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The implementation of technical energy efficiency and CO_2 emission reduction measures in shipping

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ABSTRACT

Numerous energy efficiency and carbon reduction technologies have been identified within the shipping sector but their overall implementation remains unknown. It is important to know the implementation in order to establish a credible baseline and evaluate progress towards low carbon shipping. Using a cross-sectional survey of shipowners and operators this paper attempts to gauge the implementation of over thirty energy efficiency and CO_2 emission reduction technologies. The results show that whilst there is a good spread of implementation across the different measures, only a select number of measures in each of the categories are implemented at sufficient scale. Secondly, the measures with high implementation have tended to be those that have small energy efficiency gains at the ship level, and the uptake of CO_2 reducing technologies, particularly alternative fuels is low despite their high potential for reducing CO_2 emissions. If shipping's emissions are to be in line with other sectors in the future and follow a decarbonisation pathway, it would require higher implementation of energy efficiency and CO_2 reducing technologies than those driven by current regulations alone.

1. Introduction

The shipping sector, through its exhaust emissions, is a major contributing source of several greenhouse gases and non-greenhouse gases, yet the sector was left out of the Paris Agreement (UNFCCC, 2015) and the control of emissions from the sector were left to the designated UN body, the International Maritime Organisation (IMO). The current emissions of the sector constitute of around 2% of global CO_2 emissions (Smith et al., 2014) but are likely to represent around 17% of CO_2 emissions under the business as usual scenario by 2050 (Cames et al., 2015) due to the rising demand for shipping and the reducing emissions from other sectors. Several solutions exist for shipping to mitigate its emissions and transition towards low carbon shipping;

a) Improving energy efficiency e.g. cost-effective operational measures and practices as well as using energy efficient technologies (normally resulting in a reduction in fuel consumption),
b) Using renewable energy sources e.g. wind propulsion
c) Using fuels with lower carbon content e.g. biofuels
d) Emission reduction technologies e.g. scrubbers and carbon capture and storage (CCS).

The IMO Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) aim to target the implementation of these measures in order reduce the CO_2 emissions from the shipping sector. The EEDI requires all newly built ships built from 2013 onwards to meet mandatory reduction targets, which increase in stringency every five years up until 2030. The EEDI provides a measure of the CO_2 emissions per cargo carried, measured in gCO_2/t nm. Whilst the primary aim of the EEDI regulation as a standard is to reduce emissions from ships over time, as a matter of public interest (and public regulation) the data that is generated from the EEDI standard is not publicly available and the limited data that is available through access to IMO is currently anonymised and does not report any detail on what innovative technologies or measures are being used. The lack of information disclosure from this regulation fails to garner the social and market pressure resulting from information disclosure (Tietenberg, 1998; Foulon et al., 2002).

Currently the implementation of energy efficiency and CO_2 reducing technologies by IMO, (2014, 2015, 2016) shows only two columns with binary fields (Yes/No) on implementation of the fourth and fifth terms (use of innovative electrical and mechanical energy efficiency technologies) of the EEDI. A review of IMO (2016) shows that for example, no bulk carriers (out of 356 ships) had implemented any innovative technologies, yet achieved around 15% reduction relative to the reference values. This leaves the discussion open as to what technologies have been implemented to achieve the emission reductions. Have

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the emission reductions and efficiencies been gained through better design, machinery, and decrease in design speed or increase in capacity, or any combination of these? The information gap has led to analysts using various other methods to answer the question. Faber et al. (2016) use publicly available information obtained from Clarksons to calculate an estimated EEDI for existing ships. As an example they show the estimated average EEDI for bulk carriers decreasing over the period 2009–2015. They suggest this is a result of changes in ship design and not due to innovative technologies, and due to the ratio between displacement and engine power improving over time rather than the typically assumed suggestion of design speed reduction.

The EU's recently adopted Regulation on the Monitoring Reporting and Verification of shipping emissions (EU-MRV) will to an extent tackle the lack of transparency by making the data publicly available on operational emissions (Scott et al., 2017). However, this regulation will also not provide adequate information on the extent of technologies being implemented. The only parameter that may provide some suggestions is the 'fuel used' as mandated under Article 6(3) of the Regulation. Moreover, due to the regional nature of the regulation, there will be issues around coverage and therefore a complete picture will not be gained on the implementation of technologies. The aforementioned regulations therefore do not provide sufficient information on the implementation of technologies, which as suggested have an important role in transitioning the shipping sector towards decarbonisation as implied by the Paris Agreement.

