PUBLIC PERCEPTION OF HYDROGEN: RESPONSE TO AN OPEN-ENDED QUESTION

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ABSTRACT

Widespread use of hydrogen and hydrogen-based fuels as energy carriers in society may enable the gradual replacement of fossil fuels by renewable energy sources. Although the development and deployment of the associated technologies and infrastructures represent a considerable bottleneck, it is generally acknowledged that neither the technical feasibility nor the economic viability alone will determine the extent of the future use of hydrogen as an energy carrier. Public perception, beliefs, awareness and knowledge about hydrogen will play a significant role in the further development of the hydrogen economy. To this end, the present study examines public perception and awareness of hydrogen in Norway. The approach adopted entailed an open-ended question examining spontaneous associations with the term *'hydrogen'*. The question was fielded to 2276 participants in Wave 25 of the Norwegian Citizen Panel (NCP), an on-line panel that derives random samples from the general population registry. The analysis focused on classifying the responses into negative associations (i.e. barriers towards widespread implementation of hydrogen in society), neutral associations (e.g., basic facts), and positive associations (i.e. drivers towards widespread implementation of hydrogen in society). Each of the 2194 responses were individually assessed by five researchers. The majority of the responses highlighted neutral associations, using words such as *'gas'*, *'water'*, and *'element'*. When considering barriers vs. drivers, the overall responses tend towards positive associations. Many respondents perceive hydrogen as a clean and environmentally friendly fuel, and hydrogen technologies are often associated with the future. The negative sentiments were typically associated with words such as *'explosive'*, *'hazardous'*, and *'expensive'*. Despite an increase in the mentioning of safety-related properties, relative to a previous study in the same region, the frequency of such references was rather low (4%). The responses also reveal various misconceptions, such as hydrogen as a prospective *'source'* of clean energy.

Keywords: *hydrogen, public perception, citizen panel, open-ended question, association, awareness*

1.0 INTRODUCTION

1.1. Motivation

Reducing greenhouse gas emissions in line with the targets set out in the Paris agreement can only be achieved through a global transformation of the energy infrastructure. In this perspective, widespread use of hydrogen technologies may enable the gradual replacement of fossil fuels by renewable energy sources, and considerable efforts are currently invested in the development of cost-effective ways of producing, transporting, storing, and utilising hydrogen as an energy carrier.

The development and deployment of hydrogen technologies and the associated infrastructure represent a considerable bottleneck [1], calling for significant investments in research and development. At the same time, it is clear that neither the technical feasibility nor the economic viability alone will determine

the future of the emerging hydrogen technologies [2]. The suitability of hydrogen as a mainstream energy carrier within the transport sector and other applications within the public domain, such as domestic heating and cooking, must be assessed in connection with the sociotechnical context of the energy carrier. This implies an evaluation of the complexity and overall efficiency of the hydrogen value chain, in addition to environmental, societal, and safety-related aspects. The perception of hydrogen technologies by ordinary people, and their prospective attitudes, is likely to determine whether the vision for the 'hydrogen economy' can be realised. Hence, grasping the public perception can help facilitate a dialogue between the public and the policy makers, and provide timely insights into potential reactions to the emergent technologies [3].

1.2. The Norwegian perspective

Norway, as a net exporter of energy commodities and the third largest exporter of natural gas globally, represents a compelling case study for the public component of hydrogen perception. The Norwegian government issued a national hydrogen strategy in 2020, followed by a more detailed roadmap in 2021.The roadmap outlines ambitions for the production and use of hydrogen in the short-, mid- and long-term perspective, highlighting ways in which hydrogen and hydrogen-based energy carriers can contribute to zero emission solutions and value creation for Norway as a maritime nation and a net exporter of energy commodities. After the explosion at the hydrogen refuelling station (HRS) in Sandvika on 10 June 2019, all HRSs in Norway closed for several years, the import of hydrogen cars ceased, and plans for opening new HRSs were abandoned. Nevertheless, there are numerous initiatives related to production, storage, and use of hydrogen, especially in the maritime sector. The first ferry powered by liquid hydrogen (LH2), *MF Hydra* on the triangular route Hjelmeland-Skipavik-Nesvik, conducted its virgin voyage fuelled by LH2 on 31 March 2023. In the aftermath of the Covid pandemic, and while the Russian invasion of Ukraine is ongoing, the issue of energy security is becoming increasingly salient. As hydrogen becomes gradually embedded in social activities within the Norwegian context, it is relevant to examine the public views associated with hydrogen as an energy carrier.

