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Public response to decarbonisation through alternative shipping fuels

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Abstract
Although shipping is the most energy efficient method of transporting trade goods it is held accountable for 2–3% of global greenhouse gas (GHG) emissions. The shipping industry is exploring pathways to carbon–neutral fuels to help eliminate GHG emissions by 2050. To date research on alternative fuels has not considered public opinion; it remains unclear whether the public will support alternative shipping fuels, or whether public opposition might prevent or defer their deployment. To fill this knowledge gap and help the industry and policy makers arrive at publicly acceptable decisions, our research examines UK public perceptions of six shipping fuels using a mixed-method approach. Our findings reveal that biofuels and hydrogen are clearly favoured, owing to biofuel's perceived low risk and hydrogen's lack of negative by-products. Perceptions of liquid natural gas are somewhat positive, suggesting that it provides an acceptable near-term option while other fuels are developed. Despite lingering stigma, nuclear is preferred over the incumbent heavy fuel oil, though both are perceived negatively. However, the UK public strongly dislike ammonia, perceiving it as *unproven*, *risky,* and lacking *availability*. A third support use of alternative shipping fuels, with support greater from those living near ports—a "yes in my back yard" effect. The results demonstrate that different alternative fuels are likely to elicit different public reactions as they become more widely known and show how the overall evaluations arise from specific positive or negative associations with each fuel.

Keywords Alternative fuels · Shipping · Public engagement · Hydrogen · Ammonia · Nuclear · Biofuel

1 Introduction

Global economies are reliant on the efficient movement of trade goods between nations. In this context, shipping is the most energy efficient mode of transport and accounts for 80–90% of world trade (Balcombe et al., 2019; Smith et al., 2014). However, the energy required to propel vessels across the world's oceans is also responsible for 2–3% of global greenhouse gas (GHG) emissions and produces additional pollutants such as particulate matter, nitrogen, and sulphur oxides (Faber et al., 2021; Smith et al., 2014).

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Increasingly, international organisations, scientists, private sector businesses, and the public of many nations are demanding that industries responsible for producing harmful GHG emissions implement strategies that will reduce their carbon footprints. To satisfy this demand, the maritime industry reacted with a "*Call to Action for Shipping Decarbonisation*" (2021) plan signed by 230 industry leaders and set a goal of achieving net-zero GHG emissions by 2050. However, van Leeuwen and Monios (2022) warn this goal should be more ambitious and include a complete ban on the use of fossil fuels in the shipping industry by 2050. This warning highlights the urgency to investigate alternative shipping fuels that will substantially lessen GHG emissions.

Currently, ship propulsion is dominated by fossil fuels, such as heavy fuel oil (HFO) and marine diesel. These types of fuels are cheap and operationally safe but are heavy emitters of CO_2 and leave harmful contaminating footprints. Although many in the industry recognise the need for zero-emission fuels to achieve decarbonisation targets, as yet there are no widely adopted zero-carbon solutions (Faber et al., 2021; Getting to Zero Coalition, 2021; IMO, 2018). Electrification may be suitable for short distances, but long-distance shipping requires independence from shore-side power and ocean bound ships need to carry their own fuel supplies. A palpable way forward is to research and develop alternative fuels that will be acceptable to the shipping industry and citizens.

Even though alternative fuels are key to reducing GHG emissions within the shipping industry they are not the only pathway to decarbonisation. Walsh et al. (2017) advise that changes in demand, vessel size, cargo loads, operations and technology, and the wider global system will also be required, alongside speed reduction measures. The need for several approaches to decarbonisation highlights the complexity and difficulties the shipping industry faces. However, since they can reduce GHG emissions, alternative fuels warrant further research, support, and investment.

Adoption of green technologies is critical for decarbonising the shipping sector (Di Vaio et al., 2023) requiring organisations to balance profit with societal needs (Del Giudice et al., 2022; Di Vaio et al., 2021). Shipping fuels with the potential to reduce GHG emissions will require economic viability, scale, and significant infrastructure investment, but also for policy makers and industry to give consideration to public acceptability (Balcombe et al., 2019).

Social scientists have, for more than a decade, highlighted the importance of citizen consultation in the early stages of the development of technological solutions (Corner et al., 2012; Rogers-Hayden & Pidgeon, 2007; Sturgis, 2014; Wilsdon & Willis, 2004). Citizens residing in coastal metropolitan cities that are home to some of the world's largest trading ports are especially likely to have concerns about the risks of alternative shipping fuels. To date research on alternative fuels has not considered public opinion. Consequently, it remains unclear whether the public will support alternative shipping fuels, or whether public opposition might impede their deployment.

The aim of this research is to address this knowledge gap by exploring likely public reaction to alternative shipping fuels. We systematically measure comparable public opinions through two phases of research using established methodologies. The qualitative phase is used to determine the most salient attributes non-expert citizens associate with six potential alternative fuels and explore public opinion. The results are applied in the quantitative phase to measure public perceptions of alternative shipping fuels through an online survey of UK participants ($n = 992$) using an established cognitive association technique. The technique is based on the Associative Network Theory of Memory (ANTM) widely used in psychology that was adapted for use in market research by Romaniuk (2013) and extended into scientific concepts by Wright et al. (2014) and Carlisle et al. (2020). More detailed explanations of the theoretical background and the techniques are provided in Sects. 2.1, 2.2, and 2.3. The following section provides background and context for alternative fuels that are suitable for use in shipping.

1.1 Potential alternative shipping fuels

Several fuel technologies have been proposed to help reduce emissions associated with shipping, either by capturing emissions before they are released into the atmosphere or switching to alternative fuels with lower emissions. Though many of these alternative fuels or carbon capture technologies are yet to be demonstrated at scale, it remains important to ensure their development and implementation are informed by likely public responses.

