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Norwegian ship-owners' adoption of green fuels

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Abstract: The shipping sector's rising greenhouse gas emissions are often considered "hard-to-abate", and ship-owners play an important role in emissions reduction. Some of them have recently adopted or started to consider the adoption of green fuels, but systematic studies of such adoption practices are still lacking. We address this gap by studying how ship-owners differ in both actual and intended adoption of green fuels. We analyze data from a unique survey with 281 ship-owners in Norway, a major ship-owning country and center for maritime technology development, with descriptive statistics and analysis of variance. We find lead adopters among large and established ship-owners in offshore, international cargo and domestic passenger shipping segments, which are often subjected to specific contractual demands for green fuel adoption. Laggards were typically small and young ship-owners operating in shipping segments where demands for green fuel adoption are weak. Our findings also suggest that firms' business strategy and financial and knowledge resources may have relevance for ship-owner's adoption of green fuels. Our study has implications for national and international policymaking, highlighting for example how contracting mechanisms can be an effective tool in incentivizing the adoption of green fuels.

Keywords: Green Fuels; Innovation adoption; Ship-owners; Climate change mitigation; Norway

1. Introduction

Accounting for 2.9 % of global greenhouse gas (GHG) emissions, the shipping industry is generally considered to be a "hard-to-abate" sector (IMO 2020a), similar to other energy-intensive industries such as processing and aviation (Victor, Geels, and Sharpe 2019). Shipping's emissions are "projected to increase from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 for a range of plausible long-term economic and energy scenarios" (IMO 2020a). In 2018, the UN's International Maritime Organization (IMO), which regulates environmental protection for international shipping, set the target of halving GHG emissions by 2050 compared to 2008, whilst pursuing aims of phasing them out entirely in the 21st century (IMO 2020b).

While various energy efficiency measures hold potential to abate emissions (e.g., Rehmatulla and Smith 2015, Adland et al. 2018, Poulsen and Sampson 2020), the achievement of the IMO GHG goals critically depends on widespread adoption of low- or zero-carbon fuels and energy carriers ("green fuels" in this paper), not least because of an expected growth in shipping demand (Traut et al. 2018, Psaraftis 2019, IMO 2020a). Green fuels vary substantially in terms of production, distribution and use (DNV GL 2016, Mäkitie, Hanson, et al. 2020), and also in terms of compatibility with existing maritime technology and fuel infrastructure.

Ship-owners play a key role in the choice of ship designs and propulsion systems when contracting new ships (Poulsen et al. 2021). Their views on green fuels therefore have an important bearing on the adoption of such fuels. To the best of our knowledge, ship-owners' green fuel adoption – and their variation – have not been subjected to systematic studies. We address this knowledge gap on green fuel adoption in shipping through an exploratory study of the following research question:

How do ship-owners differ in adoption of green fuels?

A wide range of candidate green fuels exist, including battery-electric and hydrogen (Bach et al. 2020), liquefied natural gas (LNG) (Bach et al. 2021), various biofuels, and ammonia and methanol (International Transport Forum and OECD 2018, DNV GL 2019b), but adoption among ship-owners remains very limited. As summarized in Table 1, green fuels differ in terms of their maturity, their requirements for adaptations in ship-designs and -operations, the availability and investment needs concerning infrastructure for production, storage and distribution (for an overview, see e.g. DNV GL 2019a) – and their environmental benefits. The latter depends on how the fuel is produced (e.g., hydrogen produced with renewable energy or from a fossil resource), how it is used (e.g., in combustion engine or with fuel cells), or other technologies that handle fuel-specific issues (e.g., scrubbers).

Table 1 Green fuels for shipping - characteristics and benefits. Based on (DNV GL 2016, 2017), Steen et al. (2019), ABS (2021).

	Biogas	**Biodiesel**	**Electric (full)**	**Electric hybrid**	**Hydrogen (carbon neutral)**	**LNG**	**Ammonia (green)**	**Methanol (green)**
Reduction of greenhouse gases	High	High	Very high	Moderate-High	Very high	Low-moderate	Very high	High
Reduction of NO_x	Low	Low (increase)	Very high	Moderate	Very high	High	High	High
Reduction of SO_x	Very high	Very high	Very high	Moderate	Very high	High	High	High
Vessel adaptation	Low	Low	High	Moderate-high	High	Moderate-high	High	High
Technological maturity	High	High	Moderate	Moderate-high	Low	High	Low	Low
Availability (incl. infrastructure production, bunkering/charging)	Low	Low	Moderate	Moderate	Low	Moderate	Low	Low
Applicability in different shipping segments	All	All	Short routes (e.g. ferries)	All – esp. variable energy demand	Short to mid-range routes (e.g. short sea cargo transport)	All	All	All

An emerging literature on maritime environmental governance has pointed out how the lack of strong and enforceable global regulation, poor alignment of interests among shipping stakeholders, and low visibility of environmental issues hamper environmental upgrading in shipping, including emission abatement (Lister, Poulsen, and Ponte 2015, Poulsen, Ponte, and Lister 2016). For instance in the international tanker and dry bulk shipping segments, market drivers in the form of cargo-owner greening demands have generally been weak (Poulsen, Ponte, and Lister 2016, Poulsen et al. 2021). In the Norwegian context, however, public procurement was decisive for the introduction of battery-electric systems in ferries, and customer demands from the energy company, Equinor, for the adoption of battery-electric systems onboard offshore supply vessels (Steen et al. 2019, Bach et al. 2020, Sjøtun 2019).