1.3. Previous work

In the literature addressing the psychology of climate change, the term 'perception' has been used to denote a broad range of psychological constructs, such as *knowledge, beliefs, attitudes, concern, affect* and *perceived risk* [4]. Previous studies on perception indicate that the public support of the emerging hydrogen technologies depends on numerous factors, including: the beliefs of the prospective users on the issues of climate change and the security of the energy supply, the critical trust in institutions and experts communicating relevant information, the costs projected on the consumers, the specific regional context, and finally the perception of the risks associated with specific hazards [3, 5-6]. According to Slovic [7], the perceived risk is a function of dread and the degree of knowledge, implying that the perception of hydrogen risk by members of the public does not necessarily correspond to the theoretical risk calculated by scientists and engineers. As such, the perception of experts and ordinary people concerning the risk associated with various technologies tend to differ [7-9].

Various researchers have studied the public perception of the emerging hydrogen technologies. Several quantitative studies conducted in the period 2005-2010 investigated the complex relationships between perception, knowledge, attitudes, and support of hydrogen applications, treating the former as observable variables [10-14]. Such efforts faced considerable challenges concerning the extraction of consistent views and opinions, pointing to limited awareness of hydrogen as an energy carrier among laypeople. Despite the limited awareness in the population, these studies demonstrated a strong positive relationship between support and the levels of existing knowledge of hydrogen and certain hydrogen applications [10-13]. At the same time, the analysis of socioeconomic characteristics (gender, proximity to hydrogen application, age, education) did not reveal consistent relationships across the various studies. Other researchers have reviewed the work on quantitative perception and acceptance of hydrogen conducted in the period 1998-2007 [15-16]. Table 1 summarises the subset of quantitative studies conducted in the period 2005-2021 that explored word associations with the term 'hydrogen', including six open-ended and three closed-ended questions. The majority of the reported associations were of neutral nature, with certain variations according to the specific regional context.

Table 1. Previous studies addressing word associations with the term 'hydrogen'.

Ref.	Survey design and question format	Key findings (word associations)
[10]	Phone interviews in wider London area during July-September 2003. N=420. Open-ended question.	A majority of neutral associations were cited: physics and chemistry-related terms accounted for 44% of total references. The positive (22%) and negative (20%) associations were balanced, and 13% mentioned explosions and flammability. Men expressed marginally more positive (and negative) associations compared to women. The impact of other socioeconomic characteristics (education, work status, income) was insignificant. Factors analysis grouping the respondents based on response length did not reveal any significant correlations.
[11]	In-person interviews: participants recruited randomly at public places in the Netherlands in 2003. N=612. Open-ended question followed by an experiment: information intervention and a closed-end question exploring degree of association with six statements.	Predominantly neutral associations: '*water'* comprised 24% of the total references. Other frequent associations: *'fuel'* (15%), *'bomb'* (15%), *'explosive'* (7%) and the *'Hindenburg disaster'* (4%). '*Bomb'* and '*Hindenburg'* were reported twice as often by men, compared to women. The responses to the closed-end question indicate that hydrogen was mostly perceived as an '*abundant'* and '*environmentally friendly'* fuel, and less as a '*dangerous'* one.
[12]	Phone interviews in Stavanger, Norway, in 2004, as part of the HyNor project. The sample (N=1000) was split in two sub-samples: "the back-yard" and the "Greater-Stavanger" area. Open-ended question.	The majority of the reported associations fell in the neutral category (55.2%). Positive associations were reported more frequently (9.1%) than negative (3.5%), with *'alternative fuel'* being the dominant positive association (7.2%). Only 0.3% of the respondents mentioned explosivity/flammability.
[14]	AcceptH2: Longitudinal surveys in Luxembourg, London, Berlin and Perth before (Ex-ante survey) and after (Ex-post survey) hydrogen bus trials. Sample size varied from N=271 to N=571. Open-ended question.	Neutral associations *('gas', 'peroxide', 'fuel'*) comprised the majority sentiment in each city. Before the trial, the positive references outnumbered the negative ones in Luxembourg and (marginally) in London. Yet, in Berlin and Perth the pattern was reversed. Post trial, a pattern of growing negative sentiment was consistent for all cities, except for London.
[17]	A US DoE survey in 2004 targeting the general public (N=889), students (N=1000), state and local government (N=236), and end-users (N=99). Closed-ended question[1].	Primarily neutral associations , such as *'chemistry class'* or *'fuel '* (ranging from 43.4% to 62.8%). '*Hindenburg'* was mentioned by 19.1% of the general public and 8.35% of the students.
[18]	An EU survey of students, teachers and parents. N=197 as part of the FCHgo project. Open-ended question.	Neutral terms, such as *'water'* (18%), '*chemistry'* (11%), *'chemical element'* (10%) and '*gas'* (4%), were more frequently cited, followed by positive sentiments such as '*clean energy'* (4%).
[19]	Reykjavik, 2004, as part of the ECTOS project: Participants were randomly recruited on the street (N=50), near bus stops (N=50), and on-board hydrogen (N=50) and diesel (N=50) buses. Closed-ended question[2].	47.7% of the participants selected *'clean fuel'* (positive sentiment), followed by 47.2% for *'domestic product'* or *'water'* (neutral sentiments). Only 5% gave a negative association ('*expensive technology', 'burning zeppelin'*). Women gave more positive associations than men, who gave predominantly neutral associations.
[20]	Mixed methods: 19 in depth- Interviews (May 2005), followed by a survey of the general public at Unst Island, UK (May 2006, N=unknown). Open-ended question.	Mostly neutral associations (*'water', 'gas', 'chemical'*, etc.) (60.6%). The positive and negative references were balanced with 19.7% each (considering the very first association of each response). The positive associations (predominantly: *'clean', 'future', 'opportunities'*) were all context specific, in relation to the utilisation of hydrogen in the PURE project at Unst Island.