Here, we investigate public responses to alternative fuels to HFO and introduce some potential options, each of which has some advantages and disadvantages with unknown potential for public reactions. Among the alternatives, liquid natural gas (LNG) is a lower-carbon, lower-pollutant option. However, its use would require substantial carbon capture and storage to offset emissions (Eide et al., 2013; McKinlay et al., 2020) and suffers from issues of methane slip. Other fuels such as hydrogen, ammonia, and nuclear emit no CO_2 at the point of use but raise concerns about their lifecycle emissions during production, storage, and transport, as well as about safety and public acceptance (Balcombe et al., 2019; Eide et al., 2013; McKinlay et al., 2020; Royal Society, 2018, 2020; Serra & Fancello, 2020). Blue and green hydrogen and ammonia production may address issues of lifecycle emissions (Royal Society, 2018, 2020). Biofuels could also deliver net-zero emissions, provided that the supply chain is also carbon–neutral (Balcombe et al., 2019; Horvath et al., 2018; Kesieme et al., 2019; Royal Society, 2008; Serra & Fancello, 2020), but have implications for land and water use, food production, and biodiversity (Balcombe et al., 2019; Kesieme et al., 2019; Royal Society, 2008).

Until a clear transitional pathway is established, many stakeholders are cautious of investing into research, development, and deployment. Due to the substantial investment and infrastructure required, action on a scale necessary to address climate change will carry implications for the shipping industry for decades to come. Thus, despite the urgent need for deep decarbonisation action, the stakeholders within the shipping industry are wary of making the wrong decisions. Nonetheless, pockets of R&D investment are beginning to emerge around the globe (e.g. Bevin, 2022) indicating the urgent need to consult citizens and ensure that their perceptions are factored into ongoing research, development, and deployment.

1.2 Public engagement and alternative shipping fuels

Adopting alternative shipping fuels has both economic and environmental consequences that will directly impact the global public. Though a few authors acknowledge the role of public involvement in deployment of alternative shipping fuels (Balcombe et al., 2019; Serra & Fancello, 2020), technological development has proceeded largely in isolation from social concerns. Under normative-democratic principles, citizens have a right to participate in decisions that affect them (Fiorino, 1990; Wilsdon & Willis, 2004). Furthermore, public engagement can help identify publicly acceptable pathways to decarbonisation and help legitimise new technologies (Serra & Fancello, 2020). Without public support, alternative shipping fuels may face substantial challenges, such as public opposition and some nations' consequential bans on nuclear energy. Thus, it is critical the shipping industry investigates alternative fuels that both achieve drastic emission cuts and are acceptable to stakeholders including civil societies (Serra & Fancello, 2020).

Previous research on alternative energy has documented public perceptions ranging from large-scale energy infrastructure projects to small-scale or consumer technologies (Boudet, 2019; Gaede & Rowlands, 2018; L'Orange Seigo et al., 2014; Liao et al., 2017; Poumadère et al., 2011; Radics et al., 2015; Ricci et al., 2008; Roche et al., 2010). However, our search of peer-reviewed literature identified no research that specifically examines public perceptions of alternative shipping fuels, highlighting the communication gap between civil society, academia, industry, and policy. In absence of data on alternative shipping fuels, we summarise public perceptions of four alternative fuels (hydrogen, ammonia, nuclear, and biofuels) alongside two incumbent fossil fuels (HFO and LNG).

1.2.1 Perceptions of alternative fuels

Perceptions of hydrogen are well studied outside of shipping contexts. Despite low levels of awareness, public perceptions are generally positive towards hydrogen (Ricci et al., 2008). Another review identified several factors with the greatest reported influence on hydrogen perceptions, including; prior awareness, cost, benefits, risks, environmental knowledge, education, income, infrastructure availability, and proximity, although it did not collate general sentiment (Emodi et al., 2021).

By contrast, perceptions of ammonia are less documented. Guati-Rojo et al. (2021) found that initial associations with the word "ammonia" raised predominantly neutral (e.g. compound, substance) or negative (e.g. poison, toxic) associations. However, after receiving information about "*green* ammonia" perceptions were generally positive, but highly dependent on the associated benefits and risks.

As with hydrogen, perceptions of nuclear are also well documented outside of the shipping context. Since its inception in the twentieth century, nuclear energy has elicited strong public reaction, particularly following high-profile disasters such as Three Mile Island, Chernobyl, and Fukushima. However, global concern for climate change and energy security appears to be driving a more favourable shift in public perception towards nuclear energy, albeit with lingering concerns about risk and disposal of nuclear waste (Poumadère et al., 2011). One study comparing UK perceptions of nuclear energy found a "reluctant acceptance" of nuclear energy, though renewable energy sources were still a preferable route to decarbonisation (Pidgeon et al., 2008).

Citizens are relatively unfamiliar with bioenergy or biofuels with low to moderate support. Since studies on perceptions of biofuels often focus on transportation, factors such as price and impact on vehicles are often important attributes; however, impacts on the environment, competing food systems, and security are also known to impact perceptions (Radics et al., 2015).

1.2.2 Knowledge gap addressed in this study

Though perceptions of alternative fuels have been studied in other contexts, there remains no peer-reviewed research focused on public perceptions of alternative shipping fuels. Our research addresses this knowledge gap, providing the first systematic measurement of public perceptions of six alternative shipping fuels: *ammonia, biofuels, heavy fuel oil, hydrogen, liquid natural gas,* and *nuclear* (Table 1).

Our research follows a two-stage, mixed-method approach. In the initial qualitative phase, we use depth interviews and self-administered surveys to explore public perceptions and identify the attributes that citizens associate with alternative shipping fuels. Next, in the second quantitative phase, we conduct a large online survey in the UK to quantify public perceptions. Here, the primary metric measures the extent that citizens associate the attributes identified in the qualitative phase with each fuel. Throughout the analyses, we cross-examine the findings of the qualitative and quantitative phases to yield richer insights and explore the potential drivers behind public perceptions of the six fuels tested.