Beyond market drivers, the different nature of shipping segments also influences green fuel adoption. Shipping is highly heterogenous, ranging from large oil tankers and container ships in deep sea trades to small fishing boats and short haul ferries. The operational profiles, power needs, sailing distances, and whether vessels operate on fixed routes or not, differ drastically (DNV GL 2016). Also, some green fuels are seen as relevant in some shipping segments, while not in others. Battery-electric solutions, for instance, may be seen as suitable for short haul ferries, but may only be relevant for efficiency and 'peak-shaving' purposes in deep sea shipping due to their low energy density (DNV GL 2019a).

In a study of environmental management strategies in shipping companies, van Leeuwen and van Koppen (2016) found that ship-owners predominantly employ 'a crisis oriented' strategy, aiming to comply with environmental regulation, and Rojon and Dieperink (2014) found ship-owners preferring a wait-and-see strategy in relation to adoption of wind propulsion due to risk aversion. However, Alger, Lister, and Dauvergne (2021) found large shipping companies pushing for higher environmental standards to raise costs for small and midsized competitors. Stalmokaitė and Hassler (2020) also found that incumbent shipping companies in the Baltic Sea region are gradually implementing proactive innovation strategies for decarbonisation in response to broader socio-political pressures. Saether, Eide, and Bjørgum (2021) found that ship-owners with a long-term orientation tend to be more active in green innovation and strategy. Recent public decarbonization commitments by major ship-owners (e.g. Maersk 2019, DFDS 2020) also indicate that some ship-owners are showing increasing interest towards the adoption of green fuels. On a general note, it also seems clear that the management-oriented literature has focused on shipping companies operating for instance within container and bulk market segments, whereas for example the fishing vessel segment has received little attention (Greer et al. 2019).

To explore how ship-owners differ in green fuel adoption, we use data from a unique survey among Norwegian ship-owners. Norway is a major ship-owning country and is among global maritime technology leaders (Tenold 2019), and has a full value chain around shipping which has been active in developing environmental innovations (Mäkitie, Steen, et al. 2020). Several Norwegian ship-owners have experience with battery-electric and LNG propulsion systems, and the world's first hydrogen-powered ferry will enter service in Norway in 2021. The Norwegian government aims to halve domestic shipping and fishery emissions by 2030 (compared to 2005) (Regjeringen 2019), and the Norwegian Ship-owner's Association has pledged to eliminate GHG emissions by 2050 (Rederiforbundet 2020). In their abatement aims, both the government and

Ship-owners' Association in Norway thus go beyond the IMO GHG goals. Stricter emission regulations will apply to cruise ships in Norwegian fjords, and several Norwegian ports use their port fee systems to incentivize adoption of green fuels (Damman et al. 2019).

We study both firms which have adopted or intend to adopt green fuels, as well as firms which do not intend to adopt them. Intentions, or perceptions, concerning future business decisions may of course change and should be treated with caution. However, they guide ship-owners' technology search activities and steer their investment decisions in certain directions, thus having important bearings on the development and adoption of green fuels (Borup et al. 2006). Shedding new light on these intentions, our study has implications for policymakers wishing to encourage green fuel adoption in shipping.

The paper proceeds as follows. Section 2 outlines our methodology, while section 3 presents the results. Section 4 discusses our results in relation to previous studies, and section 5 concludes and proposes policy implications.

2. Methodology

2.1. Data collection

To study the variation in ship-owners' adoption of green fuels, we designed an online survey for Norwegian ship-owners. Our survey questions concerned firm characteristics, green fuel adoption, and drivers and barriers to adoption. Survey questions were based on previous literature (see Section 1) but were also grounded in extensive qualitative data generated prior to the survey (e.g., Bergek et al. 2018, Bach et al. 2020). Please refer to Table A1 in the appendix for the specific measures used in this study.

Our population consists of 2,707 active public and limited liability companies with over NOK 1 Million in operating income that owned and/or operated sea-going vessels, as identified in Proff Forvalt, an online database of all registered companies in Norway.[1] We targeted CEOs because they have a critical say on investment decisions, including contracting of new ships and retrofitting. Some individuals act as CEOs for two or more registered companies, and we

[1] We used the following NACE categories: A.03.111 - Marine fishing, A.03.213 - Marine aquaculture, H.50 - Water transport (including subordinate codes 50.101, 50.102, 50.109, 50.201, 50.202, 50.203, 50.204, 50.300, and 50.400), H.52.22 - Service activities incidental to sea transport, and H.52.29 - Ship brokering

identified 2,005 individual CEOs of companies with seagoing vessels. Some email addresses for firms and their associated executives were available in the Proff Forvalt database, while additional emails were gathered via phone, online searches, and contacting maritime organizations and alliances. Ultimately, we were able to identify 1,045 unique email addresses.

We pretested the survey with a pilot group of practitioners to ensure comprehensibility before we distributed the questionnaire in late 2019. We requested respondents to answer on behalf of one of their associated companies to avoid multiple responses from the same individual. Individual respondents and their respective companies were guaranteed confidentiality, and they were also ensured that collected survey data would only be presented and/or published in aggregate form to prevent the possibility of individual identification. After following up by phone and email to increase the response rate we received 287 responses with sufficient information for this study (response rate of 28%). Of these 287 companies, we excluded 6 which were ship-operators only (i.e., did not own ships).

Our sample is closely representative of the Norwegian ship-owner population. Specifically, our study's respondents resemble non-respondents based on characteristics such as size, age, and segment. We also conducted a T-test to check for differences between early and late respondents as this is an effective test for non-response bias (Lambert and Harrington 1990). Analyzing all 96 variables in the survey, we only found one statistically significant difference at the 5 percent confidence interval (i.e. environmentally friendly operations, $p < .01$), which indicates that non-response bias is of little concern.