[1] Five discrete choices: *'the H-bomb', 'chemistry class', 'fuel', 'the Hindenburg', 'no opinion'*.
[2] Five discrete choices: *'burning zeppelin', 'expensive technology', 'water', 'domestic production', 'water', 'clean fuel'*.

These studies, with notable exceptions [12, 17], employed medium sample sizes in the range of 200-600 participants. Tarigan et al. [21] employed Structural Equation Modelling (SEM) to explore the influence of unobservable variables on the public acceptance of hydrogen vehicles and refuelling stations in Stavanger, Norway. The study suggested that hydrogen knowledge influences indirectly, via pro-environment attitudes, the propensity to accept the hydrogen application in question[3]. More recently, Bentsen *et al.* [3] explored how information about the method of production (i.e. 'green' vs. 'blue' vs. 'grey' hydrogen) influences the perception of hydrogen as an energy carrier in Norway. In a European setting, the FCHgo project explored the awareness of hydrogen by students, teachers, and parents [18]. Gallup International on behalf of Clean Hydrogen Partnership conducted a public opinion survey in Europe. The survey explored the awareness, acceptance and uptake of hydrogen technologies, in addition to the perception of the associated safety and sustainability of the citizens in the 27 member states of the European Union [22]. There are also several examples of qualitative research [5-6, 23-24]. Flyn *et al.* [6] studied the perceived risk of the emergent hydrogen technologies by members of two citizen panels, one in Wales and one in the UK. This study highlighted regional context as an important aspect, influencing the exposure and experiences of the respondents. The authors demonstrated that the perception of hydrogen was influenced by the: *(i)* industrial history, *(ii)* employment type, and *(iii)* economic situation of the respondents in the area the panel took place. The research team acknowledged the limitations to transferability of the findings considering the non-representative nature of the panel.

1.4. The present study

This study focuses on the public component of the perception of hydrogen technologies by exploring associations to the word *'hydrogen'* from a random selection of adults in the Norwegian society. The primary objective is to identify barriers and drivers towards widespread use of hydrogen as an energy carrier in society. In this perspective, worries, concerns, and negative affect by the citizens as the prospective end-users of hydrogen applications are assumed to pose barriers towards the adoption of hydrogen as a mainstream fuel in transportation and other sectors in the public domain. Conversely, expectations and beliefs associated with a positive sentiment are assumed indicators of support, driving the large-scale implementation of hydrogen as an energy carrier in society. To this end, the analysis of the responses focusses on classifying the statements into negative associations (hereinafter barriers), neutral associations (e.g. basic facts), and positive associations (hereinafter drivers).

2.0 METHODOLOGY

2.1. Survey design

A survey-embedded vignette experiment in Wave 19 of the Norwegian Citizen Panel (NCP) demonstrated that the framing of the survey questions can have significant impact on the results [3]. To this end, the present study employed an open-ended question examining spontaneous associations with the word *'hydrogen'*. Unlike multiple-choice questions, an open-ended question probes the respondent to freely express their views, and indirectly prioritise their own meanings and beliefs. Moreover, considering the mixed awareness of hydrogen technologies reported in previous studies [10-14], this approach avoids the use of predefined options that are likely to influence the results [25-26]. Yet, it is more challenging and time-consuming to analyse the responses to open-ended questions, especially when human coding is employed [27]. The wording of the open-ended question, after translation to English[4], was:

> *'What comes to mind when you hear or read the word 'hydrogen'? Please write down the first thoughts that occur to you. We welcome all type of responses, either a couple of sentences, or just a few words if you prefer.'*

This question was fielded over the period 31 October - 28 November 2022 in Wave 25 of the NCP, one of the main components of the Digital Social Science Core Facility (DIGSSCORE) at the University of

[3] This impact was more pronounced for residents in the proximity of the refuelling station in question.