These methods and their theoretical foundations are discussed in the sections below.

2 Method

Our research uses a two-stage, mixed-method approach to assess public perceptions of alternative shipping fuels. The methods are established in brand research (Bech-Larsen & Nielsen, 1999; Romaniuk, 2013) and public engagement (Carlisle et al., 2020, 2022; Wright et al., 2014), and begin with a qualitative phase to generate and validate measures used in the subsequent quantitative phase. However, our study makes a novel

Table 1 Summary of the alternative shipping fuels analysed in this study

Fuel	Description
Hydrogen	Hydrogen is a non-toxic gas that is already used in a variety of industrial processes. Ships using hydrogen produce no carbon dioxide; instead, the exhaust includes mostly water
Ammonia	Ammonia is a chemical that is already used to produce fertiliser and cleaners. Ships using ammonia produce no carbon dioxide, but could release pollutants
Biofuels	Biofuels are made from plants that absorb carbon dioxide as they grow. Ships using biofuels release carbon dioxide back into the atmosphere and could release other pollutants
Nuclear	Nuclear fuels like uranium are mainly used for producing large amounts of electricity. Ships using nuclear produce no carbon dioxide, but the fuels remain radioactive and require careful disposal after use
Heavy fuel oil (HFO)	Heavy fuel oil is a common fossil fuel used for international shipping. Ships using heavy fuel oil will continue to produce carbon dioxide and other pollutants
Liquid natural gas (LNG)	Liquid natural gas is a common fossil fuel used for heating and cooking. Ships using liquid natural gas will continue to produce carbon dioxide and other pollutants

Balcombe et al. (2019), Eide et al. (2013), Kesieme et al. (2019), McKinlay et al. (2020), Royal Society (2008) methodological contribution by cross-examining the findings from the two stages in a mixed-method (rather than sequential) approach.

2.1 Theoretical foundations

The primary tool used to measure public perceptions of alternative shipping fuels is based on cognitive association methods. Cognitive association methods draw on Associative Network Theories of Memory (Anderson & Bower, 1973) that describe how humans encode, store, and retrieve information in memory. Here, information is stored in memory as a network of concepts (or nodes) that are linked to one another in a large associative network. When a particular concept is activated, information about that concept is retrieved via a spreading activation throughout the associated network (Wright et al., 2014). For example, if a citizen thinks about hydrogen, they may also think about related concepts in their associative network such as “dangerous” or “sustainable”. Thus, according to ANTM, perceptions towards concepts (like alternative fuels) are mediated by citizens’ underlying associative networks and can therefore be measured. This is done by simply presenting respondents with a concept (e.g. a fuel) and asking them to identify attributes they associate with that concept (Romaniuk, 2013).

To this end, experts drew on ANTM theories to measure consumers cognitive associations with brands (Romaniuk, 2013). These methods were later adapted and validated as a tool for modelling cognitive associations (i.e. public perceptions) towards emerging technologies (Carlisle et al., 2020, 2022; Wright et al., 2014). We describe these methods below, beginning with a qualitative phase to identify relevant attributes followed by a quantitative phase to model citizens cognitive associations (i.e. public perceptions) between the six alternative fuels and fourteen associated attributes.

2.2 Qualitative phase

The aims of the qualitative phase are twofold: First, we aim to *explore public perceptions of alternative shipping fuels* using qualitative depth interviews. Second, we aim to *generate a list of attributes that the public associate with alternative shipping fuels* that are used in the quantitative phase as the primary measure of public perceptions. Attributes are generated using two established elicitation techniques *Kelley’s repertory grid* and selection from a *pre-determined list* (Bech-Larsen & Nielsen, 1999; Carlisle et al., 2020; Rogers & Ryals, 2007; Wright et al., 2014).

The *Kelley’s repertory grid* technique involves comparing similarities and differences between three fuels at a time and was administered during the depth interviews ($n=13$). The *pre-determined list* technique was collected using an additional self-administered survey ($n=30$) to cross-validate the findings of the first technique.

Depth interviews were conducted using Zoom video conferencing software and the materials were designed and administered virtually using the Qualtrics survey platform and the share-screen function. Lay participants were recruited using convenience and snowball sampling that involves asking a participant to provide further contacts. The participant’s demographics were varied and achieved a spread that is satisfactory for an exploratory stage (Supplementary Table 1). The interviews begin with a brief introduction to the topic and some open-ended warm-up questions. Participants then read short paragraphs about six fuels. Since participants typically have low familiarity with emerging technologies, the stimuli are carefully designed to convey information in an accessible manner, while balancing the uncertainty inherent with emerging technologies. Concept descriptions are carefully designed to avoid introducing framing artefacts or biases. Content for the descriptions (Supplementary materials) is drawn from peer-reviewed literature on alternative fuels (Balcombe et al., 2019; Eide et al., 2013; Kesieme et al., 2019; McKinlay et al., 2020; Royal Society, 2008, 2018, 2020). The paragraph descriptions are designed using strict matching criteria for content, length, and balance of positive and negative comments, and the adjectives used in the descriptions have no overlap with the attributes used for measurement. The final descriptions were subject to expert review for scientific accuracy, and pre-tested within the authorship team and with lay citizens for comprehensiveness. Next, in the Kelley's repertory grid task, participants are asked to compare three fuels at a time and explain why two fuels are similar, but different from the third. The materials are designed so that each fuel appears three times and randomisation is used to avoid order effects. Participants are also asked what "important qualities" they would consider if they had to choose a fuel to implement. The survey finishes with further open-ended questions and demographics. Interview transcripts were analysed using NVivo to identify common themes and generated a list of 43 attributes associated with alternative shipping fuels.