2. Literature review

On the implementation of cost-effective operational measures Rehmatulla and Smith (2015a) and Rehmatulla and Smith (2015b), show that the uptake of cost-effective operational measures centred only around three measures, general speed reduction, fuel consumption monitoring and weather routing. The lower implementation of these and other cost effective measures, such as Just In Time or virtual arrival is due to barriers such as the split incentives, that exhibit in various charterparties. There is also good data available on some energy efficient operational measures such as speed reduction, routing and capacity utilisation through the use of Satellite Automatic Identification System S-AIS as presented by Smith et al. (2013) and Smith et al. (2014).

Regarding the implementation of technical energy efficiency measures only a handful of attempts have been made. None of these except for Rojon and Smith (2014) are academic studies and therefore lack methodological rigour for example in the way the samples have been recruited and the way survey was designed and executed. The first study that attempted to gauge the implementation of technical measures energy efficiency measures was by Faber et al. (2011). The study surveys five shipowners and operators using semi-structured interviews. Individual measures are grouped according technical, alternative fuels and operational measures and implementation rates (as %) are calculated by asking the respondents whether they have implemented the specific measure. Whilst the sample size is extremely small, the study shows varying implementation between operational and technical energy efficiency measures. Across the fifteen operational measures, the average implementation rate is just over 60%, close to that observed in Rehmatulla and Smith (2015a). The technical measures are categorised as resistance reducing measures, engine related measures, other technical measures and alternative fuels. Engine related measures are the most implemented, by the four firms that responded, with average across the measures being just over 50%, followed by resistance reducing measures at 40%, other technical measures (e.g. waste heat recovery) averaging 35% and alternative fuels averaging 14% across the measures.

HSH Nordbank (2013) surveyed the implementation of technical energy efficiency measures in its portfolio of shipowners. Sixty shipping companies responded but it is not known what response rate this represents and nor is this a representative sample of shipping companies. The study starts with a general approach asking respondents on their strategy to implement energy efficiency measures, 49% of the respondents used new building as an opportunity to implement technical energy efficiency measures (of these 94% used an energy efficient design over a standard design) and 42% of the respondents used retrofitting to implement technical energy efficiency measures. With regards to retrofitting the firms were either implementing only in some of their fleet e.g. almost 40% of the respondents applied retrofits to under 10% of their fleet, and almost a third of the respondents had implemented the measures in more than 50% of their fleet. Most popular retrofit technical energy efficiency measures at 33% were optimisation or modification of rudder and or propeller, followed by design optimisation of bulbous bow and the hull, which was implemented by 20% of the respondents.

Rojon and Smith (2014) survey of 130 shipowners and operators shows that 58% of the respondents made machinery modifications and 55% made propeller modifications to their fleet in the last five years, this level is similar to that suggested by HSH Nordbank (2013) and Faber et al. (2011). Whilst the survey had a good sample of respondents, and the data is disaggregated by ship type and type of company, the survey lacks details on the size of the ships on which the measures are implemented and whether the measures were retrofitted or for newbuilds.

DNV GL (2014) survey seventy five shipowners, operators and management companies and focus on the implementation of twenty one energy efficiency measures, which includes nine technical energy efficiency measures and twelve operational energy efficiency measures. The results are corroborative of those found in the earlier studies, but with a higher average of around 75% implementation across all the measures and high implementation of operational measures (slow steaming), maintenance strategies (hull cleaning and hull coatings) and retrofitting of energy saving devices. The survey respondents have the best representation geographically compared to the aforementioned studies, although 45% of the respondents come from Germany and Greece.

IMarEST and Colfax (2015) survey of eighty two shipowners, operators and charterers attempts to gauge the implementation in some detail e.g. whether the company has already implemented, planning to implement or will not implement a particular measure as suggested by Tornatzky and Klein (1982). Combining the 'already implemented' and 'planning to implement' categories, the average for the energy efficiency measures is quite high for alternative energy sources and lower for machinery measures, design measures and operational measures compared to previous studies. Table 1 provides a summary of the key findings from the aforementioned studies.

