing literature on public

Table 2
Descriptive statistics for the sample asked a general question on hydrogen.

Variables	Values	Frequencies	Valid	Missing
Perception towards hydrogen	Mean: 5.7 Standard deviation: 1.6	1: 32 (1.3 %) 2: 54 (2.2 %) 3: 82 (3.3 %) 4: 454 (18.1 %) 5: 347 (13.9 %) 6: 767 (30.6 %) 7: 335 (13.4 %) 8: 432 (17.3 %)	2503 (98.82 %)	30 (1.18 %)
Gender	1. Female	1272 (50.2 %)	2533	0
	2. Male	1261 (49.8 %)	(100 %)	(0 %)
Highest education	1. No education/ elementary school	123 (5.0 %)	2486	47
	2. University/ University College	1595 (64.2 %)	(98.14 %)	(1.86 %)
	3. Upper secondary education	768 (30.9 %)		
Age	1. 1959 or earlier	1218 (48.1 %)	2533	0
	2. 1960–1989	1154 (45.6 %)	(100 %)	(0 %)
	3. 1990 or later	161 (6.4 %)		
Party preference	1. The Progress Party	185 (7.3 %)	2523	10
	2. The Green Party	166 (6.6 %)	(99.61 %)	(0.39 %)
	3. The Liberal Party	77 (3.0 %)		
	4. The Socialist Left Party	211 (8.4 %)		
	5. The Red Party	136 (5.4 %)		
	6. The Labour Party	430 (17.0 %)		
	7. The Centre Party	457 (18.1 %)		
	8. The Christian Democrats	69 (2.7 %)		
	9. The Conservative Party	576 (22.8 %)		
	10. Other	216 (8.6 %)		
Climate concern	Mean: 3.5 Standard deviation: 1.1	1: 124 (5.2 %) 2: 302 (12.8 %) 3: 691 (29.2 %) 4: 756 (32.0 %) 5:489 (20.7 %)	2362 (93.25 %)	171 (6.75 %)

support for new hydrogen technologies and outline the theoretical foundations of our experimental analysis. In Section 3, we describe in detail our data and our survey-experimental research design. Section 4 presents the results of our experiments. Finally, in Section 5, we summarize our main results and discuss implications of our findings that policymakers and others should consider when planning and rolling out large hydrogen initiatives.

2. Background and literature review

2.1. The future of hydrogen as an energy carrier

The idea to use hydrogen as an energy carrier is not new. According to Ball and Wietschel [6], hydrogen was used until the 1960s in many countries as a part of a mixture of gasses for street lighting as well as for cooking and heating in homes. The very idea of a hydrogen-based energy system was formulated in the aftermath of the oil crises in the 1970s. However, it was the breakthroughs in fuel cell technology in the

Table 3
Descriptive statistics for the sample asked experimental questions on hydrogen.

Variables	Values	Frequencies	Valid	Missing
Hydrogen (treatment)	1. Grey 2. Blue 3. Green	661 (33.7 %) 664 (33.9 %) 634 (32.4 %)	1959 (100 %)	0 (0 %)
Acceptance	Mean: 3.1 Standard deviation: 1.2	1: 195 (10.2 %) 2: 369 (19.4 %) 3: 596 (31.3 %) 4: 500 (26.2 %) 5: 246 (12.9 %)	1906 (97.29 %)	53 (2.71 %)
Attitude towards Norwegian Petroleum Industry	1. Industry-voters 2. Green-voters 3. Other	983 (68.4 %) 455 (31.6 %) 179 (11.1 %)	1617 (82.54 %)	342 (17.46 %)
Climate concern	Mean: 3.5 Standard deviation: 1.1	1: 60 (4.3 %) 2: 200 (14.3 %) 3: 432 (30.9 %) 4: 456 (32.6 %) 5: 250 (17.9 %)	1398 (71.36 %)	561 (28.64 %)

late 1990s that led to a revival of interest in hydrogen, especially with the transport sector in mind [7].

Hydrogen offers a range of benefits as a clean energy carrier, the most important being that it is emission-free at the point of final use [6]. It is also seen as playing a critical role in renewable energy storage [8]. Still, for hydrogen to play a significant role in future low-carbon energy systems, it is necessary to demonstrate that hydrogen systems are at least as safe as systems based on conventional fuels [9] and that the production of hydrogen also entails sufficiently low carbon emissions [10].

Because hydrogen is an energy carrier, as opposed to an energy source, any advantage of using hydrogen as a fuel depends on how it is produced [11]. Today, most hydrogen is being produced from coal or natural gas by reforming without carbon capture (so-called 'grey' hydrogen), implying low overall energy efficiency and large emissions of carbon dioxide. However, if CO_2 can be captured and stored (so-called 'blue hydrogen'), the emissions will be reduced. This blue option has been seen as a critical prerequisite for taking the pathway of producing hydrogen from coal and gas [6], and the EU also recognizes a need for the production of blue hydrogen in a transition phase to a more renewable option [1].

Finally, hydrogen can be produced from non-fossil fuels such as nuclear power or renewable energies. This so-called 'green hydrogen' is today seen by the European Union (EU) as "a key priority to achieve the European Green Deal and Europe's clean energy transition" ([1], p. 1). Yet, while the use of green hydrogen can reduce CO_2 emissions, this option is only viable in so far as the non-fossil fuel source is additional to what would otherwise be needed in society. Accordingly, any assessment of the virtues of switching to hydrogen as a transportation fuel needs to consider several assumptions about long-term developments in climate and energy policy [6,7].

2.2. Hydrogen in Norway

As a supplier of energy, Norway is integrated into the EU's energy market. Norway's power sector, which is predominantly based on hydropower, is 94 % renewable. Coupled with large on- and offshore wind resources, there is a great potential for large-scale renewable hydrogen production [12]. However, Norway's economy is heavily dependent on the income from the export of oil and gas, meaning that a transition to a low-emission society can have a large impact on the economy. Consequently, recently renewed interest in hydrogen in Norway is predominantly based on the expectation that blue hydrogen produced from natural gas with CCS may become a profitable export commodity [13].