The pre-determined list technique used a self-administered survey design with participants drawn from panel provider *Dynata* ($n = 30$). The survey begins with demographics and screening questions, followed by a brief introduction to the topic and warm-up questions. Next, participants read short paragraphs about the six fuels and select which attributes they associate with each fuel. Thirty-one pre-determined attributes (separate to those generated in the depth interviews) were identified through content analysis of ten peer-reviewed articles on alternative shipping fuels, published between 2019 and 2020. The authors were careful to avoid any priming effects by excluding attributes that appeared in the concept descriptions or were direct synonyms. A gender quota ensured an even gender split and analysis indicates a satisfactory spread on the age demographic (Supplementary Table 1). Following the depth interviews, the frequencies of participants' memory associations were tabulated and compared against the results of the Kelley's repertory grid method. The cross-analysis by frequency of mentions arrived at a final list of fourteen common attributes, seven positive (*reduces emissions, safe, sustainable, available now, beneficial, shows potential, interesting*), and seven negative (*resource intensive, negative by-products, dangerous, unproven, expensive, risky, challenging*).

2.3 Quantitative phase

The main research aim for the quantitative phase is to *assess public perceptions and support for alternative shipping fuels*. Our approach involves a large quantitative survey in the UK ($n = 992$) using a commercial panel provider, *Dynata*. The survey follows a similar format to the qualitative survey, beginning with demographics, screening, introduction, and warm-up questions (see Supplementary Figs. 1—3).

Next, we apply a brand metric technique (Romaniuk, 2013) adapted to measure public reactions to emerging technologies (Carlisle et al., 2020, 2022; Wright et al., 2014). The technique allows researchers to compare respondents' perceptions of alternative shipping fuels by examining the attributes respondents associate with each fuel. Participants read descriptions of each fuel (Supplementary Fig. 4) in a randomised order. Using a randomised, multi-choice, pick-any format, respondents are asked to select which of the 14 attributes identified in the qualitative phase they associate with each fuel (Supplementary

Fig. 5). Additional questions assess support for research and use, understanding, and prior awareness of each fuel (Supplementary Fig. 6). The survey concludes with an open comment box (Supplementary Fig. 7).

The data were cleaned to remove incompletes ($n = 362$), speeders that spent less than 10 s per attribute task on average ($n = 354$), and participants that selected no attributes in all six tasks ($n = 18$). The final sample ($n = 992$) has satisfactory demographic characteristics compared to population estimates with only a slight under-representation of the 18–34 age brackets (Supplementary Table 2). To test comprehension, we asked if participants believed they could explain each fuel to someone else. Analysis shows satisfactory comprehension with an average of 43% of participants agreeing and 38% neutral (Table 3). Thus, we conclude that the data are acceptable for our research purposes.

2.4 Quantitative measures

For each fuel, attribute associations are coded as "1 = associated" or "0 = not associated". First, we use Kendall Tau-b nonparametric correlations (Supplementary Table 3) to test for overlapping memory associations (i.e. attributes with similar meanings; Romaniuk, 2013). The attributes *beneficial* and *dangerous* showed substantially higher correlations with the attributes *sustainable* and *risky*, meeting the criteria for removal (Carlisle et al., 2020, 2022; Wright et al., 2014) based on a > 0.35 threshold (Cohen, 1988). The remaining analyses were conducted with the 12 retained attributes.

The *net associations* variable is calculated as the sum of each respondent's positive attribute associations minus the sum of their negative attribute associations, for each fuel, and as an aggregate across all six fuels. To enable more intuitive comparison between fuels, we also calculate a *net association metric* for the whole sample as the percentage of positive attribute associations for each fuel, minus the percentage of negative attribute associations (Fig. 2 and Table 2).

Next, we examine the statistical properties of the *net association* variables prior to further analyses. The aggregate *net associations* variable across all six fuels can take any value between − 36 and 36 where "0" represents net-zero associations (i.e. neutral perceptions). The individual *net associations* for each fuel variable can take any value between -6 and 6. Variable properties are presented in Supplementary Table 4 and show a close

Table 2 Attribute associations with alternative shipping fuels

	Biofuel	Hydrogen	LNG	Nuclear	HFO	Ammonia	Total
Total associations	2871	3039	2237	2920	2190	2467	**15,724**
Average associations	2.9	3.1	2.3	2.9	2.2	2.5	**15.9**
Positive associations	61%	60%	55%	42%	40%	30%	**49%**
Negative associations	39%	40%	45%	58%	60%	70%	**51%**
Net associations (%)	**21%**	**20%**	**10%**	**− 15%**	**− 20%**	**− 40%**	**− 3%**

The net association metric reveals biofuels and hydrogen are clearly favoured, while perceptions of liquified natural gas are somewhat positive, suggesting that it provides an acceptable near-term option. Despite lingering stigma, nuclear is preferred over the incumbent heavy fuel oil, though both are perceived negatively. Respondents strongly dislike ammonia

Bold indicates a total or average calculation

Table 3 Summary of participant responses to additional questions (%)

	Biofuel	Hydrogen	LNG	Nuclear	HFO	Ammonia	Avg
Awareness of alternative fuels							
Have heard of [fuel] as an alternative shipping fuel	19	18	18	27	31	8	**20**
Have heard of [fuel], but not for shipping	52	55	44	46	17	15	**38**
Total	**71**	**73**	**62**	**73**	**48**	**22**	**58**
Have not heard of [fuel]	29	27	38	27	52	78	**42**
Could explain to someone else							
Agree	50	53	44	43	36	32	**43**
Neutral	36	33	39	36	40	42	**38**
Disagree	14	14	17	21	24	27	**19**
Support for research							
Agree	66	71	47	46	32	38	**50**
Neutral	26	24	35	25	33	37	**30**
Disagree	8	5	18	29	35	24	**20**
Support for use							
Agree	48	53	34	32	21	21	**35**
Neutral	41	40	46	37	40	48	**42**
Disagree	10	7	20	32	40	31	**23**
Net associations	**21**	**20**	**10**	**– 15**	**– 20**	**– 40**	**– 3**

UK citizens were familiar with most fuels, but often not in the context of shipping. Support for research or use varied between fuels, with high support for biofuel or hydrogen, and low support for ammonia and HFO. Support for research and use closely followed the net associations metric

Bold indicates a total or average calculation

approximation to a normal distribution, indicating that they are suitable for further analysis. Univariate tests identify a small, but statistically significant relationships with the *age* variable and the *aggregate net associations* variable; however, multivariate analysis with 2-way interactions does not reveal significant relationships (Supplementary Table 5). Accordingly, we conclude that no covariates are necessary for further statistical tests.