[4] The original wording of the question in Norwegian: *'Hva tenker du på når du hører eller leser ordet «hydrogen»? Vennligst skriv ned det første du kommer på. Vi ønsker alle typer svar, gjerne et par setninger, eller bare noen få ord om det passer bedre for deg.'*

Bergen. The NCP is an online panel that derives random samples from the general population above 18 years of age. For Wave 25, the NCP had 13,740 panel members, randomly divided into six sub-panels. A total of 2276 panel members received the open-ended question above, of which 2194 responded (i.e. a response rate of 96.4 %).

2.2. Sentiment analysis

The first level of the analysis investigates the extent to which hydrogen is associated with a positive, neutral or a negative sentiment. The responses were manually classified according to whether they contained statements that were considered negative (i.e. barriers), neutral (e.g. basic facts), or positive (i.e. drivers). Each of the 2194 responses were individually assessed by five researchers, where each 'analyst' assigned either '1' or '0' to each of the three categories. Table 2 summarises the 2^3=8 possible combinations, including examples of typical statements.

Table2: The eight categories of responses used for the sentiment analysis.

Negative	Neutral	Positive	
0	0	0	No opinion, or statements without a clear classification: 'do not know', etc.
1	0	0	Only negative associations: 'explosive', 'bomb', 'expensive', etc.
0	1	0	Only neutral associations: 'element', 'colourless', 'gas', etc.
0	0	1	Only positive associations: 'emission-free', 'clean energy', etc.
1	1	0	Both negative and neutral statements.
1	0	1	Both negative and positive statements.
0	1	1	Both neutral and positive statements.
1	1	1	Balanced responses with negative, neutral, and positive statements

Fig. 1 shows the overall results of the manual classification of the responses by the five analysts. The total score for each analyst is based on normalised values for each response. As an example, a response introducing only negative associations (classified as '100') contributes with 1 towards negative sentiment, while a balanced response (classified as '111') contributes with 0.333 to each of the three sentiments.

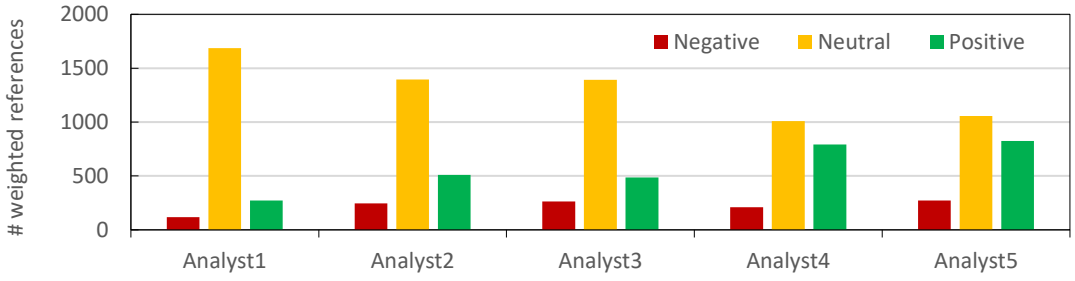

Figure 1. Manual classification of responses according to sentiment by the five analysts.

There is a considerable spread in the scores assigned by the different analysts. This shows that a given statement can be interpreted differently by researchers with diverse backgrounds and belonging to different disciplines. The five analysts unanimously agreed on the classification of statements involving terms such as *'risk'* (… of explosion, … of greenwashing, etc.), *'expensive'* (… to build infrastructure, … for end-users, etc.), and statements highlighting dread (e.g. *'scary', 'hazardous', 'extremely flammable')* or scepticism towards the technology (e.g. *'no, it will never be mainstream as a fuel for cars', 'simply a hype'*, etc.) as negative. There was also general agreement concerning the positive nature of statements addressing benefits for the environment and/or the prospective hydrogen economy, such as *'sustainable fuel' 'clean energy', 'cutting down emissions', 'the future in energy',* or simply *'future'*. However, statements that required interpretation according to the specific context were more challenging to classify unambiguously. For example, one analyst classified statements such as *'the green shift', 'climate', 'environment',* and *'alternative to fossil fuels'* as factual information, and hence

neutral, whereas the others perceived such statements as positive. Due to the reported variation, the discussion of the results in section 3 focuses on the average distribution of the classification results by the five analysts.

2.3. Word frequency analysis

The next level of the analysis explored the 15 most frequent terms in the responses. The word frequency table was generated using the Quanteda package in R [28]. The script counts the overall word frequencies across the responses using lemmatisation. The analysis evaluates the most frequent terms in the overall responses, as well as the responses including *positive statements* (i.e. the combinations *'001', '011', '111', '101'* in Table 2), negative statements (i.e. combinations *'100', '111', '101', '110'* in Table 2), and neutral statements (i.e. the combinations *'111', '010', '011', '110'* in Table 2*)*. Given the considerable variation between the assessments of the five analysts (Fig.1), the word frequency assessment was only performed for the responses with agreement among the analysts.