Norway is, however, facing substantial challenges regarding the export of blue hydrogen to European countries due to scepticism towards hydrogen produced from natural gas, as well as changing perceptions when it comes to the acceleration of phasing out natural gas and scepticism towards CCS in some European countries [13,14]. According to Torvanger ([13], p. 8), "a more promising avenue for Norwegian collaboration with EU is on improving green hydrogen technologies, and especially hydrogen applications for transportation, including shipping, as well as using hydrogen to reduce dependency on fossil inputs in the industry".

While the export of blue hydrogen seems of primary interest, the 2020 Norwegian Hydrogen Strategy [15] emphasizes efforts to stimulate the development of technologies to produce green hydrogen from electrolysis. The sectors seen as particularly relevant for the consumption of green hydrogen are the maritime and heavy-duty transport and industrial processes. Regarding shipping, there are today several initiatives in Norway to develop hydrogen-fuelled ships. Given Norway's high competence in marine-related technologies, particularly when it comes to designing and building ships, hydrogen-based shipping can be a great opportunity for a new and internationally competitive industry in Norway [13].

Norway is a compelling case to examine how different types of hydrogen production influence public perceptions and support for hydrogen usage. There are currently several hydrogen initiatives in Norway that might expose citizens to information on hydrogen, and the transition to a low-emission society can potentially have large economic consequences for the government and the public at large.

2.3. Perceptions of new energy technologies: knowledge and predispositions

Several studies have focused on public perceptions of new energy technologies. A consistent finding in the literature is that the public is often unfamiliar with new energy technologies. Low knowledge can be explained by a lack of salience on these issues. With notable exceptions for extraordinary circumstances, such as an energy crisis or periods of unusually high costs for electricity or fuels, energy is often invisible to the average consumer, particularly for those living in developed countries. Furthermore, the public is often removed from decision-making when it comes to centralized energy systems [3].

Despite low public knowledge, support for new energy technologies is often high [16]. Reviewing the literature on public perceptions of low-carbon energy technologies, Peterson, Stephens and Wilson [17] found that studies on public opinion, both in the United States and Europe, show remarkably constant levels of support over time for wind, solar, and other renewable technologies. Individuals tend, however, to be less positive towards biomass and low-carbon fossil fuel technology such as natural gas, or towards technologies that enable us to control fossil fuel emissions, such as carbon capture and storage (CSS).

Public perceptions and acceptance might be relevant both at the stage of initial technology development and proposed deployment and at the stage of actual deployment and adoption. These two stages are likely to receive different levels of support and have different predictors. During the initial development, people are likely to have little knowledge of energy technology. How do they then form their opinions about such difficult issues? Recent scholarship find that, due to limited time and resources, people use cognitive shortcuts or heuristics to filter information and develop opinions [18]. Cognitive shortcuts can be based on factors such as ideological predispositions [19], environmental and altruistic values [16,20], media portrayals [18], and elite cues [21,22].

Although support for new energy technologies may be high, public

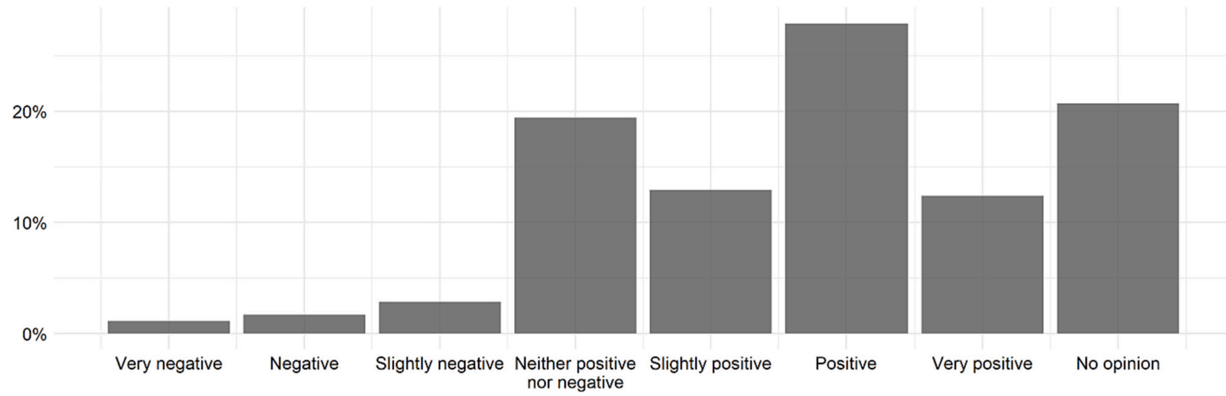

Fig. 1. Perceptions of hydrogen as a fuel for ferries and passenger ships. $N = 2503$.

opinion often becomes divisive once new energy technologies become familiar and more salient to the public, for example as a result of extensive deployment, media coverage or proximity to proposed development [23]. Acceptance of different renewable technologies can furthermore depend on whether the technology is presented on an abstract or concrete level. As new energy technologies become more salient to the public, and when people consider drawbacks and required trade-offs on a concrete level, support for new technologies may decrease [24]. For example, people who use a cognitive shortcut based on environmental concerns might reduce their support for energy technologies if they learn that the technology might have negative environmental impacts.

Generally, people may rely on several different predispositions when evaluating new energy technologies. For example, the reasons for supporting renewable energy transitions in the United States have been found to differ with political affiliation, with global warming concerns driving support among democrats and reduced energy cost driving support among republicans [25]. In addition, a range of sociodemographic factors, such as gender, age, and education, can influence perceptions and attitudes towards new energy technologies. One example is differences in respondents' associations with wind energy, which have been found to differ based on gender and age groups, as well as between opponents and supporters. Associations of local wind projects were evaluated less positively among those voting for the national conservative party compared to all other parties, and by older age groups (above 30) compared to the youngest [28].