Concept maps are constructed by tabulating the observed attribute counts for each fuel, calculating the Chi-square expected attribute counts, then calculating the percentage point deviations between the observed and expected counts (Supplementary Table 6; Fig. 3).

Additional questions are outlined in Supplementary Fig. 6 with analysis reported in Table 3. Prior awareness was coded as “1 = have heard of [fuel] as an alternative shipping fuel”; “2 = have heard of [fuel], but not for shipping”; “3 = have not heard of [fuel]”. Likert questions were coded on a 5-point scale where “1 = Strongly Agree” and “5 = Strongly Disagree” and were truncated to “Agree”, “Neutral”, and “Disagree” for reporting. To test for the NIMBY effect, we calculate an *average support for use* variable as the mean of the six *support for use* variables for each fuel. Since the variable is an aggregate of several ordinal items, we treat the variable as interval data (Norman, 2010) and deem parametric two-sided statistical tests appropriate.

2.5 Mixed-method analysis

Throughout the article we report the results of statistical analyses from the large, quantitative survey. Although quantitative research can provide broad, generalisable insights that are representative of a population, such methods do not allow researchers to probe respondents for the "why?" behind their answers. Accordingly, in our mixed-methods approach, we supplement our quantitative findings with insights and direct quotes from the 13 participants in the qualitative depth interviews. We use thematic analysis from the Kelley's repertory grid tasks to understand *why* participants associated certain attributes with each fuel, and therefore obtain a fuller picture of the drivers behind the differences in perceptions of alternative shipping fuels.

2.6 Pseudo-opinions

One concern sometimes raised against public engagement with emerging technologies is whether survey mechanisms elicit measurement artefacts, rather than genuine public perceptions. In particular, there are concerns that surveys elicit pseudo-opinions or non-attitudes where participants respond to questionnaire items despite holding no genuine prior opinion on the matter (Asher, 2017). In part, this concern is attributed to the limited information and time afforded to participants assessing emerging technologies. However, recent evidence suggests that more thorough consideration is unlikely to change respondent evaluations (Carlisle et al., 2022). This result can be explained by the design of these methods to access existing memory structures (Anderson & Bower, 1973; Romaniuk, 2013) using the fast intuitive judgements common in everyday decision-making (Kahneman, 2011).

Nonetheless, the method used in this study is specifically designed to mitigate the risk of pseudo-opinions. Unlike traditional survey mechanisms that ask respondents to self-report their attitudes (e.g. Likert scales), the current method measures the underlying cognitive associations that participants draw on to assess emerging technologies. Where a respondent has no opinion towards a fuel, the attribute selection task would yield few attribute associations compared to respondents with strong opinions. At the aggregate level, participants with no legitimate opinions and few associations towards each fuel are therefore given proportionally less weight compared to participants with strong opinions and several attribute associations. Consequently, cognitive association methods are comparatively less prone to bias from pseudo-opinions and non-attitude responding (Carlisle et al., 2020). Additionally, with no obvious mid-point or "agree" option, the method also mitigates common mid-point or acquiescence biases.

3 Results

3.1 Awareness of alternative shipping fuels

Findings from the qualitative depth interviews suggest that citizens have heard of many of the six fuels but are unaware of their maritime applications. This exploratory finding is quantified in the online survey where on average 58% of participants had heard of each fuel, though only 20% were aware they could be used for shipping (Table 3).

Despite variability in prior awareness, there was no substantial difference in the number of attributes that participants associated with each fuel (avg. 2.2–3.1 attribute associations per fuel; Table 2) indicating prior awareness had little effect on participants' ability to identify relevant attribute associations.

3.2 General perceptions of alternative shipping fuels

The most frequently mentioned attribute associations for alternative maritime fuels are *risky, negative by-products* and *available now* (Fig. 1), accounting for a third of the total associations. This indicates that these topics are the most salient concerns of UK citizens.

3.3 Comparing perceptions between alternative shipping fuels

To compare perceptions between fuels, we subtract the percentage of negative associations from the percentage of positive associations to produce a *net association metric* (see Fig. 2 and Table 2). At the aggregate level, respondents' perceptions of alternative shipping fuels are approximately neutral with only 3% more negative associations than positive association. However, there are substantial differences in perceptions between fuels (Fig. 2).

Biofuel and hydrogen are clearly preferred with approximately 20% more positive associations than negative associations. LNG is also positively perceived despite being a fossil fuel. Interestingly, nuclear is favoured over the incumbent HFO, suggesting that there is a "reluctant acceptance" of nuclear energy (Pidgeon et al., 2008), despite the lingering stigma. Ammonia is strongly disliked by participants with 40% more negative associations than positive associations.