We asked ship-owners to estimate when they would adopt the following green fuels on at least one of their vessels: A) electric battery, B) liquefied natural gas (LNG), C) biodiesel, D) biogas (liquified biogas/ LBG), E) hydrogen, F) ammonia and G) methanol. Furthermore, we asked survey respondents about their motivations and barriers for adoption of green fuels. We based our motivation measures primarily on Bansal and Roth (2000) who distinguish between three types of motivations for firms to adopt environmentally friendly initiatives, namely, *legitimation* (e.g., 'it will improve the company's reputation), *competitiveness* (e.g., 'it will provide long-term profitability') and *environmental responsibility* (e.g., it is important for us to contribute to a cleaner environment). Furthermore, we measured barriers with items inspired by literature on technological responses to environmental issues (Ashford 1993) and innovation barriers (D'Este et al. 2012, Madrid-Guijarro, Garcia, and Van Auken 2009). The barriers we measure include *economic* (e.g., investment costs are too high), *informational* (e.g., lack of information about new technologies), *supply chain* (e.g. lack of infrastructure), and *technological uncertainty* (e.g., changes in green fuels are difficult to predict). Finally, to gather contextual information about the ship-owners' general approach towards environmental upgrading, we also asked them about their adoption of modifications in design, maintenance, and operations related to emission reduction.

2.3. Data analysis

2.3.1 Categories of ship-owners

To structure our analysis of differences on green fuel adoption among ship-owners, we categorized respondents using well-established terms from the literature on innovation diffusion (Rogers 1962, Triguero, Moreno-Mondéjar, and Davia 2016, van Mossel, van Rijnsoever, and Hekkert 2018). If a firm had adopted at least one green fuel, we categorized it as a *leader* (N=39). If it intended to adopt at least one green fuel within the next 5 years, we categorized it as an *early follower* (N=108). If it intended to adopt at least one green fuel in more than 5 years' time, we categorized it as a *late follower* (N=97). Finally, if a firm never expected to adopt any green fuels, we categorized it as a *laggard* (N=37).

2.3.2 Descriptive statistics and analysis of variance

Our analyses of survey data were done in SPSS v.27. As an exploratory study with quantitative data regarding differences in adoption behavior, it was important to investigate attributes of the categories of ship-owners. Thus, we used descriptive statistics to get an overview of our sample and ship-owner characteristics. Specifically, we analyzed frequencies in the respective categories of ship-owners related to green fuel adoption, age and size of the firms, segment composition, and whether their operations were predominantly international or domestic shipping segments.

We also explored key differences between the four groups, to shed light on the potential drivers and challenges for green fuel adoption by ship-owners. We followed Bergek and Mignon (2017) in using one-way analysis of variance (ANOVA) to test differences of mean scores between multiple groups. Illuminating the specific motivations, barriers, and characteristics with significant differences, we explored on the reasons for varying adoption rates. Moreover, we conducted Tukey's honestly significant difference (HSD) post-hoc tests to assess which groups differed the most.

3. Results

3.1 Descriptive statistics

Table 2 provides descriptive statistics for the four ship-owner groups in relation to their green fuel adoption, firm and fleet age, firm size (number of employees and vessels), segment and whether they operated primarily internationally or domestically. We see that leaders and laggards are substantially different from each other across all variables, while both follower categories share some similarities with each other. It however appears that late followers are most similar to laggards, while early followers resemble leaders.

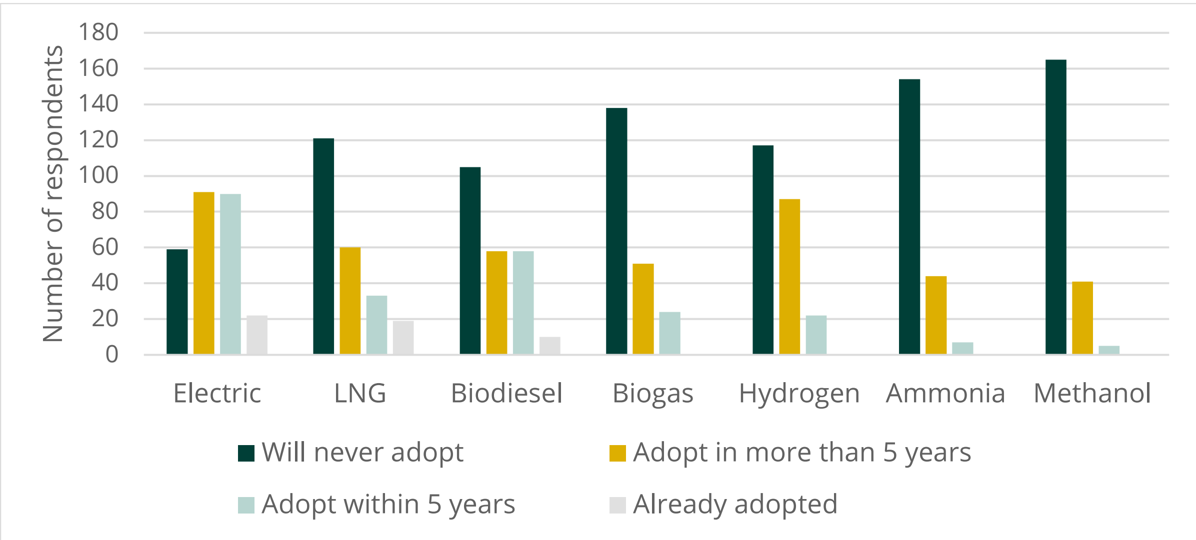
Table 2 Ship-owner green fuel adopter groups