The influence of sociodemographic factors on support for energy technologies and policies can also vary based on political preferences. Hamilton et al. [29] find that the younger and better educated more often tend to prioritize renewable energy over increased exploration and drilling for oil, however, education has the opposite effect among the most conservative. Furthermore, Gustafson et al. [25] ran separate analyses for Republicans and Democrats when investigating predictors for support for renewable energy policies and found a statistically significant effect of gender for Republicans, but not for Democrats. Focusing on a general climate policy index, Goldberg et al. [30] have also reported a significantly stronger effect of gender and age for Republicans than for Democrats.

In summary, when individuals rely on predispositions and cues to form an opinion about new technologies, they may support technologies that they know little about. Likewise, when a new technology gains more attention and salience, similar predispositions might lead to divisive opinions on these issues. This process of forming an opinion is in line with the concept of motivated reasoning where people tend to seek out and believe information about emerging technologies that are consistent with and confirms their prior attitudes [31].

2.4. Perceptions of hydrogen technology

As with other energy technologies, the available studies on perceptions of hydrogen show that public knowledge about hydrogen and associated technologies is generally low, but that the level of support for hydrogen technology is high [16,32,33]. Furthermore, although perceptions of risk may negatively influence the acceptance of hydrogen [5,34,35], studies find that hydrogen is perceived more as an environmentally friendly fuel than as a dangerous fuel [36]. In other words, when people are asked about their opinions about hydrogen, they tend to emphasize the potential benefits of hydrogen as an energy carrier, and hence an enabler for renewable energy sources. This finding echoes studies showing that perceived benefit is the single strongest predictor of acceptance for a range of different energy technologies [37–40].

One reason why hydrogen is viewed positively despite relatively low levels of public knowledge appears rooted in the individual's predispositions and cognitive shortcuts. For example, in a study of support for hydrogen technology in the Netherlands, Achtenberg et al. [16] show that cultural predispositions (i.e., trust in technology and environmental concerns) are more important than knowledge in determining people's support for hydrogen. Nevertheless, increased knowledge does influence support, but the influence varies depending on an individual's cultural predispositions. For those who are culturally predisposed to trust new technology and who are highly concerned with the environment, more knowledge about hydrogen technology will lead to greater support. On the other hand, for those who are sceptical towards new technology and less concerned about the environment, increased knowledge may not garner greater support. Similarly, Tarigan et al. [41] show that increased knowledge of hydrogen appears to indirectly affect hydrogen acceptance through a more positive attitude towards a sustainable environment.

A few studies examine how the framing of hydrogen technology influences public perceptions and support. Zachariah-Wolff and Hemmes [36] show that people who are exposed to negative information on hydrogen evaluate hydrogen more negatively than people who are not exposed to hydrogen information. They also find that providing negative information has a stronger effect on public acceptance than providing positive information. A possible reason for this finding is that information concerning negative aspects of hydrogen technologies describes tangible hazards, for example, associated with catastrophic explosions, and that these dangers might feel closer to people in the sense that they

Table 4
OLS regression models. Individual's background and attitudes and hydrogen perceptions.

	(1)	(2)	(3)	(4)
Male (compared to female)	0.560*** (0.078)	0.637*** (0.076)	0.605*** (0.075)	0.656*** (0.075)
Born 1960–1989 (compared to those born earlier than 1960)	−0.176* (0.084)	−0.109** (0.085)	−0.156 (0.082)	−0.095 (0.085)
Born in 1990 or later (compared to those born earlier than 1960)	0.081 (0.141)	0.060 (0.133)	0.034 (0.133)	0.048 (0.128)
University/ University College (compared to no education/ primary school)	0.189 (0.153)	−0.078 (0.152)	0.105 (0.147)	−0.102 (0.154)
Upper secondary education (compared to no education/ primary school)	0.018 (0.154)	−0.097 (0.149)	0.034 (0.147)	−0.074 (0.147)
Concern about climate change		0.233*** (0.040)		0.206*** (0.042)
Green Party (compared to the Progress Party)			0.568* (0.245)	0.157 (0.253)
Liberal Party (compared to the Progress Party)			0.979*** (0.275)	0.622* (0.258)
Socialist Left Party (compared to the Progress Party)			0.766*** (0.192)	0.423 (0.216)
Red Party (compared to the Progress Party)			0.070 (0.242)	−0.249 (0.261)
Labour Party (compared to the Progress Party)			0.470* (0.187)	0.200 (0.200)
Centre Party (compared to the Progress Party)			0.291 (0.189)	0.075 (0.201)
Christian Democrats (compared to the Progress Party)			0.341 (0.297)	0.271 (0.296)
Conservative Party (compared to the Progress Party)			0.418* (0.183)	0.226 (0.197)
Other (compared to the Progress Party)			−0.024 (0.225)	−0.198 (0.235)
Constant	4.899*** (0.136)	4.204*** (0.167)	4.545*** (0.195)	4.149*** (0.218)
N	2039	1916	2035	1913
Log Likelihood	−3730.315	−3467.508	−3690.297	−3442.823
AIC	7472.630	6949.017	7410.594	6917.646

* $p < .05$.
** $p < .01$.
*** $p < .001$.

can directly affect their daily lives. In contrast, positive information given to the subjects highlight environmental benefits, which only have an indirect positive effect on the daily lives of people.

Another study investigates German citizens' attitudes towards hydrogen-powered cars [42]. Among other things, the authors ask a representative sample whether natural gas should be used to produce hydrogen as a less costly bridge technology for a transition period, or whether hydrogen should be produced in a more costly but environmentally friendly way from the start. The results of this study show that a clear majority would prefer hydrogen produced in an environmentally friendly way even though costs would be higher. The findings from this study are informative for the research question posed in this paper. However, they do not ask respondents to evaluate a "blue" alternative where the carbon dioxide stemming from hydrogen production based on natural gas is captured.