The surveys conducted to date to assess the current implementation of technical energy efficiency measures have lacked methodological rigour, for example in representing fairly the population due to use of biased sampling frames. This is a criticism which can be found in other diffusion studies such as lack of reliability, replicability and statistical power to generalize. Another methodological weakness has been the sample size of the studies, which has been low, in the region of 50–100, and is not enough to attain statistical significance even if the whole shipping population was deemed homogeneous. Moreover, the implementation of measures is generally at an aggregate level and at the firm level. Specific details of implementation have generally been left out, for example whether the measures were applied as retrofits or in newbuilds and the ship type and ship size in which the measures have been implemented.

This aim of this study is therefore to go further than the general level implementation of technical energy efficiency measures by assessing the implementation at the ship level, for example the implementation of a measure by ship type, ship size and number of ships and at the company level, for example the implementation of a particular measure

Table 1
Key findings and comments of the studies seeking to gauge implementation of technical energy efficiency measures in shipping.

Study	Year	Sample size	Key finding on implementation	Methodological comments
Faber, Behrends and Nelissen	2011	4	Engine related measures implementation – 50% Resistance reducing measures – 40%, Other technical measures – 35% Alternative fuels averaging – 14%	Very small sample
HSH Nordbank	2013	60	Optimisation or modification of rudder – 33% design optimisation of bow and the hull – 20%	Non –representative sample
Rojon and Smith	2014	130	Machinery modifications – 58% propeller modifications – 55%	Does not disaggregate data by ship size
DNV GL	2014	75	Engine related measures – 70% Hydrodynamic measures – 73%	Does not disaggregate data by ship type and size
IMarEST and Colfax	2015	82	High implementation for alternative fuels Lower implementation for other measures	Does not disaggregate data by ship type and size

by type of company and size of company. The second aim is to improve the methodological rigour by obtaining a representative cross-section of the population. This would allow to build an accurate picture of the take-up of the energy efficiency measures in shipping and to establish a credible baseline on the implementation of technical energy efficiency measures in shipping.

3. Method

This paper forms part of a series of methods for collecting data on implementation of technical energy efficiency measures, in order to validate the different data sets with each other. Table 2 briefly discusses each of the remaining methods, and their strengths and weaknesses.

A cross-sectional survey administered online was deemed to be the most appropriate research design, method and mode for collecting data, due to the global nature of the shipping sector. Since a cross-sectional survey approach was used, the findings will only be a 'snapshot' in time and therefore provides the best answer to what the current baseline on implementation of technical measures is in shipping. However, this does not limit the survey to be administered periodically to make into a longitudinal panel study, in order to observe changes in implementation rates over time. Whilst most technical measures' implementation means that the measure will be continuously used, it is important to note that implementation of some measures may not necessarily lead to usage, for example air lubrication and waste heat recovery.

This strategy was chosen in order to leverage from previous experience of using the Tailored Design Method (TDM) (Dillman, 2009) to administer the operational measures survey (Rehmatulla, 2014). The survey was conducted between January 2015 and March 2015, which was a period of regulatory and economic changes. The new IMO regulations on sulphur emissions were effective from January 2015, requiring a reduction on marine fuel Sulphur content from 1.00% to 0.10% in the Emission Control Areas (ECAs) or adoption of alternative solutions that achieve an equivalent effect. The effect of this regulation could be that shipping companies could be prioritising their investment to meet the Sulphur regulations over energy efficiency investments. This could have a large effect on the CO_2 emissions of a particular ship, such as in the case of investing in Liquid Natural Gas (LNG) instead of Marine Diesel Oil (MDO) or Heavy Fuel Oil (HFO), or have a small effect, such as investing in an Exhaust Gas Scrubber. A smaller effect can be suggested for the impending ballast water regulations. The IMO EEDI Phase 1 (2015–2019) also took effect in January 2015, requiring a 10% reduction in EEDI relative to the EEDI reference line for each ship type and size category. This would have a bias on the implementation of energy efficiency measures for new builds over existing ships. Finally, the HFO fuel price dropped to its lowest during the beginning of the year (under \$300 per tonne compared to \$600 per tonne over a year ago), which has an effect of increasing the payback period of various energy efficiency measures and therefore potentially affecting the investment decisions of firms considering their implementation.