Name and size of group	**Laggards** *N*=37	**Late followers** *N*=97	**Early followers** *N*=108	**Leaders** *N*=39
Green fuel adoption	***Never***	***More than 5 years*** Electric (77%) Biodiesel (45%) Hydrogen (42%) LNG (39%) Biogas (30%) Methanol (23%) Ammonia (21%)	***Within 5 years*** Electric (72%) Biodiesel (46%) LNG (28%) Biogas (13%) Hydrogen (15%) Ammonia (4%) Methanol (4%)	***Already adopted*** Electric (56%) LNG (49%) Biodiesel (26%) Methanol (0%) Biogas (0%) Hydrogen (0%) Ammonia (0%)
Number of employees in firm	***Micro and small*** 1-9 (73%) 10-49 (24%) 50-249 (0%) 250 or more (3%)	***Micro and small*** 1-9 (72%) 10-49 (25%) 50-249 (3%) 250 or more (0%)	***Micro to medium*** 1-9 (41%) 10-49 (31%) 50-249 (18%) 250 or more (10%)	***Micro to large*** 1-9 (15%) 10-49 (21%) 50-249 (18%) 250 or more (46%)
Age of firm (in years)	***Very young to middle-aged*** 1-10 (41%) 11-20 (33%) 21-40 (21%) 41 or more (5%)	***Very young to middle-aged*** 1-10 (36%) 11-20 (28%) 21-40 (26%) 41 or more (9%)	***Very young to old*** 1-10 (30%) 11-20 (23%) 21-40 (20%) 41 or more (27%)	***Young to old*** 1-10 (8%) 11-20 (23%) 21-40 (28%) 41 or more (41%)
Fleet size (number of vessels)	***Small to medium*** 1-3 (78%) 4-10 (19%) 11 or more (3%)	***Small to medium*** 1-3 (81%) 4-10 (16%) 11 or more (3%)	***Small to large*** 1-3 (53%) 4-10 (23%) 11 or more (23%)	***Small to large*** 1-3 (28%) 4-10 (18%) 11 or more (54%)
Age of fleet (in years)	***Young to old*** 1-10 (27%) 11-20 (24%) 21-30 (22%) 31 or more (27%)	***Young to old*** 1-10 (31%) 11-20 (27%) 21-30 (18%) 31 or more (24%)	***Young to middle-aged*** 1-10 (39%) 11-20 (31%) 21-30 (18%) 31 or more (13%)	***Young to middle aged*** 1-10 (51%) 11-20 (38%) 21-30 (8%) 31 or more (3%)
Domestic vs. International	***Domestic majority*** (76%)	***Domestic majority*** (72%)	***Balanced*** (53%) domestic	***International majority*** (59%)

Segments (Top 4 reported)	Coastal fishing (57%) International cargo (11%) Ship lessors (8%) Multiple other segments, each at (5%)	Coastal fishing (54%) Sea fishing (13%) International cargo (8%) Domestic passenger (7 %)	International cargo (28%) Coastal fishing (25%) Aquaculture (13%) Sea fishing (10%)	Offshore oil & gas (26%) International cargo (21%) Domestic passenger (11%) Coastal fishing (11%)

Figure 1 shows the adoption in terms of different green fuels. Here we see that some ship-owners have already adopted electric battery, LNG, and biodiesel. In addition, these same fuels are also expected to be the most adopted green fuels within the next 5 years. Meanwhile, 49 percent or more of the ship-owners responded that they would never adopt biogas, ammonia, or methanol. Given the immaturity of these fuels, with lacking availability in ports as well as need for adaptation of onboard machinery and propulsion systems, this is not surprising.

Figure 1. Estimated adoption timeframe of green fuels in percent. N=281 (some respondents did not answer all options).



3.2 ANOVA results

3.2.1 Firm characteristics

The ANOVA results outlined in Table 3 reveal substantial differences between the ship-owner groups. We see a general pattern of ascension from laggards to leaders in variables, excluding fleet age which is descending. Specifically, leaders are generally larger, older, and more international than the other groups, and they have the youngest fleets. Leaders are followed by early majority followers across variables. Finally, laggards and late majority followers are generally smaller, younger, have older vessels and a more domestic focus in their operations than the other two groups. Based on the post-hoc tests we can see that the laggards and late majority followers are often significantly different from one or both of the other groups, but not from each other, which is similar to the patterns observed in Table 2.

Table 3 ANOVA results for ship-owner characteristics

	Item	**Mean**	**SD**	**A) Laggards**	**B) Late followers**	**C) Early followers**	**D) Leaders**	**F-value**	**Tukey HSD comparison**
Characteristics	***No. of employees***	3.49	2.03	2.54	2.54	3.93	5.54	33.42***	A, B < C < D
	Firm age	3.34	1.60	2.73	3.00	3.48	4.36	9.63***	A, B, C < D
	No. of vessels	2.69	1.85	1.95	1.88	3.07	4.38	26.24***	A, B < C < D
	Age of vessels	3.49	1.85	3.92	3.83	3.33	2.67	5.10**	A, B > D
	Domestic (1) vs. international (2)	1.39	0.49	1.24	1.28	1.47	1.59	6.33***	A, B < C, D

Note. 1-7 measurement scale for all variables except domestic vs. international. Tukey's comparisons: A=Laggards, B=Late majority followers, C=Early majority followers, D=Leaders.
****p*<.001, ***p*<.01, **p*<.05

3.3.2 Green fuel types and modifications

We analyzed key differences in adoption of green fuel types with ANOVA (Table 4). From the mean scores and the F-values, we observe notable differences between the four groups, which is expected since the categories were based on green fuel adoption estimates. For example, the laggards are least positive for adoption of all types of green fuels. The groups also get progressively more optimistic heading toward the leaders. The Tukey's comparisons show there are significant differences between at least two groups in all green fuel and green modification variables. Additionally, we see that the laggards and late followers are more often together (not significantly different from each other), while the early followers and leaders are more often "in the same boat".