Regarding sociodemographic backgrounds, the available studies show that the higher educated, males, and young people have stronger support for hydrogen technology [16,43]. In addition, studies have shown that the same groups tend to be more knowledgeable about hydrogen than their counterparts [36]. To the best of our knowledge, no study exists that examines the influence of party preference on support for hydrogen technologies. However, based on existing research on perceptions of new energy technologies (discussed in Section 2.1), we may expect party preferences to influence views about different hydrogen production methods. Specifically, we might expect varying support for different production methods among voters for green parties or for parties that are generally more optimistic about the use of new energy technology to solve climate issues.

3. Data and research design

To examine citizens' perceptions of hydrogen production methods we rely on public opinion data. Specifically, the analyses utilize two survey items (one general survey question and a survey-embedded vignette experiment) fielded in Wave 19 of the Norwegian Citizen Panel (NCP) conducted between November 2, 2020, and November 27, 2020 [44].[1] The NCP is a research-purpose internet panel. The participants have been recruited via random sampling from the official national population registry and are representative of both the online and offline population older than 18 years of age in Norway. The more than 10,000 active participants are randomly divided into subpanels, each consisting of about 2000 respondents.

Our general survey question and the vignette experiment were fielded to two different subsamples. The general question on perceptions of using hydrogen as a fuel for ferries and passenger ships (not specifying production method) was fielded to a subsample consisting of 2533 individuals. Of these, 30 participants did not provide an answer, yielding a sample size N of 2503. The survey-embedded experiment was fielded to a subsample consisting of 1996 individuals. Of these, 90 participants did not answer the question, yielding an N of 1906. Analysing the two survey items in tandem enables us to draw comparisons between citizens' general perceptions of hydrogen and citizens' informed perceptions of hydrogen. This comparison is important as it enables us to examine with greater confidence whether citizens' perceptions of hydrogen as an alternative fuel source are linked to perceptions of hydrogen as a climate-friendly fuel.

3.1. General survey question

Our first item is a general survey question designed to measure citizens' perception of the use of hydrogen as a fuel for ferries and

[1] The Norwegian Citizen Panel is financed by the University of Bergen (UiB) and the Trond Mohn Foundation (TMS). Data collection was coordinated by UiB, implemented by Ideas2Evidence, and distributed by Sikt and UiB. For more information about the Norwegian Citizen Panel, see http://digsscore.uib.no/panel. Documentation of the field methods used, response rates, and representativeness is reported in the online methodology report, while the data and codebook are available from https://www.uib.no/medborger. All analysis were performed using R (version 4.0.2) through the RStudio interface. An R script that reproduces the results reported in this study is also available from the authors.

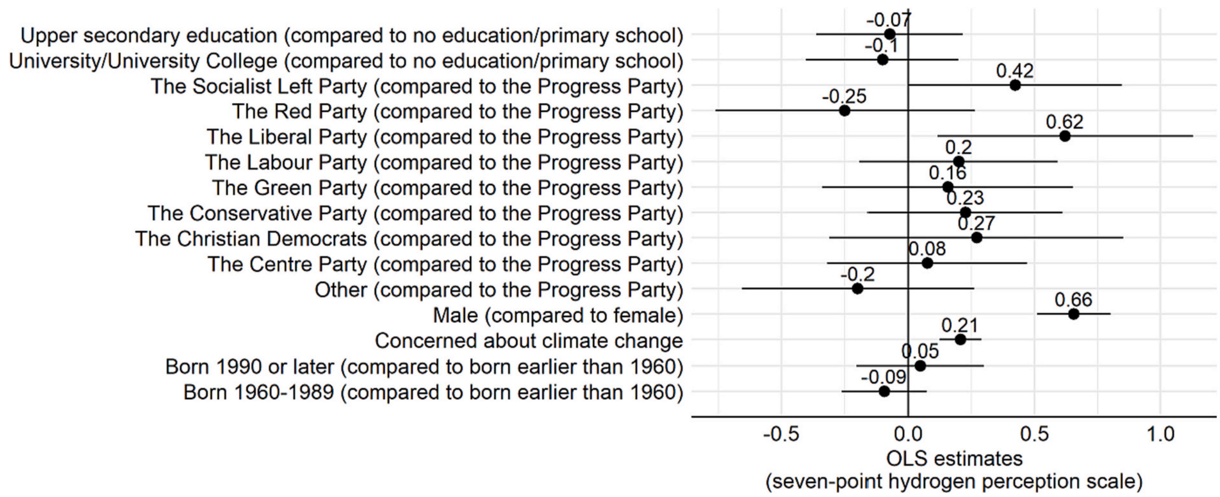

Fig. 2. Covariates of hydrogen perceptions. $N = 1913$.

passenger ships.[2] The question reads:

> Do you have a positive or negative impression of hydrogen as a fuel for ferries and other passenger ships?

Survey participants express their perceptions on an eight-point scale with the following options: very positive, positive, somewhat positive, neither positive nor negative, somewhat negative, negative, very negative, no opinion. In our analysis, we flip this scale so that higher values represent more positive hydrogen impressions.

We use this survey question to describe citizens' general perceptions of using hydrogen as a fuel for ferries and passenger ships, as well as to describe how perceptions of hydrogen vary between sociodemographic groups and across individuals with different party preferences. For the former, we simply present the distribution of respondents on the hydrogen question. For the latter, we use OLS regression models, which we discuss in more detail below. In both analyses, we use survey weights to account for observed biases in the NCP sample.[3] With existing literature in mind, we included the "no opinion" option to account for the information gap that is assumed to either force uninformed answers or prevent citizens from expressing their views on hydrogen.[4]

3.2. Survey-embedded vignette experiment

Our second item is a survey-embedded vignette experiment designed to measure citizens' acceptance of hydrogen-powered ferries depending on the type of hydrogen production method. Using a survey experiment allows us to expose respondents to randomly assigned descriptions of how hydrogen is produced, with the implication that we can interpret differences in the outcome variable between different types of hydrogen as causal estimates. The treatments in our survey experiment are the three most common methods of hydrogen production (green, blue, and grey). Each treatment is composed of a short vignette describing the energy source that is used to produce hydrogen, as well as its consequences for CO_2 emissions. The outcome variable in the survey experiment is the level of acceptance, which is measured on a five-point scale. The experiment is presented to respondents in the following way. First, all respondents are exposed to a short text describing the scenario. The scenario reads:

Hydrogen is an alternative fuel source for shipping in Norway. Among other things, hydrogen will be used for Norway's first hydrogen ferry, which will be in operation for Norled on the Hjelmeland connection from 2021. Hydrogen can be produced in various ways.