2.4. Awareness and misconceptions

The last level of the analysis explored the level of awareness and typical misconceptions concerning hydrogen as an energy carrier. The evaluation entailed a semi-quantitative approach that extended the close reading conducted as part of the sentiment analysis by identifying statements containing facts or misconceptions that have been reported in similar studies [3, 10-11].

3.0 RESULTS AND DISCUSSION

The following sections present the results from the analysis and discuss the main findings.

3.1. Sentiment analysis

Fig.2 reports the average distribution of the normalised references for the *negative*, *neutral* and *positive* sentiment based on the corresponding assessments by the five analysts.

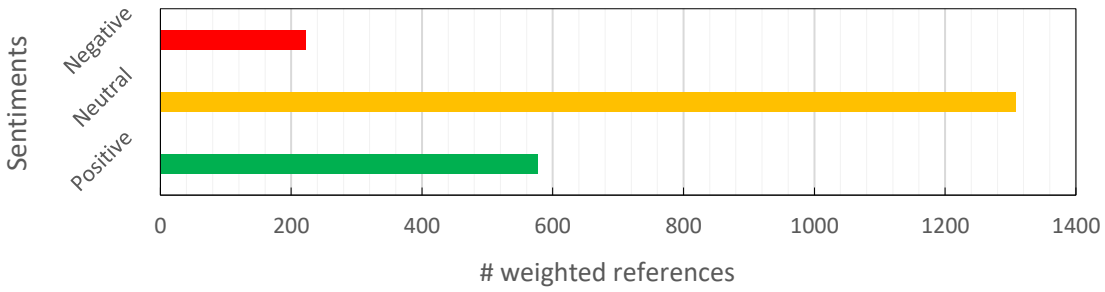

Figure 2. Reported sentiment in the responses: based on the average distribution of the manual classification by each of the five analysts.

Most of the reported associations belong to the neutral category. This is consistent with previous work [10-12,17-18,20]. Furthermore, a significantly higher fraction of the respondents has positive sentiments towards hydrogen, compared to negative: positive associations were reported three times as often as the negative associations (Fig. 2). This is consistent with the results obtained for Stavanger in 2006 by Thesen and Langhelle [12], while for the London Metropolitan area [10] and the Island of Unst in the UK [20] the two sentiments were almost balanced.

3.2. Word frequency analysis

Fig. 3 summarises the 15 words that occur most frequently in the overall responses, and Fig 4. present the results for the neutral, negative, and positive sentiments, respectively. After removing keywords included in the question[5] and aggregating the frequency of certain terms that are used interchangeably

[5] The word *'think'*, or *'tenk'* in Norwegian, and the lemma '*hydrog-*' were removed.

in the Norwegian language[6], the ten most frequent words used in the responses, are, in descending order: *'fuel', 'water', 'gas', 'car', 'energy', 'element', 'future', 'bomb' 'environmentally friendly',* and *'green'*. In addition, both *'energy source'* and *'energy carrier'* feature among the 15 most frequent terms. The term *'green'* typically occurred with the word *'shift'* (i.e. *'the green shift'*), or *'energy'* (in addition to references to *'green hydrogen'*) and was typically interpreted as positive.

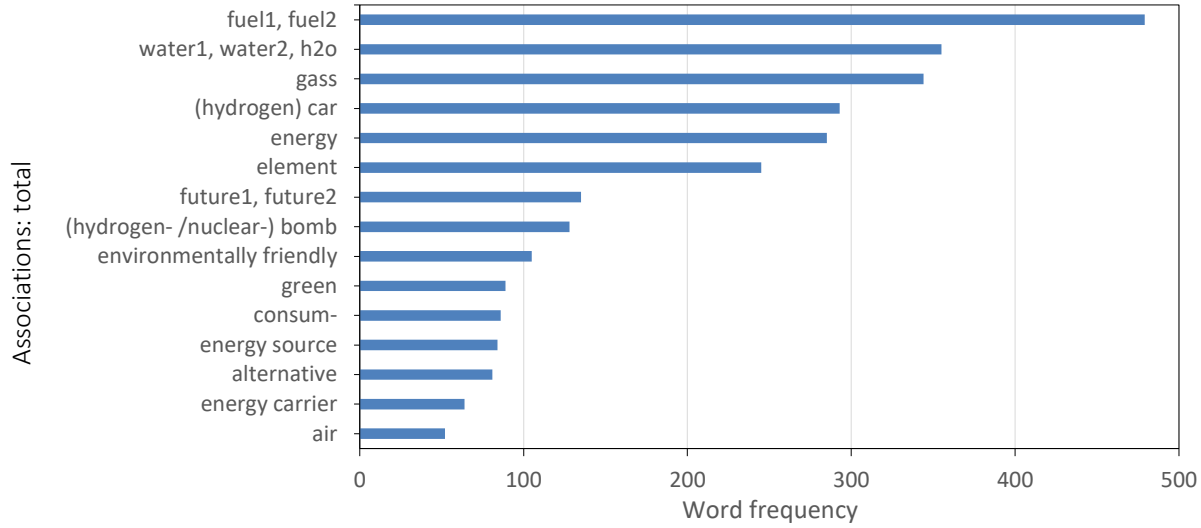

Figure 3. Frequency for the 15 words that occurred most frequently in the overall responses.