Our survey also asked ship-owners regarding the adoption of green modifications in ship designs, maintenance and operations. We use these measures to provide a point of comparison for green fuel adoption. Green modifications are arguably more incremental and easier to implement than green fuels. Interestingly, as presented in Table 4, the results show that the green fuel laggards were laggards also in the adoption of green modifications, while green fuel leaders and early-followers were early-movers. This shows that our groupings applied also to the adoption of other green improvements, which lends support to our groupings and overall findings.

TABLE 4 ANOVA RESULTS FOR GREEN FUEL TYPES AND MODIFICATIONS

	Item	Mean	SD	A) Laggards	B) Late majority followers	C) Early majority followers	D) Leaders	F-value	Tukey HSD comparison
Green fuels	***Electric***	3.79	2.00	1.00	2.84	4.92	6.05	169.46***	A < B < C < D
	LNG	2.60	2.02	1.00	1.90	3.03	4.88	39.83***	A < B < C < D
	Biodiesel	2.89	2.03	1.00	2.26	3.76	4.22	32.83***	A < B < C, D
	Biogas	1.91	1.47	1.00	1.67	2.24	2.80	11.86***	A, B < C, D
	Hydrogen	2.15	1.44	1.00	1.94	2.62	2.80	16.04***	A < B < C, D
	Ammonia	1.51	1.05	1.00	1.41	1.68	2.00	6.24***	A < B, C < D
	Methanol	1.47	1.05	1.00	1.41	1.63	1.66	3.32*	A < C
Modifications	***Design – drag* reduction**	4.14	2.36	2.70	3.60	4.72	5.35	13.02***	A, B < C, D
	Design – emission reduction	3.84	2.35	2.35	3.28	4.57	4.71	13.18***	A, B < C, D
	Maintenance	6.18	1.66	5.35	6.15	6.34	6.67	4.68**	A < C, D
	Operations	6.27	1.78	4.77	6.31	6.52	6.82	11.39***	A < B, C, D

Note. 1-7 measurement scale where 1=will never adopt and 7=already adopted. Tukey's comparisons: A=Laggards, B=Late majority followers, C=Early majority followers, D=Leaders.
***$p<.001$, **$p<.01$, *$p<.05$

3.3.3 Perceived barriers and motivations

Table 5 outlines ANOVA results on ship-owners' barriers and motivations for adoption of green fuels. Laggards see higher barriers than the other groups. Mean scores of the various perceived barrier items generally get progressively smaller going from laggards toward leaders, who thus see the lowest barriers. There are two items representing information barriers with high and significant F-values, i.e. lack of information (F=6.22, p<.001) and lack of knowledge (F=9.05, *p*<.001)[2], indicating that leaders perceived these barriers to be lower than other groups. Additionally, there are two barrier items with low but significant F-values, namely, public policy (*F*=3.39, *p*<.05) and lack of suppliers (*F*=3.23, *p*<.05), showing that again leaders perceived relatively lower barriers. Outside of these there are no other statistically significant differences between groups on barriers. We can nevertheless note that the highest perceived barrier in all four adopter groups was the economic item of high investment costs (*M*=4.13).

Regarding motivations, laggards claim the lowest scores of all groups and the mean scores of motivations generally ascend going toward leaders. Unlike barriers, most motivation items see significant differences between at least two groups. Competitive motivations (see "C" motivations in Table 5) stand out, with all four items having relatively large F-values. Leaders and early followers had higher competitive motivations than late followers and laggards. Among all motivations, competitive advantage has the highest F-value (*F*=17.91, *p*<.001), while the lowest significant difference is found relative to the legitimacy item covering rules and regulations (*F*=2.70, *p*<.05). We also observe that early followers and leaders have few significant differences between each other and the same can be seen between laggards and late followers. Lastly, the highest overall motivation is the environmental motivation, i.e. that it is important to contribute to a better environment (*M*=4.28).

TABLE 5 ANOVA RESULTS FOR BARRIERS AND MOTIVATIONS TO ADOPT GREEN FUELS.

	Item	M	SD	A) Laggards	B) Late followers	C) Early followers	D) Leaders	F-value	Tukey HSD comparison
Ba	*High investment costs (Ec)*	4.15	1.08	4.33	4.30	4.06	3.86	1.96	

[2] 'Lack of information' refers to an experienced lack of publicly available information about new technologies/green fuels. Lack of knowledge refers to experienced lack of knowledge within the company about new technologies/green fuels.