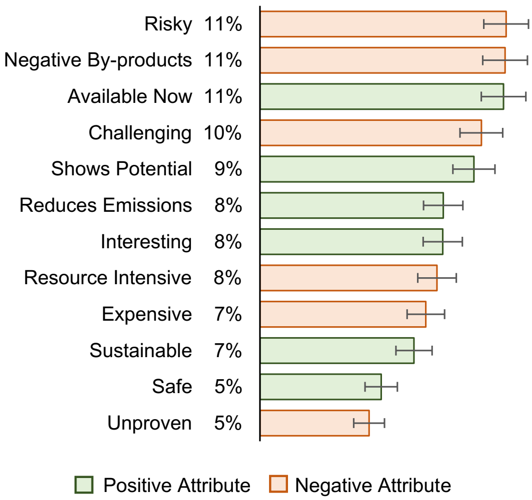

Fig. 1 Percentage share of attribute associations across alternative shipping fuels: The top three attributes (*risky, negative by-products,* and *available now*) account for a third of all associations. Error bars show standard error

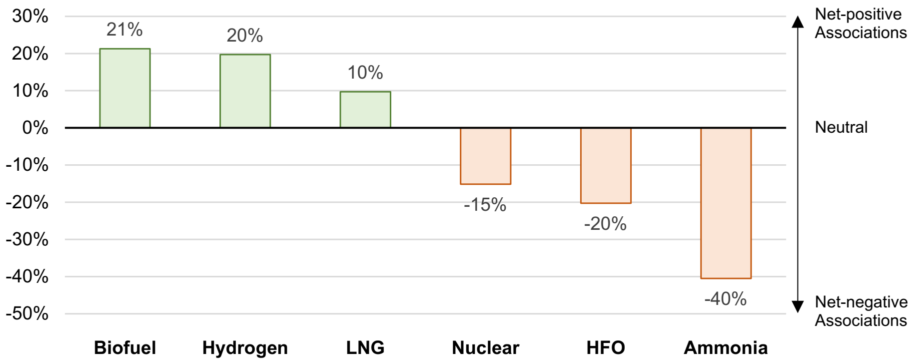

Fig. 2 Net associations with alternative shipping fuels. Bars show the net associations (positive associations minus negative associations) for each fuel. Perceptions of biofuel, hydrogen, and LNG are mostly positive, whereas perceptions of nuclear, HFO, and ammonia are mostly negative

3.4 Concept maps

To explore the reasons behind respondents' differing perceptions, we construct concept maps that show how attribute associations differ between fuels. For each fuel, we calculate the percentage difference between actual and Chi-square expected counts for each attribute (Fig. 3; Supplementary Table 6). This approach controls for baseline associations, so deviations reflect differences in public perception for specific attributes on individual fuels.

Skews (Fig. 3) show that the more favourably perceived fuels, *biofuel* and *hydrogen,* have more positive associations and fewer negative associations. In contrast, the least favoured fuel, *ammonia*, has fewer positive associations and more negative associations. This pattern aligns with broader findings from the risk literature that people with favourable perceptions of an activity typically perceive high benefits and low risk (and vice versa; Slovic & Peters, 2006) and is consistent with similar analysis conducted on climate engineering proposals (Carlisle et al., 2020, 2022; Wright et al., 2014). Middling fuels like LNG show little pattern with predominantly small, irregular deviations. However, some noteworthy deviations (greater than ± 5%; dark fill) stand out from the patterns described above, indicating that they are a major driver of perceptions for that fuel.

Biofuels has exceptionally low rates of association with the attribute *risky* (7.6% less than expected), indicating that citizens view biofuels as relatively low risk. This is also reflected in the qualitative depth interviews with participants remarking *"It feels much safer"* and "*even the name of it sounds softer and greener to the layman"*.

Hydrogen has exceptionally low rates of associations with *negative by-products* (8.0% less than expected) which contributes to its positive perceptions. Findings from the depth interviews suggest that this is due to hydrogen only emitting water at the point of use. For example, one qualitative participant remarked "*Hydrogen only produces water vapour, whereas obviously liquid natural gas produces* CO_2 *and nuclear produces nuclear waste. So, hydrogen doesn't produce anything harmful"*. Another agreed, stating "*with renewable electricity to produce hydrogen, that could be completely emission free"*.

LNG has relatively small deviations, indicating that it has few distinctive characteristics and is unlikely to elicit a strong public reaction. The one exception is the high rate of association with the positive attribute *available now* (7.8% more than expected). *HFO* also