Consistent with previous work [11-12, 14, 18-20], many respondents associate *'water'* and *'gas'* with hydrogen. A recent survey of the spontaneous associations to the word *'hydrogen'* among students, teachers, and parents in Europe highlighted '*water'*, '*chemistry',* and '*chemical element'* as the most frequent responses [18]. However, relative to the results obtained by Thesen and Langhelle [12], this study highlights a temporal change in the awareness of hydrogen as fuel for transport among Norwegian citizens, with 479 references (21.8 %) of the word *'fuel'*. This is not surprising considering the results of the contemporary public opinion survey in Europe, highlighting that hydrogen as a fuel of transport is the most widely known application of hydrogen across the 27 member states in the European Union [**22**].

The results reported for the neutral category in Fig. 4a resemble those for the total responses: *'water', 'gas', 'element', 'energy', 'fuel', 'car',* an old Norwegian word for hydrogen *('vannstoff'), 'energy carrier', 'atom',* and *'chemical'* are the 10 most frequent terms in descending order. Yet, the terms *'gas'*, '*element'* and *'energy'* are reported more frequently than *'fuel'*, altering the distribution relative to the total word frequency in Fig. 3. This can be explained by references to hydrogen as *'sustainable fuel'* or *'environmentally friendly fuel'*, typically coded as positive. The words *'periodic'* and *'chemistry',* as well as the symbol *'H'* for the chemical element hydrogen, also appear among the 15 most frequent terms in the neutral category.

The ten most frequent words in the responses contributing towards the negative sentiment are (Fig. 4b): *'energy', 'fuel', 'expensive', 'much', 'explosive', 'consume/consumption' 'gas', 'hazard(ous)', 'produce',* and *'energy carrier'.* The distribution highlights two alternative terms associated to explosion/ explosive. One term (*'eksplosjonsfarlig'*) incorporates the Norwegian word *'fare'*, meaning *'danger'* or *'hazard'* (*'fare'*). In principle, only three terms have an obvious negative meaning: *'hazard(ous)', 'expensive',* and '*explosive'*.

[6] The Norwegian language has two official forms, 'Bokmål' and 'Nynorsk'. As such, both *'fremtid'* and *'framtid'* were translated to *'future'('future1', 'future2'* in Fig. 3-4) , *'vann'* and *'vatn'* were translated to *'water'('water1', 'water2', in Fig. 3-4), 'drivstoff'* and *'brennstoff'* were both translated to *'fuel'('fuel1', 'fuel2' in Fig 3-4),* etc.