Respondents are then randomly assigned to one of three treatments (see Table 1) and then finally asked the following question:

> To what degree do you think it is acceptable that shipping traffic in Norway is operated by hydrogen produced in this way?

Survey participants express their level of acceptance on a five-point scale with the following options: (1) to a very high degree, (2) to a high degree, (3) to some degree, (4) to a small degree, (5) not at all. In our analysis, we flip this scale so that higher values represent higher acceptance.

3.3. Background characteristics and party preferences

To examine how individual background characteristics and attitudes are related to hydrogen perceptions in our two survey items, we draw on a set of background variables available in the NCP. We base our selection of variables on existing studies of perceptions of new energy technologies [3,16]. Tables 2 and 3 show descriptive statistics for the two subsamples. We include a different set of background variables for the analysis of the general survey question and the analysis of heterogeneous effects in the survey experiment. Details on these analyses are presented in Section 4. The background variables that we include in our analyses are:

- Citizens' concern about climate change: A five-point scale variable ranging from 1 not concerned at all to 5 extremely concerned.
- Gender: A categorical variable with the values Female (reference category) and Male.
- Highest level of education: This is a categorical variable measuring individuals' highest level of completed education, with three values:

[2] Our survey items focus on the use of hydrogen as an energy source for maritime transport. There is little reason to expect citizens' perceptions of hydrogen as an energy source to vary across different types of transport. In Fig. A1 in the supplementary appendix, we show that more citizens are slightly negative towards using hydrogen as fuel for cars than for maritime transport, but otherwise, the distribution of responses is very similar.

[3] We use "Weight 2" in the NCP, which combines demographic variables with education.

[4] In Fig. A2 in the supplementary appendix, we report results on who is less likely to express an opinion on hydrogen. We use the eight-point scale to construct a dichotomous variable "no opinion on hydrogen" (taking the value 1 if participants express no opinion and 0 otherwise). We then regress this outcome on citizens' background characteristics and attitudes. The results show that females are less likely to have an opinion compared to males, and that citizens in the oldest age group are more likely to have an opinion compared to younger citizens.

No education/elementary school (reference category), Upper secondary education and University/University College.
- Age: A categorical variable measuring age cohort, with three values: 1959 or earlier (reference category), 1960–1989 and 1990 or later.
- Party preference: A categorical variable measuring which political party citizens would vote for if there was an election tomorrow, with nine values: The Progress Party (reference category), the Green Party, the Liberal Party, the Socialist Left Party, the Red Party, the Labour Party, the Centre Party, and the Christian Democrats. Party preference is also used to create variable measuring citizens' attitudes towards the Norwegian petroleum industry.

4. Results

4.1. Public views towards using hydrogen as a fuel in maritime transportation

What are citizens' views on hydrogen as a fuel source for ferries and other passenger ships? Fig. 1 provides the answer by plotting the distribution of respondents' hydrogen perceptions. There are two main takeaways from Fig. 1. First, we find that the public generally expresses positive views towards using hydrogen as a fuel for ferries and passenger ships. Most respondents answered that they are slightly positive (13 %), positive (28 %), or very positive (13 %). On the other end of the scale, very few citizens are negative. Around 6 % of citizens express very negative to slightly negative impressions of hydrogen. Excluding respondents that have no opinion, the weighted average score on the perception scale is 5.2 (95 % confidence interval: 5.1–5.3), close to slightly positive, while the median response is 6 (positive).

Second, while a majority express positive sentiments, there is also a substantial number of citizens expressing that they are neither negative nor positive (about 20 %) or have no opinion (about 20 %) regarding using hydrogen as a fuel for ferries and passenger ships.

4.2. Climate concern, green party preference and gender

How do hydrogen perceptions vary among individuals with different backgrounds and attitudes? To examine this we use ordinary least squares (OLS) regression models with citizens' expressed perceptions of hydrogen as the outcome variable (a seven-point scale excluding respondents expressing no opinion) and a set of variables that measure citizens' backgrounds and attitudes: concern about climate change, party preferences, age, gender, and level of education.[5] We run four different regression models to examine descriptive patterns between individuals' backgrounds and attitudes. The results of all regression models are reported in Table 4. Model 1 includes only background characteristics: age, gender, and education. Model 2 adds the variable measuring concern about climate. Model 3 removes the climate concern variable and adds party preferences. Model 4 includes all covariates. We build our model stepwise because climate concern is associated with party preferences [45].[6] Estimating the correlation between climate concern and party preferences both separately (model 2 and 3) and together (model 4) enables us to examine how the correlation between party preferences and hydrogen perception is driven by climate concerns.[7]

In Fig. 2, we show results from Model 4 graphically and refer to results in Table 4 where necessary. There are four main findings. First, males are more positive towards hydrogen than females. On average, males score 0.66 points higher on the hydrogen perception scale than females (95 % confidence intervals: 0.51–0.802). Second, in contrast to earlier studies, our results do not show any differences between individuals with different levels of education. Nor do our results show any differences between different age groups. Third, citizens who are more concerned about climate change are more positive towards using hydrogen as a fuel for ferries and passenger ships. A one-unit increase on the concerned scale is associated with a 0.21 increase on the hydrogen perception scale (95 % confidence intervals: 0.124–0.289).