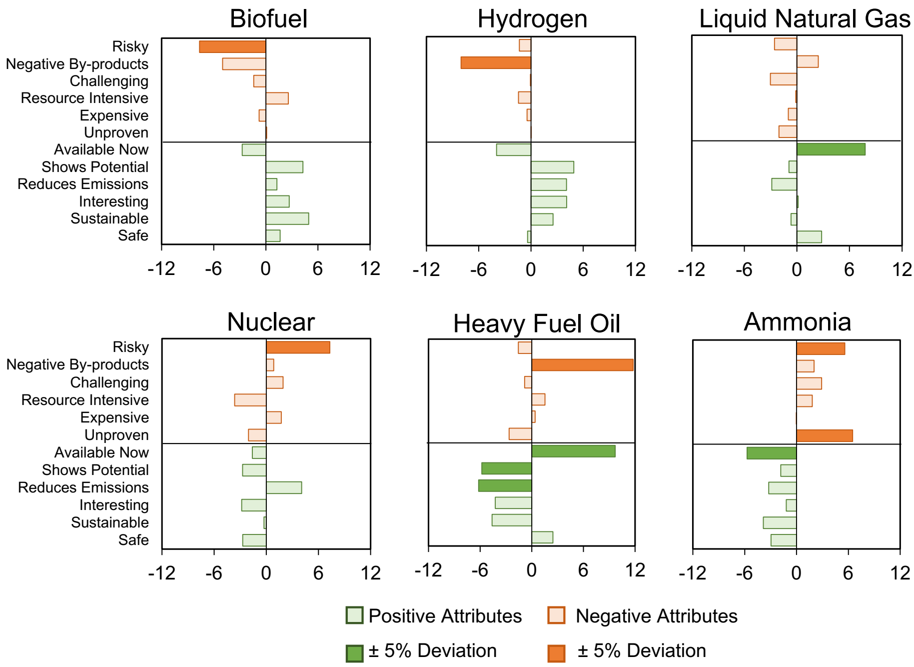

Fig. 3 Concept maps for alternative shipping fuels. Negative attributes (orange) and positive attributes (green) are presented in descending order of popularity. Bars show the percentage point deviations between actual and expected attribute associations for each fuel. Positively perceived fuels like biofuel and hydrogen have higher than expected associations with positive attributes and lower than expected associations with negative attributes. Negatively perceived fuels like ammonia show the opposite pattern. Dark fill indicates that noteworthy deviations (greater than ± 5%) indicating those attributes contribute heavily to citizens' perceptions

has similarly high associations with *available now* (9.7% more than expected); however, its overall perception is substantially worse than LNG due to exceptionally high associations with *negative by-products* (11.8% more than expected) and low associations with *reduces emissions* and *shows potential* (6.2% and 5.8% less than expected). For the two currently available fuels, our findings suggest that LNG is preferred over HFO, at least as a short-term transitional fuel.

Nuclear's negative perceptions are largely driven by exceptionally high associations with the attribute *risky* (7.6% more than expected). This is unsurprising given the salience of nuclear disasters noted by participants in the depth interviews. As one qualitative participant put it; *"if there was an oil spill, it's terrible. But if there's a nuclear spill it's a freaking disaster"*. Another participant added that nuclear shipping *"would probably only take one accident in the world, and that would kill it"*.

Despite **Ammonia's** use as a major industrial chemical that is transported in many industrial countries, the UK public's perceptions of it are negative. Ammonia's strong negative perceptions are driven by several attributes, including high rates of associations with the attributes *unproven* and *risky* (6.5% and 5.6% more than expected) and low rates of associations with *available now* (5.7% less than expected). Participants' dislike for ammonia is also apparent in the qualitative depth interviews, described as *"dangerous"*, *"toxic"*, *"hazardous"*, and *"poisonous"*. One participant described ammonia as "*relatively untested"* stating; *"it's a bit more dangerous, I guess, in the sense that it is corrosive… and toxic, but… there aren't as many safety protocols established"*. Another dismissed ammonia completely, stating; "*I don't think it has anything going for it at all. It looks pretty dreadful to me"*.

The public's dislike for ammonia is particularly relevant following a recent techno-economic assessment that labelled ammonia "one of the most balanced carbon-free fuels" (Stolz et al., 2022). The contradiction between science and the public's perceptions of ammonia is a timely reminder for scientists and the shipping industry to consider public concerns alongside techno-economic evaluations of emerging shipping fuels.

An important component of ammonia may be the distinction between fossil fuel sourced *brown ammonia* and renewable sources of *green ammonia.* Our findings above align with Guati-Rojo et al.'s findings that general perceptions of ammonia were mostly neutral or negative (2021). However, Guati-Rojo et al. surprisingly found that *green ammonia* yielded positive perceptions. As shipping industries begin to implement ammonia infrastructure, they will almost certainly rely on brown ammonia in the near-term while greener production technologies are developed. Accordingly, there is a risk that long-term ambitions to implement green ammonia solutions may be hindered by public concern towards the transitional use of use of brown ammonia in the near-term. This is an important avenue for future public engagement research that will provide further critical information to inform industry and policy decision-makers. Nonetheless, the non-renewable production of hydrogen in the near-term did not raise the same negative response as observed towards ammonia, indicating that the other negative attributes will nonetheless affect perceptions of ammonia.

3.5 Support for research and use

The initial qualitative depth interviews suggest that participants generally support research into alternative shipping fuels, with many motivated by the shipping industry's significant contributions to global emissions and/or the urgent need to address climate change. Some participants thought research could reduce uncertainty around any negative side effects. To this effect, one participant mentioned *"it has to be something that isn't going to make the problem worse"* and gave the analogy of the *"cure"* being worse than the *"disease"*. Only one of the thirteen interview participants stated they would not support research, instead suggesting that we should avoid shipping and shop locally.

These qualitative findings are also reflected in the quantitative stage where participants were asked whether they would support research or use of each fuel (Table 3). Unsurprisingly, research has higher rates of support compared to use. On average, 50% of participants supported research (20% opposed), whereas only 35% supported use (23% opposed).

Support for individual fuels followed a similar pattern to the net associations' metric with approximately two-thirds of participants supporting research into hydrogen or biofuels (5 and 8% opposed, respectively) and approximately half supporting their use (7 and 10% opposed, respectively). In contrast, less than 40% supported research into ammonia or HFO (24 and 35% opposed, respectively) and only 21% supported their use (31 and 40% opposed, respectively).

3.5.1 "Yes in my backyard" (YIMBY)

Previous research on emerging technologies has observed a "not in my backyard" (NIMBY) effect, whereby citizens show stronger opposition to the deployment of new technologies near where they live (Braun, 2017). To establish whether this phenomenon affects alternative shipping fuels, we compared participants *average support for use* between those that reported living near a port, and those that did not. Interestingly, our analysis indicates participants who self-identified that they live near a port are slightly more supportive of using alternative shipping fuels ($t_{947} = -3.563$, $p < 0.001$) suggesting a "yes in my backyard" (YIMBY) effect. We also compared whether living near a port affected participants perceptions using the net associations variable but found no significant difference ($t_{947} = 0.674$, $p = 0.500$). These findings also rule out NIMBY effects for these data.