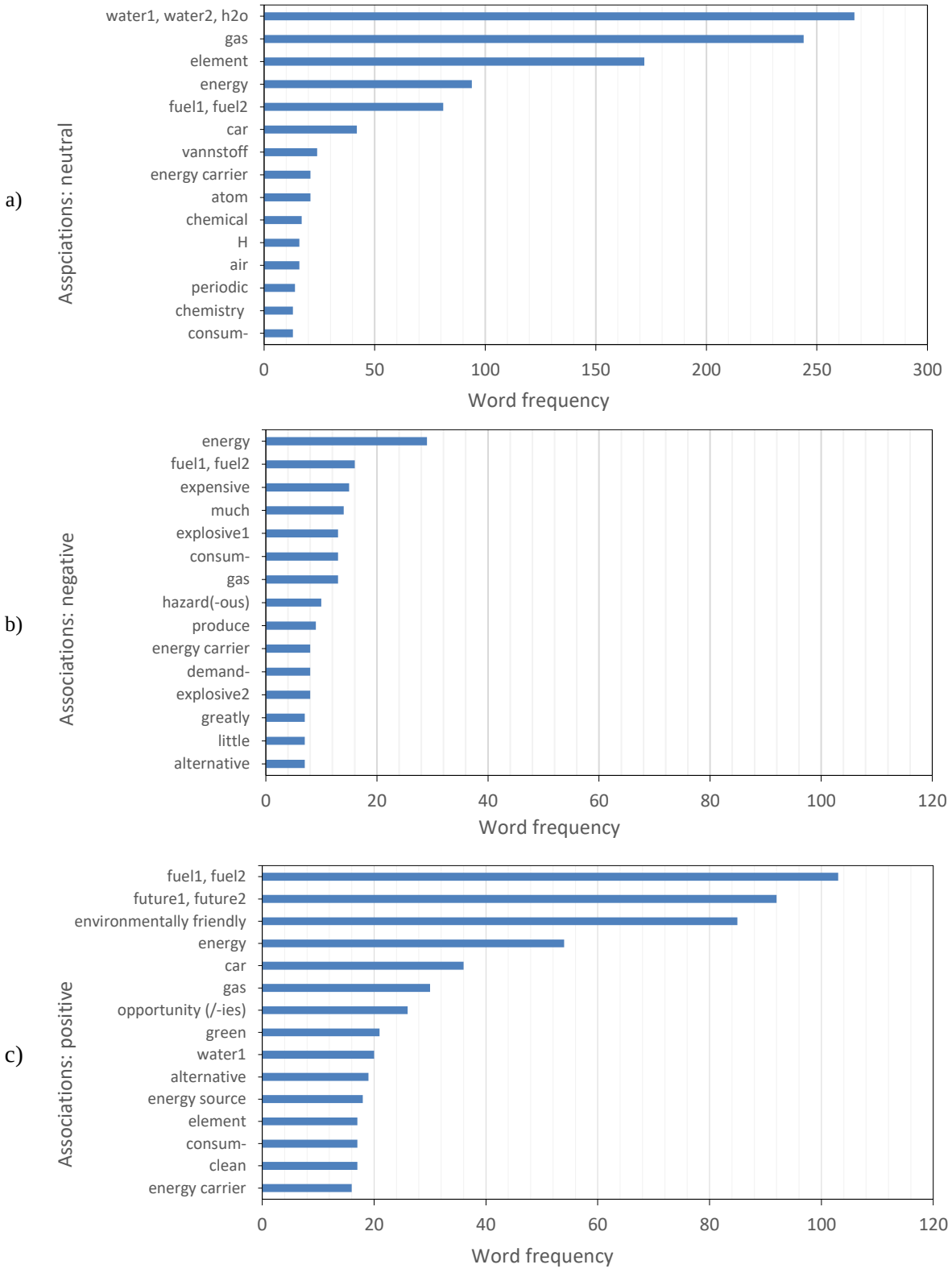

Figure 4. Frequencies of the 15 words occurring most frequently in the responses classified as neutral, negative and positive.

However, the lemmas *'consum-'* and *'demand-',* pointing to the terms '*consume'/'consumption'* and '*demand'/'demanding',* respectively, have been used sporadically by the respondents to critically describe the overall energy efficiency of hydrogen technologies, in addition to challenges establishing the required infrastructure. Several of the respondents commented that hydrogen technologies imply *'poor use of electricity',* or that hydrogen is *'energy demanding to produce*'.

Overall, the spontaneous associations of the members of the NCP to the word *'hydrogen'* are more positive than negative. This is reflected in Fig. 4c, plotting the most frequent terms belonging to the positive sentiment: the word counts for the positive associations in Fig. 4c are significantly higher than the corresponding numbers for the negative sentiments in Fig. 4b. The most frequent associations in the positive category are the words *'fuel'* and '*future'*, followed by *'environmentally friendly'*. Considering the remaining words reported in this group (*'green', 'alternative', 'clean'),* and the qualitative reading of the responses in Level 1 of the analysis, the citizens tend to perceive hydrogen as a clean fuel and a sustainable energy technology (in line with previous findings [11-12, 20]). The word *'water'* typically appeared in statements such as *'water is the only emission'*. Overall, hydrogen and the emerging hydrogen technologies are perceived as opportunities[7] for value creation for the industry and Norway as a net exporter of energy commodities.

3.3. Awareness of hydrogen as an energy carrier

The final level of the analysis examined the extent to which the citizens mentioned specific facts or misconceptions about hydrogen. Knowledge about the awareness of hydrogen as an energy carrier in the population can be useful for all stakeholders, including schools and universities. Table 3 summarises the results as absolute values and percentages of the total responses.

Table 3: Typical associations reported in the responses highlighting mixed level of hydrogen awareness.

Description	#references	% of total
Elementary knowledge of physical and chemical properties	91	4.2
Gas (at standard conditions)	333	15.2
Water constituent / water[8]	335	15.3
Safety: flammability, reactivity, low ignition energy, explosion risk	93	4.2
Energy carrier	62	2.9
Energy source	80	3.7
(hydrogen) bomb	127	5.8
Air (composition)	46	2.1
Hydroelectric power	18	0.8

About 15% of the respondents mention that hydrogen is a gas and a constituent of water, or simply associated hydrogen with water. Since any mentioning of water as *'the only emission'* is not included here, the absolute word count is somewhat lower than indicated in Fig. 3. About 4% of the respondents mentioned at least one physical or chemical property of hydrogen, such as *'the lightest element'*, *'a small molecule'*, *'the first element of the periodic table'*, and *'the simplest element of all'.* In addition, some of the respondents commented specifically on the tendency of hydrogen to *'disperse quickly',* and that hydrogen is *'colourless'*, *'odourless'*, or *'the most abundant element in the universe'*.