Fourth, Model 3 in Table 4 shows that individuals with different party preferences have different perceptions of hydrogen. Compared to Progress Party voters ('Fremskrittspartiet'), Liberal Party ('Venstre'), Socialist Left Party ('Sosialistisk Venstreparti'), Green Party ('De Grønne'), Labour Party ('Arbeiderpartiet'), and Conservative Party ('Høyre') voters express more positive attitudes towards hydrogen (the names in parentheses are the official names of the political parties in Norway). The difference is most pronounced among those who prefer parties with an environmental or green profile: the Liberal Party, the Socialist Left Party, and the Green Party. As depicted in Fig. 2, when we control for individual climate concern, only individuals whose preferences align with the Liberal Party and the Socialist left party is more positive towards hydrogen than individuals whose preferences align with the Progress Party. Individuals intending to vote for the Socialist Left Party score 0.42 points higher on the hydrogen perception scale than individuals intending to vote for the Progress Party (95 % confidence intervals: 0–0.847). Individuals intending to vote for the Liberal Party score 0.62 points higher on the hydrogen perception scale than individuals intending to vote for the Progress Party (95 % confidence intervals: 0.116–1.128). These findings suggest that climate concern is not the sole driver of individuals' perception of hydrogen and are also consistent with data showing that Liberal- and Socialist Left party voters are more positive towards technology as a solution for the climate crisis compared to the green party voters [46].

4.3. Public acceptance of hydrogen depends on how it is produced

So far, we have shown that the public is generally positive about using hydrogen as fuel in maritime transport. Fig. 3 illustrates the results of the survey experiment focusing on differences in acceptance between grey, blue, and green hydrogen.[8]

[5] After removing 432 individuals expressing no opinion, we are left with 2071 responses on the hydrogen perceptions variable. After listwise deletion of observations in our regression models we are left with 2039 observations in model 1, 1916 observations in model 2, 2035 observations in model 3 and 1913 observations in model 4.

[6] In Fig. A3 in the supplementary appendix, we show that citizens' concern for climate change and party preferences are correlated.

[7] Whether climate concern affects party preferences, or party preferences affect climate concern, is not obvious. Our aim here, however, is not to claim a causal effect between either party preferences or climate concern on hydrogen perceptions, but rather to describe which individuals that are supportive of hydrogen.

[8] Fig. A4 shows the distribution of responses on the five-point acceptance scale by three types of hydrogen: green, blue, and grey. Table A1 shows that missingness on the acceptance variable is significantly higher among individuals exposed to the blue treatment compared to the grey treatment. This could reflect the technicality of the blue treatment or that the text used to describe the blue-treatment is longer than the grey- and green treatment. To account for this, we replicated the main analysis with multiple imputation in Model 2 in Table A2. Model 2 in Table A2 shows that our main results remain substantively the same when we replace missing values using multiple imputation [47]. We used the R package mice [48] to perform the analysis. We generated five independent data sets where missing values were replaced with values that keep the relationship between the observed variables. For each data set we regressed acceptance on treatment, and then pooled the estimates together to get average regression coefficients and correct standard errors.

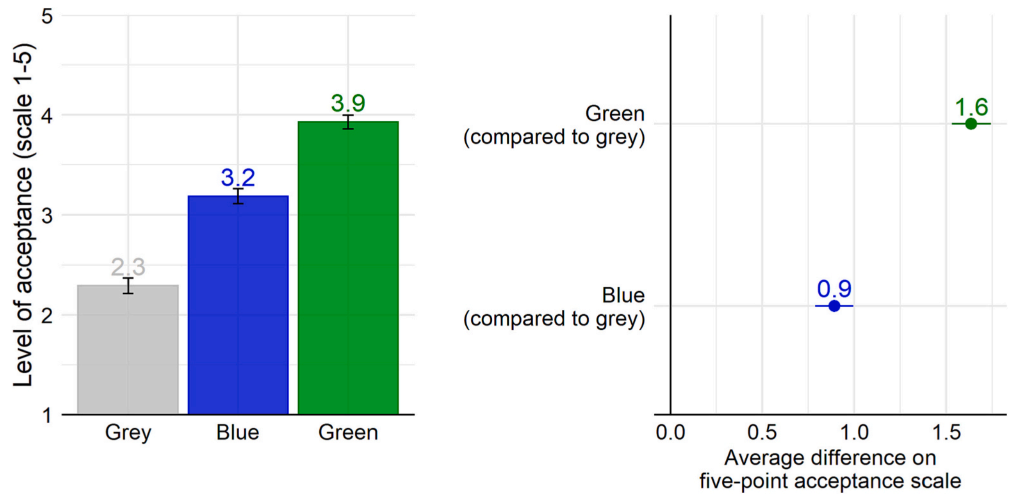

Fig. 3. Public acceptance of grey, blue, and green hydrogen. $N = 1906$.

The bars on the left-hand side show the average acceptance levels for the three hydrogen production methods. The results support our expectation that the level of acceptance of using hydrogen as fuel on ferries depends on how hydrogen is produced. On the five-point acceptance scale, respondents exposed to green, blue, and grey hydrogen score on average 3.9 (95 % confidence interval: 3.858–3.996), 3.2 (95 % confidence interval: 3.108–3.259) and 2.3 (95 % confidence interval: 2.213–2.37), respectively. The coefficient plot on the right-hand side demonstrates that differences in acceptance between green and blue hydrogen, compared to grey hydrogen, are statistically significant and quite substantial. Respondents exposed to green hydrogen score on average 1.6 points higher (95 % confidence interval: 1.53–1.742) than those exposed to grey hydrogen, while the corresponding estimate for those exposed to blue hydrogen is 0.9 points (95 % confidence interval: 0.787–0.997). There is also a difference in levels of support for blue and green hydrogen. As shown in Fig. A5 in the supplementary appendix, respondents exposed to green hydrogen show higher levels of acceptance than those exposed to blue hydrogen. The difference is 0.7 points (95 % confidence interval: 0.642–0.846) and is statistically significant at conventional levels.

Overall, the results strongly suggest that citizens care about how hydrogen is produced and the level of CO_2 emissions that result from different methods of hydrogen production.