4 Discussion

Our mixed-method approach involving qualitative depth interviews and a large online survey marks the beginning of academic inquiry into public perceptions of alternative shipping fuels. Though the UK public generally accept the need to decarbonise the shipping industry, their perceptions and support differ substantially between alternative shipping fuels with hydrogen and biofuel eliciting positive responses but ammonia evoking strong negative reactions. With techno-economic assessments highlighting ammonia as a suitable frontrunner for decarbonising the shipping sector (Stolz et al., 2022), it is crucial that scientists, researchers, policy makers, and industry consider the public's concerns. Additionally, it is striking that nuclear was perceived more favourably than the incumbent heavy fuel oil.

The attributes, *risky, negative by-products, and available now*, are the most salient across the fuels (Fig. 1) and yielded large deviations in associations between fuels (Fig. 3), suggesting that issues of risk, negative by-products, and availability are topmost in citizens' minds. Industry and policy makers, therefore, need to consider these evaluative attributes during communications; for example, reassuring citizens that risks are recognised, and negative by-products will be mitigated.

Overall, support for research is higher than support for use, indicating that the public would prefer alternative shipping fuels thoroughly understood before implementation. This finding is promising for researchers, industry, and policy makers who are considering alternative shipping fuels, and highlights the need for increasing research and investment in the field. As one depth-interview participant put it; *"climate change is a pressing issue that needs to be solved as fast as possible, and I think throwing it as much money as possible and as many minds as possible is probably the only solution"*.

Although this research examines public perceptions from the UK, it lays the foundations for a broader research agenda to engage the global public and inform decision-making on alternative shipping fuels. As with other emerging technologies, social scientists must be careful to ensure globally diverse perspectives are considered, including indigenous populations and the global south, who are disproportionally affected by climate change and may be the last to benefit from technological improvements. Our research indicates that the public has low awareness of alternative shipping fuels, yet still forms well-considered and, in some cases, strong opinions. Accordingly, as the need to address climate change continues to grow, it is important that industry and policy makers continue open communication and engagement with public to identify acceptable pathways for decarbonising the shipping industry.

4.1 Theoretical and academic implications

The research here adds to the growing literature demonstrating the usefulness of ANTM (Anderson & Bower, 1973) and cognitive association methodologies (Carlisle et al., 2020, 2022; Romaniuk, 2013; Wright et al., 2014) for public engagement with emerging technologies. Additionally, the cross-validation of the quantitative findings against insights from the qualitative phase demonstrate the value of a mixed-method approach to modelling cognitive associations. Though mixed-method approaches are not new to public engagement, this is the first known application of a mixed-method approach to modelling cognitive associations in a peer-reviewed journal.

The qualitative data provided valuable insights into the driving factors and nuances behind participants' perceptions of alternative fuels. In particular, direct participant quotes from the qualitative phase helped to cross-validate the quantitative findings and explain why certain attributes were (or were not) associated with each fuel. The concept maps further identified the attribute associations that were primarily responsible for more positive or negative evaluations, providing additional reasons for public concern. Put simply, the mixed-method approach helped explain why participants perceived each fuel the way they did.

Additionally, this study contributes to the growing number of publications investigating decarbonisation technologies in the shipping industry (Di Vaio et al., 2023) as the first to investigate public perceptions of alternative shipping fuels.

4.2 Implications for the shipping industry and investors

We determined that, overall, the UK public support research, development, and implementation of alternative shipping fuels over incumbent fossil fuels. As the first study to explore perceptions of alternative shipping fuels, industry players and investors can take comfort that preliminary findings suggest that their ongoing investment will be positively regarded by the UK public, particularly for hydrogen and biofuels. The near-term use of LNG also appears likely to be positively regarded by the UK public as a transitional solution and is unlikely to raise significant public concern.

Although nuclear was evaluated negatively, it was surprisingly perceived less negatively than HFO and ammonia. Consideration of nuclear as an alternative marine fuel may therefore result in less public resistance than some other options, although a net negative public reaction can still be expected given these data. Conversely, given the greater negative associations with HFO, it can be expected that if the characteristics of HFO become more widely known there is likely to be increased public opposition to its use, and greater public pressure for the shipping industry to move towards alternative marine fuels.

In line with previous research (Guati-Rojo et al., 2021), the public associate negative traits with ammonia (e.g. toxic, corrosive), leading to negative evaluations and low support for research and use. This is an important finding for industry and investors developing ammonia infrastructure for what is already a widely transported industrial commodity. Industry may wish to incorporate the risk of public opposition in their ongoing decision-making. It remains unclear whether *green ammonia* produced from renewable sources will resolve or outweigh the public concern reported here. This route of enquiry should be of high priority to inform the increasing investment and commitment towards cleaner ammonia production.

It is also important to consider that public concern may not manifest itself in a linear fashion alongside development and implementation of infrastructure. In one scenario, it is feasible that public opposition may remain dormant towards less-favoured fuels like ammonia, provided that there are no major incidents that raise public concern and relatively little awareness of the infrastructure associated with this fuel. However, drawing parallels to nuclear energy (a fuel with similar negative associations) the risk of a major spill or incident could abruptly ignite public outcry and significantly affect shipping operations. As such, industry and investors implementing ammonia infrastructure (or indeed any alternative fuel) ought to carefully consider how cognitive associations may exacerbate the public relations risk associated with a major disaster, and factor pre-existing associations into their crisis communications plans.

Overall, the main implication for the shipping industry and investors is that public perceptions are neither uniform, nor static. The UK is only one country and perceptions of alternative fuels may differ abroad. Likewise, as emerging technologies become better understood and more commonplace, public perceptions may indeed shift over time. The gradual shift from strong opposition to "reluctant acceptance" of nuclear power (Pidgeon et al., 2008) is a prime example of this. It is, therefore, important that industry and investors work alongside public engagement researchers to expand on the work reported here into other countries and continue to monitor public perceptions over time to ensure their operations meet publicly acceptable standards and avoid the potential for significant backlash.

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