	Difficult to finance (Ec)	3.85	1.09	3.93	3.93	3.86	3.60	0.82	
	Insufficient support from public policy (Ec)	3.79	1.15	3.79	3.94	3.84	3.24	3.31*	B, C > D
	Lack of information on green fuels (Inf)	3.39	1.17	3.44	3.69	3.34	2.71	6.36***	A, B, C > D
	We lack knowledge on green fuels (Inf)	3.34	1.25	3.30	3.79	3.21	2.60	9.05***	B > C > D
	Lack of infrastructure. (SC)	3.75	1.15	3.74	3.76	3.88	3.40	1.50	
	Lack of suppliers (SC)	3.41	1.15	3.30	3.64	3.39	2.97	3.02*	B > D
	Changes in green fuels difficult to predict (TU)	3.48	0.98	3.46	3.45	3.57	3.32	0.56	
	Changes in green fuels dependent on many factors (TU)	3.87	0.91	3.85	3.95	3.85	3.71	0.61	
Motivations	*Financially prudent. (C)*	4.11	1.06	3.61	3.91	4.40	4.22	6.10**	A, B < C
	Will give us competitive advantage (C)	3.88	1.14	3.11	3.45	4.28	4.46	19.19***	A, B < C, D
	Will lead to long-term profitability (C)	4.16	1.08	3.41	3.94	4.46	4.43	10.20***	A, B < C, D
	Benefits outweigh costs (C)	3.43	1.16	2.79	3.25	3.79	3.37	7.37***	A, B < C
	We are required to (L)	3.55	1.09	2.93	3.40	3.74	3.85	5.95**	A < C, D
	Will improve firm's image. (L)	3.86	1.08	3.07	3.64	4.09	4.39	11.96***	A < B < C, D
	We feel pressure to. (L)	3.18	1.17	2.86	3.04	3.35	3.31	1.96	
	We need to follow rules and regulations. (L)	3.96	1.11	3.46	3.87	4.07	4.26	3.31*	A < D
	Helping environment is right thing to do. *(En)*	4.24	0.93	3.63	4.16	4.41	4.40	5.96**	A < B, C, D
	Important for us to contribute to better environment. (En)	4.29	0.92	3.86	4.24	4.39	4.49	3.14*	A < C, D

	Helping environment helps us feel good. (En)	3.69	1.12	3.52	3.72	3.85	3.31	2.18	
	Our responsibility to do it. (En)	4.00	1.05	3.39	3.87	4.26	4.09	5.96**	A, B < C, D

Note. 1-5 measurement scale where 1=full disagreement and 5=full agreement. Barriers: (Ec)=Economic, (Inf)=Information, (SC)=Supply chain, (TU)=Technological uncertainty. Motivations: (C)=Competitive, (L)=Legitimacy, (En)=Environmental. Tukey's comparisons: A=Laggards, B=Late majority followers, C=Early majority followers, D=Leaders. *** $p<.001$, ** $p<.01$, * $p<.05$.

4. Discussion

A typical storyline in the green innovation literature is that leaders are new entrant firms, while large incumbents tend to resist change, and act as followers or laggards (Christensen 2003, Hockerts and Wüstenhagen 2010). While our exploration of Norwegian ship-owners also identifies significant firm differences in relation to the adoption of green fuels, adoption leaders were however mainly large and well-established ship-owners, while laggards were mainly young and small ship-owners. It seems that very recently a small but distinct group of Norwegian ship-owners has emerged, who have adopted green fuels. This sets them apart from the majority of Norwegian ship-owners, who still express widespread skepticism about green fuels and efficiency measures to mitigate climate changes.

Some of the leader companies operate vessels on relatively short and predictable routes within offshore and passenger shipping (see Table 2). For instance ferries have lower energy requirements than large deep sea vessels, which facilitates the adoption of green fuels, and both segments are subject to specific Norwegian customer demands for green fuel adoption. Demands come especially from public procurement in ferry shipping and from the Norwegian energy company Equinor in offshore shipping. Laggards and late followers mainly come from coastal fisheries, which generally do not face customer requirements for adoption of green fuels. Operating under a fishing licensing system, fishing companies compete for licenses, and GHG abatement is currently not included as a decision variable in this system.

In international tanker and dry bulk shipping, Poulsen et al. (2021, 2016) found weak cargo-owner demands for emissions abatement and major ship-owner difficulties in relation to environmental upgrading investments beyond energy efficiency. Nevertheless, we now find some Norwegian ship-owners engaged in international cargo shipping among green fuel adoption leaders and early followers. This suggests that a recent change in some international cargo ship-owners' perspectives on green fuels may have occurred. It also suggests that the national climate mitigation agenda in Norway spills over also to Norwegian ship-owners who do not operate only on Norwegian waters.

We found that ship-owners quest for long-term profitability, competitive advantage, and improved public image were important motivations for leaders and early-followers. While our survey data does not allow us to explain why, recent studies provide relevant elaborations. Steen et al. (2019) found that some shipping companies no longer see 'business as usual' – characterized by fossil fuels and significant GHG emissions – as viable, and Saether et al. (2019) argued that some Norwegian ship-owners now attempt to secure future market opportunities through adoption of green fuels. Stalmokaitė and Hassler (2020) had similar findings.

Our survey data and these studies indeed suggest that the environmental management strategies of major ship-owners may no longer be only dominated by a 'crisis-oriented' approach (van Leeuwen and van Koppen 2016) and a strong preference for a wait-and-see strategy in relation to green fuels (Rojon and Dieperink, 2014). Instead, some major ship-owners are adopting a more proactive approach in green fuel adoption, possibly anticipating stronger environmental regulations and/or increasing demand for GHG abatement.

We found environmental regulation to be of relatively low importance for Norwegian ship-owners' adoption of green fuels, although leaders reported higher regulatory motivations than laggards. As the Norwegian government and the Norwegian Ship-owner's Association have recently raised the ambition level in reducing the emissions of shipping, we speculate that these results may also point to expectations regarding future regulatory changes.