4.4. Citizens concerned about climate change more supportive of green hydrogen

To further examine the basis of support for green, blue, and grey hydrogen, we explore whether the effect of the type of hydrogen on acceptance is moderated by citizens' 1) concern for climate change and 2) attitudes towards developing the Norwegian petroleum industry. We expect that individuals who are more concerned about climate change will show greater support for green hydrogen compared to both blue and grey. In the context of support for different types of hydrogen in Norway, the use of oil to produce grey and blue hydrogen is possibly a cue that generates higher support among citizens who emphasize economic costs and benefits over policies aimed at tackling climate change. Thus, we expect citizens who to a greater extent want to maintain and develop the Norwegian petroleum industry to be less concerned with how hydrogen is produced than citizens who are more eager to phase out the Norwegian oil industry.

To proxy attitudes towards developing the Norwegian petroleum industry, we use citizens' vote intention to create a categorical variable that measures whether citizens intended to vote for an "industry party" seeking to continue to maintain and develop the Norwegian petroleum industry (The Labour Party, The Conservative Party, The Centre Party, The Christian Democrats or The Progress Party) or a "green party" that wants a faster phase-out of the oil industry (The Green Party, The Red Party, The Liberal Party or The Socialist Left Party). Individuals that did not vote for any of these parties are coded as "Other" and are composed of both non-voters and individuals voting for other parties.

We explore heterogeneous effects by estimating two OLS regression models with acceptance as the dependent variable. Regression coefficients are reported in Table 5. In model 1, we include the type of hydrogen, climate concern, and an interaction term between the type of hydrogen and climate concern as independent variables. In model 2, we include the type of hydrogen, vote for green- or industry party, and an interaction term between the type of hydrogen and vote for green- or industry party as independent variables.[9]

Model 1 in Table 5 shows that, on average, the difference in acceptance levels between respondents exposed to green and blue hydrogen compared to grey hydrogen, is larger among citizens that are more concerned about climate change. The effect of being exposed to blue hydrogen, compared to grey, increases by 0.2 points (95 % confidence interval: 0.086–0.312) for a unit increase on the climate concern scale. Among individuals exposed to green hydrogen, compared to grey hydrogen, the corresponding estimate is 0.42 points (95 % confidence interval: 0.305–0.535). Model 2 in Table 5 shows that the effect of being exposed to blue hydrogen, compared to grey, increases by 0.33 points (95 % confidence interval: 0.068–0.591) on the acceptance scale among green voters compared to industry voters. The effect of being exposed to green hydrogen, as compared to grey, increases with 0.37 (95 % confidence interval: 0.106, 0.639) points on the acceptance scale among green voters compared to industry voters. Overall, these results show that the type of hydrogen production method is more important to individuals who show greater concern about climate change or vote for green parties compared to industry parties.

To illustrate how these interaction effects play out, Fig. 4 plots predicted average acceptance score (y-axis) for different types of hydrogen (green, blue, grey) depending on concern about climate change (x-axis left) and for industry voters, green voters, or others (x-axis right). The

[9] We lose a substantial number of respondents in these interaction models due to missingness on the climate concern and vote intention variables. However, this missingness is not related to treatment status. Among respondents without missing on both acceptance and climate concern (Model 1 in Table 5), 34.3 % were exposed to grey-, 33.3 were exposed to blue-, and 32.5 % was exposed to green treatment. Similar numbers for Model 2 in Table 5 are 34.4 %, 33.2 % and 32.4 %, respectively.

Table 5
Interaction effect between the type of hydrogen production methods and climate concern (model 1) and vote for industry or green party (model 2).

	Acceptance	
	(1)	(2)
Blue	0.240 (0.206)	0.808*** (0.074)
Green	0.201 (0.213)	1.595*** (0.074)
Concern about climate change	−0.185*** (0.040)	
Blue * Concern about climate change	0.199*** (0.058)	
Green * Concern about climate change	0.420*** (0.059)	
Green voters		−0.255** (0.097)
Non-voters etc.		−0.381** (0.134)
Blue * Green voters		0.329* (0.133)
Green * Green voters		0.372** (0.136)
Blue * Other		0.138 (0.194)
Green * Other		0.043 (0.191)
Constant	2.907*** (0.143)	2.398*** (0.051)
N	1363	1574

* $p < .05$.
** $p < .01$.
*** $p < .001$.

left part of Fig. 4 shows that acceptance for green hydrogen increases with growing concern for climate change, while acceptance for grey hydrogen decreases. Acceptance for blue hydrogen is largely unaffected by citizens' concern for climate change.

Furthermore, the right part of Fig. 4 shows that acceptance of grey hydrogen is somewhat higher among industry voters than green voters, and that acceptance of blue- and grey hydrogen is slightly higher, but not statistically significantly different, among green voters than industry voters. Thus, while industry voters and green voters have slightly different preferences towards different types of hydrogen, both groups prefer blue hydrogen over grey hydrogen and green hydrogen over blue hydrogen.

5. Discussion

Understanding public perceptions of, and responses to, new energy technologies can help facilitate communication between policymakers and the public, as well as provide critical information for anticipating potential public reactions to new technologies [3,14]. In this regard, our study shed light on important drivers of support for hydrogen technology that policymakers and others should consider when planning and rolling out large hydrogen initiatives.

In line with previous literature [16,32,33], we find that the public is generally positive towards using hydrogen as a fuel for ferries and passenger ships. However, the results of our study demonstrate that acceptance depends on how the hydrogen is produced; people prefer green and blue hydrogen over grey and green hydrogen over blue. Hydrogen is often promoted as an environmentally friendly alternative to fossil fuels. Our study indicates that people generally tend to perceive hydrogen as environmentally friendly, but as people are informed that the production of hydrogen involves CO_2 emissions and/or that there is a need for CO_2 storage, they become less supportive. Our results thus suggest that people will be less supportive when they are informed that the production and usage of hydrogen do not necessarily contribute to the "green shift". This includes the production of blue hydrogen – which involves further extraction and exploitation of oil and gas – even though it can be argued this method of production leads to low CO_2 emissions due to the use of CCS.