A substantial number of the respondents were aware that hydrogen is a highly flammable substance, as indicated by statements such as *'risk of explosion'*, *'fire hazard'*, *'very reactive'* and *'easily ignitable'*. Although the 4.2 % that mentioned such terms in the present study is significantly lower than the 13 % reported for London [10], it represents an increase relative to the 0.3 % reported from the survey conducted in Stavanger in 2006 [12]. It is likely that the general awareness of the explosion hazard associated with hydrogen has increased after the accident at the HRS in Sandvika in 2019.

Table 3 also includes some typical misconceptions concerning hydrogen, such as hydrogen being a major component of air (in reality there is only about 0.6 ppm of hydrogen in air at ground level [29]), or hydrogen being a source of energy. In fact, whereas only 2.8 % of the respondents mention hydrogen

[7] The frequency of the term opportunity/-ies was produced using the grep-i pattern matching function.
[8] The numbers do not reflect references to water as the only emission from combustion processes and fuel cells.

as an '*energy carrier'*, 3.7% considers it an *'energy source'*. Other apparent misconceptions include the associations to the *'hydrogen bomb'* and *'hydroelectric power'*.

3.4. Overall discussion

Most of the spontaneous associations to the word *'hydrogen'* are considered neutral, including terms such as '*water'* and *'gas'*. This is consistent with previous studies [10-12]. Apart from the neutral terms, the results show a clear trend towards positive associations, focusing on hydrogen as a clean fuel that will benefit the environment. Furthermore, contemporary issues, such as the prospect of climate change and the increasing energy prices resulting from the Russian invasion of Ukraine, are likely to contribute to the framing of hydrogen technologies as promising solutions to the energy problem. This may have contributed to the prevalence of positive responses to the open-ended question. There are also several misconceptions concerning hydrogen, some related to negative statements (e.g. *'hydrogen bomb'*), some related to neutral statements (e.g. *'hydroelectric power'*), and some related to positive statements (e.g. *'energy source'*). This information may provide useful insights for educators involved in primary and secondary education, as well as other stakeholders that address the general public. Previous studies highlight a positive relationship between prior awareness of hydrogen and the propensity for support of hydrogen applications [10-13]. Hence, investing in education of the public is likely to promote hydrogen acceptance and raise awareness of the safety-related characteristics of hydrogen, and as such contribute towards the safe implementation of hydrogen technologies in society.

4.0 CONCLUSIONS AND FURTHER WORK

This study explored the public perception and awareness of hydrogen in Norway through an open-ended question concerning spontaneous associations with the word *'hydrogen'*.

4.1. Main conclusions

The main findings from this study are:

- The meaning citizens attach to the word *'hydrogen'* is more positive than negative, even though the majority of the responses highlighted neutral associations or facts.
- The words *'fuel'*, *'future'* and *'environmentally friendly'* are the most frequent terms related to positive associations.
- The results indicate a mixed level of awareness in the population: *'water'*, *'gas'* and *'element'* are the leading words in the neutral category.
- The misconception that hydrogen is an energy source, and not (only) an energy carrier, appears quite often.

The results can be valuable for stakeholders engaged in competence building, public education, and vocational training.

4.2. Study limitations and further work

To ensure consistency of the findings, the methodology involved five analysts in the classification of the responses into negative, neutral and positive statements (data triangulation). Yet, the produced classifications (Fig. 1) and the subsequent frequency analysis (Figs. 3-4) are subject to interpretation factors that are unique for each individual. While introducing a commonly accepted classification protocol would, in principle, reduce the systematic differences between the analysts, this approach would likely influence the independent assessment of the reported associations. To this end, the authors plan to explore alternative ways of analysing the responses. One example could be Structural Topic Modelling (STM), a text mining method based on word clustering. STM would allow for exploring the prevalence of themes without requiring a priori definitions of the dimensions in which the data will be coded [27, 30]. This methodology reduces the human intervention and interpretation factor and would likely reduce the bias associated with different interpretations of the same statements.

More detailed analysis of the data will explore how perception and awareness of hydrogen among Norwegian citizens relates to the individual's socioeconomic background and preferences. The data

from the NCP can be correlated with factors such as gender, age, level of education, political preferences, etc. Flyn et al. [5] demonstrated the impact of employment type (industrial or non-industrial) in the perceived risk and Tarigan et al. [21], suggested that the hydrogen knowledge in the population influences indirectly, via pro-environment attitudes, the propensity to hydrogen acceptance. To this end, political leaning can reveal attitudes towards industry development and the environment and climate issues. As such it would be relevant to explore the influence of political preferences on the reported sentiments.

Finally, it would be interesting to repeat the same study in the future, to explore whether the spontaneous associations to the word 'hydrogen' in the Norwegian population change over time.

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