As far as environmental motivations for green fuel adoption are concerned, we found that such are strongest among leaders and early-followers, but they also seemed to matter for late-followers and laggards. Thus, environmental motivations and awareness about climate change alone do not seem to be enough to motivate ship-owners to adopt green fuels.

Unsurprisingly, all ship-owners in our sample found high investment cost and financing difficulties as major barriers for green fuel adoption, but leaders could more easily overcome them. Moreover, leaders seemed to possess more knowledge about green fuels. They also generally had large fleets, which allows them to more easily experiment with green fuels on a limited number of vessels. This reduces the overall risk associated with the new technologies, which are higher for smaller companies with fewer vessels (often only one). As Steen et al. (2019) point out, large firms may also have advantages in relation to applying for public R&D funding in relation to green fuels. These findings suggest that the ship-owners' resources (e.g., knowledge, finances, and vessels) may affect the likelihood of adoption of green fuels, and this topic merits further research attention.

5. Conclusion and policy implications

In a survey of Norwegian ship-owners' adoption of green fuels, large and old firms with relatively new fleets engaged in offshore supply, international cargo, and passanger shipping stand out as adoption leaders. In contrast, small and young firms with old fleets, especially within coastal fisheries were generally laggards or late adopters. Awareness about environmental issues is generally high among Norwegian ship-owners, but such considerations alone have not driven the option of green fuels. Instead, many leaders were subjected to emission reduction requirements by their Norwegian public and private customers, whereas such pressures were largely absent for laggards in e.g. coastal fisheries. For the relatively small group of leaders as well as early followers, quest for long-term profitability, competitive advantage, and improved public image were important motivations for adoption of green fuels. This may suggest that they anticipate stricter GHG regulation and/or customer demand in the near future.

Previous studies have pointed out that ship-owners predominantly have 'crisis-oriented' environmental management strategies and a strong preference for wait-and-see in relation to green fuels. In Norway, however, a small, but distinct group of adoption leaders, who think differently about these matters, has recently emerged. It is noteworthy that some international cargo ship-owners belong the early adopter group, and this might suggest that the national climate mitigation agenda has spilled over also on ship-owners who operate far from Norwegian waters.

5.1. Policy implications

In identifying the main characteristics of green fuel adoption leaders and laggards in Norway, our study has implications for national as well as international policymakers.

Norwegian policymakers should be particularly aware of the small and new companies, mainly in coastal fisheries, which do not intend to adopt green fuels. These companies do not seem to have resources to experiment with green fuels or apply for public R&D funding for such ventures, and they do not experience any strong market pressures to do so. Our results thus suggest that while the conditions for green fuel adoption have been somewhat conducive in Norway for large and established ship-owners, smaller companies in general have been less able to follow suit. Hence, companies with limited in-house resources and capabilities may require additional support through financing and competence building opportunities. Moreover, Norwegian as well as other national policymakers may consider designing R&D support programs specifically for such shipping companies, and possibly include GHG abatement as a decision criterion when granting e.g. fishing licenses.

Our results suggest that market-pull mechanisms rolled out by both public and private actors may be effective in driving green fuel adoption. Many leader firms were from market segments which had been subjected to emission reduction requirements in contracting mechanisms, such as passenger vessels and offshore supply vessels, governed by publicly owned organizations. While similar governance mechanisms may not be applicable in all market segments, early adoption in some segments may create important niche markets for green fuels, thus driving the important innovation processes of e.g. experimentation, demand and learning around green fuels (cf. Bach et al. 2020). These processes are likely to result in cost reductions, building of infrastructure, diminishing technological uncertainty and knowledge building, thus reducing barriers for broader adoption. Active market creating governance by national policymakers, e.g. through public procurement for innovation, may thus be a crucial policy mechanism in stimulating the emergence of early niche markets for green fuels in shipping.

Our results also show that even in a front-runner country like Norway, green fuel adoption in shipping is yet in an early phase. It is therefore still necessary to support green fuel innovations with technology push mechanisms, such as with R&D funding. Battery-electric technology appears to have momentum and are most widely adopted, but it should be noted that batteries are unlikely to generate major GHG emission reductions in shipping globally. In our survey, green fuels such as ammonia and hydrogen that have higher potential for emission reductions (due to their applicability in vessels with longer operational distances) were seen as solutions for the more distant future. For the global shipping sector to meet its emission reduction targets, R&D support related to such green fuels is crucial, including in e.g. infrastructure and other complementary technologies.

On an international scale, policy makers should consider how to support the emergence of market pull mechanisms, similar to those observed to incentivize green fuel adoption in domestic shipping in Norway. In international cargo shipping, governments are not the main customers, and they can only use their procurement policies to incentivize green fuel adoption to a limited extent. It is therefore important that they support the development of market pull mechanisms, which can cause key shipping customers (e.g. oil majors, commodity traders and major consumer goods companies) to demand emissions reductions from ship-owners.

5.3. Limitations and future studies

Our findings have provided some of the first systematic insights on ship-owners' adoption of green fuels in a frontrunner country. The results should be of interest and relevance also beyond the Norwegian context. However, our study is not without limitations.

First, we define adoption leaders as any ship-owner who has adopted at least one green fuel onboard one vessel. Thus, we do not distinguish between ship-owners who have equipped only one ship with a battery-storage system for ‘peak-shaving’, and ship-owners with more comprehensive decarbonization initiatives in their entire fleet. However, as the adoption of green fuels in shipping is yet a marginal phenomenon, we believe our operationalization of 'adoption' to be valid.