That support for blue hydrogen is lower than for green hydrogen is in line with previous research showing that individuals tend to be less positive towards technologies that enable us to control fossil fuel emissions, such as carbon capture and storage when compared to more renewable technologies such as wind- and solar power [14,17]. One central reason why CCS is seen as less acceptable is that citizens may worry that CCS technologies fail and that carbon dioxide might leak back into the atmosphere [37]. If governments are to successfully implement plans to produce blue hydrogen, they need to carefully address these and other public concerns about CCS.

Support for different methods of hydrogen production is also influenced by people's level of concern with the environment and party preferences. In line with previous research, this might reflect different motivations for welcoming new (energy) technologies – such as environmental concern versus economic benefits [25]. Our results show higher support for green hydrogen among citizens who show higher concern about climate change more generally. There is also higher support for green hydrogen than for grey hydrogen among those with low climate concern. For blue hydrogen, concern about climate change appears to have little influence on acceptance, meaning that there is a moderately high level of acceptance across all groups for this method of production. One possible reason for this might be that blue hydrogen's reliance on the continuing exploitation of oil and gas touches base with industry voters, while the potential of limiting CO_2 by using CSS is at the same time important to those who are more concerned with environmental protection.

Importantly, around 20 % of citizens express that they are neither negative nor positive towards using hydrogen as a fuel, which could reflect indifference or that they lack sufficient information or knowledge to take a firm stance. Additionally, close to 20 % express explicitly that they have no opinion on using hydrogen as a fuel for ferries and

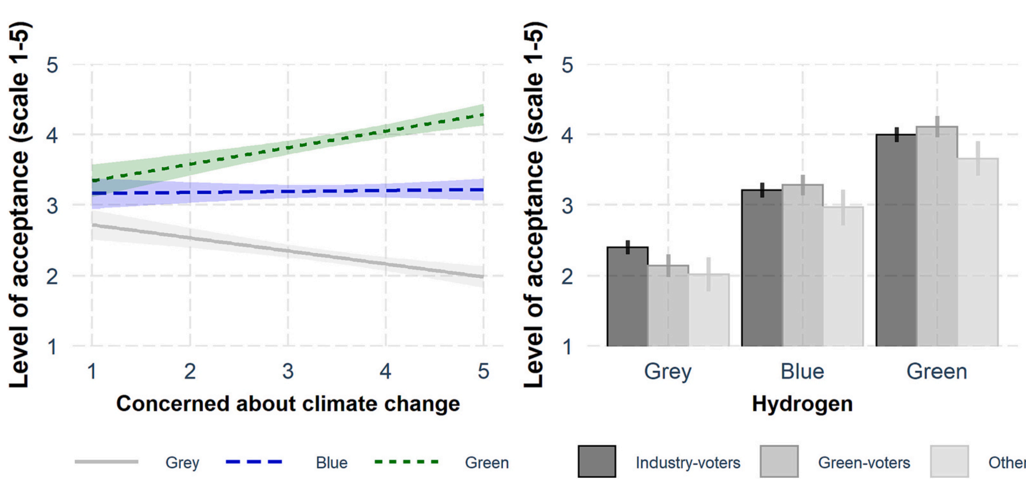

Fig. 4. Climate concern (left) and attitudes towards the Norwegian petroleum industry (right) and support for hydrogen. $N = 1363$ (left) and 1574 (right).

passenger ships. This finding is in line with previous research [16,32,33,35], and indicates a possibility of public opinion change as knowledge increases and potential benefits or drawbacks become publicly salient. Our study thus suggests some important practical implications. Lacking or ambiguous communication concerning projects using grey, and to a certain degree blue hydrogen, could lead to an opinion backlash regarding new hydrogen technologies, as well as reduced trust in politicians and companies if the proposed projects do not align with the public's expectations of emission reductions. Given the relatively high proportion of people with weak or no opinion regarding hydrogen fuel, as well as the common perception of hydrogen as a "green technology", there is a potential for misunderstandings which should be taken seriously by policymakers and considered when communicating about hydrogen technology and use.

Some limitations should be mentioned. First, the generality of the results should be established in future studies. Given that our study is carried out in the Norwegian context, we cannot leave out the possibility that Norwegian citizens' opinions about new hydrogen technology are coloured by the fact that Norway has a large oil industry and is dependent on income from the export of oil and gas. Second, the purpose of this study was to gain a better understanding of the degree to which people's acceptance of using hydrogen as a fuel depends on its production method (grey, blue, or green). This is relevant as several projects, first and foremost focusing on blue hydrogen, are currently being developed as alternative energy carriers. In terms of future research, public support of other production methods, such as those based on nuclear energy (red or purple), might be relevant to examine in countries where this is a viable option.

It would also be useful to extend the current findings by considering other factors that are likely to influence the level of support for different production methods. For example, previous research has highlighted perceived cost, safety and economic benefits as relevant [35,50]. In this regard, our study does not examine whether individuals would support the use of grey or blue hydrogen in a transition period [42], or whether citizens would be willing to pay extra for the use of green hydrogen as opposed to blue or grey. Furthermore, support might differ based on how and where hydrogen fuel is being produced [35,51–53]. In line with the Not in my backyard (NIMBY) effect, the level of support for different hydrogen production methods, as well as the relevant predictors, may be influenced by citizens' attitudes towards the development of industry needed to support different methods of hydrogen production in the proximity to where one lives.

Finally, although our study shows high support for green hydrogen among Norwegian citizens, this may change as the costs of producing green energy increase because of growing electricity prices. At the time of writing this article (though after the time of the fielding of our survey), the world is facing an energy crisis following the rapid economic rebound after the covid pandemic and Russia's invasion of Ukraine in February 2022. The impact of these developments on plans for investing in hydrogen as a potential solution to meet the goals of carbon dioxide reductions, as well as how citizens evaluate the production and use of hydrogen in periods when energy has become a salient public issue, remains unclear and should form the basis for future studies.

Declaration of competing interest

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Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2023.102985.

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