Second, we did not analyze how the preferred green fuels may have affected the perceived motivations and barriers. This can be relevant as some more mature technologies, like battery-electric, may not be applicable in some shipping segments. Responses may therefore be affected by a perceived lack of available green fuels both now and in coming years. The connection between the availability of green fuel solutions in different shipping segments and ship-owners’ attitudes and expectations to adoption thus remains an important topic for future studies.

Third, our study concerned ship-owners in Norway, which is a center for maritime technology development and has a government with more ambitious GHG abatement goals than the IMO. We suggest that further studies should study green fuel adoption in other major ship-owning countries, to explore how national contexts may affect ship-owners’ decarbonization efforts.

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Appendix

Table A1. Survey measures

Variable/construct	Response question, scale, and items
Firm age (year of establishment)	In what year was your firm established? **1** = 2015-2019, **2** = 2010-2014, **3** = 2000-2009, **4** = 1980-1999, **5** = 1950-1979, **6** = 1900-1949, **7** = before 1900
No. of employees	How many employees does your firm have? **1** = 1-2, **2** = 3-5, **3** = 6-9, **4** = 10-19, **5** = 20-49, **6** = 50-249, **7** = 250 or more
No. of vessels	How many vessels does your firm own? **1** = 1, **2** = 2-3, **3** = 4-5, **4** = 6-10, **5** = 11-20, **6** = 21-30, **7** = 31 or more
Age of vessels (in years)	On average, how old are your vessels? **1** = 0-5, **2** = 6-10, **3** = 11-15, **4** = 16-20, **5** = 21-30, **6** = 31-40, **7** = 41 or more
Segment *(D) = domestic* *(I)= international*	What segment does your firm primarily belong to? (choose one) *sea fishing (I); coastal fishing (D); international cargo (I); domestic cargo (D); international passenger (I); domestic passenger (including car ferry) (D); offshore supply and services (I); ship lessors (I); tug services (D); other*
Green fuel adoption	When do you expect your firm to adopt the following technology/fuels on at least one of your vessels? **1** = will never adopt, **2** = over 20 years, **3** = within 20 years, **4** = within 10 years, **5** = within 5 years, **6** = within 2 years, **7** = already adopted *Electric; LNG; Biodiesel; Biogas; Hydrogen; Ammonia; Methanol*
Green modifications adoption	When do you expect your firm to adopt the following modifications, maintenance, or operations on at least one of your vessels? **1** = will never adopt, **2** = over 20 years, **3** = within 20 years, **4** = within 10 years, **5** = within 5 years, **6** = within 2 years, **7** = already adopted *Design modifications to reduce drag (e.g. rotor sails, streamlined hull, ligher materials, aerodynamic improvements, propellers with fins, copper hull, etc.); Design modifications for cleaner or reduced emissions (e.g. scrubber, carbon capture, etc.); Environmentally friendly maintenance (e.g. polarizing propellers, cleaning ships to reduce drag, etc.); Environmentally friendly operations (e.g. sailing slower, using more efficient routes, etc.)*
Barriers (Ec) = Economic, (Inf) = Information, (SC) = Suply chain, (TU) = Technological uncertainty	My firm is hindered from adopting emission-reducing technology/fuels because . . . **1** = completely disagree, **2** = slightly disagree, **3** = neither disagree nor agree, **4** = slightly agree, **5** = completely agree *. . . of high investment costs. (Ec)* *. . . it is difficult to finance. (Ec)* *. . . there is insufficient support from public policy. (Ec)* *. . . there is a lack of information on ECs. (Inf)* *. . . we lack knowledge on ECs. (Inf)* *. . . there is a lack of infrastructure. (SC)* *. . . there is a lack of suppliers. (SC)* *. . . changes in ECs are difficult to predict. (TU)*

	. . . changes in ECs are dependent on many factors. (TU)
Motivations (C) = Competitive, (L) = Legitimacy, (En) = Environmental	My firm is interested in adopting emission-reducing technology/fuels because . . . **1** = completely disagree, **2** = slightly disagree, **3** = neither disagree nor agree, **4** = slightly agree, **5** = completely agree *. . . it is financially prudent. (C)* *. . . it will give us competitive advantage. (C)* *. . . it will lead to long-term profitability. (C)* *. . . the benefits outweigh the costs. (C)* *. . . we are required to. (L)* *. . . it will improve our firm's image. (L)* *. . . we feel pressure to. (L)* *. . . we need to follow rules and regulations. (L)* *. . . helping the environment is the right thing to do. (En)* *. . . it is important for us to contribute to a better environment. (En)* *. . . helping the environment helps us feel good. (En)* *. . . it is our responsibility to do it. (En)*

Table A2 Green fuel adoption groups and respective shipping segments

	Laggards	***Late majority***	***Early majority***	***Leaders***	Total
Sea fishing	1	13	11	2 (1 electric; 1 biodiesel)	27
Coastal fishing	20	52	27	4 (3 electric; 1 biodiesel)	103
Aquaculture	2	4	14	3 (1 electric; 2 biodiesel)	23
Domestic passenger (including ferries)	2	7	12	5 (4 electric; 2 LNG; 3 biodiesel)	26
International passenger	0	1	1	2 (1 electric; 1 LNG; 1 biodiesel)	4
Domestic cargo	2	5	2	3 (3 LNG)	12
International cargo	4	8	30	8 (3 electric; 5 LNG; 2 biodiesel)	50
Offshore supply and services	1	1	3	10 (9 electric; 6 LNG)	15
Ship lessors	3	4	6	1 (1 LNG)	14
Tug services	2	2	2	1 (1 LNG)	7
Total	37	97	108	39	281

Note. Alternative fuels in parentheses are used to denote those already adopted.

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