The survey covered all the technical measures and excluded operational measures. The measures were collated from Buhaug et al. (2009), Lockley et al. (2011) and Wang et al. (2010) and grouped in the following categories; design measures, hydrodynamic measures, machinery measures, alternative energy measures, maintenance strategies and after-treatment measures.

Table 2
Other methods to collect data on implementation of technical energy efficiency measures.

	Method	Strengths	Weaknesses
1	Shipowning companies: case studies on implementation of measures (ongoing)	Can provide detailed insight into the decision making process ex ante and ex post results. Can reveal characteristics of diffusion of the measure within the fleet.	Results are not generalizable and can be resource and time intensive to collect the data.
2	Technology suppliers: data regarding sales and/or installations (ongoing)	Can provide an accurate picture of the implementation of a particular measure, especially where there are few monopoly suppliers.	Difficult to access data from some technology suppliers. Can suffer from coverage issues, when many suppliers provide a single technology.
3	Classification societies: data regarding newbuild designs/EEDI, approvals and installations of retrofits	Can provide a good picture of the measures implemented by customers of particular class societies. Obtaining data from top classification societies can lead to good coverage of the population.	Difficult to access data from some classification societies. Some classification societies do not record this information centrally (i.e. data held in different offices globally).
4	Shipyards & ship repair yards: data on retrofit installations during drydock/ad-hoc	Data from the largest shipyards can provide good coverage on measures being implemented.	Difficult to access data from most shipyards and fragmented industry especially drydock yards.
5	Banks and insurance providers: data on approvals and/or financing projects	Can generally show which measures are being retrofitted by the shipowners.	Can suffer from coverage issues as not all retrofits will be financed by banks

Table 3
Sampling frame.

Sector	Size	Europe	N & S America	Asia	Far East	Total
Large	Wetbulk	9	6	2	10	27
Large	Drybulk	4	3	1	10	18
Large	Container	13	0	0	11	24
Large	Mixed	23	1	4	21	49
Medium	Wetbulk	88	6	14	33	141
Medium	Drybulk	75	11	6	49	141
Medium	Container	37	4	2	14	57
Medium	Mixed	80	1	8	54	143
Small	Wetbulk					942
Small	Drybulk					685
Small	Container					146
Small	Mixed					163

3.1. Sampling strategy

The unit of analysis or the target population were global shipping companies, which were recruited from Clarksons Shipping Information Network (SIN) database of shipowners. In order to be representative, the study mainly uses a stratified sampling approach, complemented by a non-random sampling approach (e.g. memberships of associations). A list of all shipping companies globally was acquired from Clarksons Shipping Information Network and this was stratified according to the company's size, its sector of operation and geographical location. This study mainly focusses on the tanker (wetbulk), drybulk and container sector, which account for 60% of emissions from shipping (Smith et al., 2014) and account for over 85% of merchant vessels by tonnage (UNCTAD, 2016). Table 3 shows the target population i.e. number of firms which operated in each sector and size broken down by their geographical location (by headquarters). Note that the sampling frame could also be stratified according to the country of ownership and country of registration of the world fleet. However, the choice to stratify according to headquarters was because it was felt that there would be better chance of contacting senior level of management e.g. directors, technical managers and fleet managers.

Large firms (with fifty ships and above) represent only 5% of the population (just over 100 companies) but control almost 33% of the fleet. Similarly, medium size firms (between eleven and forty nine ships) represent around 20% of the population (around 500 companies) but control almost 33% of the fleet. Small size firms (10 ships and under) represent almost 75% of the population (just under 2000 companies) and control 33% of the fleet (Stopford, 2009). Therefore for the large organisations (118 companies) and medium sized companies (482 companies) the census approach was taken i.e. all the companies were included in the sample, called a census tracts approach.

A simple random sample was used to sample the significantly large tail of small sized firms (as shown in Fig. 1), the majority of these were single ship companies which are created to protect the beneficial owner of ships (Stopford, 2009). The sampling strategy was changed due to several reasons; in business surveys smaller firms are often difficult to reach (Eurostat, 2008), the sampling frame required merging and validating the Clarksons shipping company databases with other freely available databases, which was a resource intensive task and therefore the change sampling strategy was deemed to be an acceptable trade-off. It should also be noted that relative to previous studies mentioned in Section 3, the approach used in this study is a significant improvement in the methodology and therefore resulting in lower sampling and non-sampling errors (Groves, 1989). Nonetheless, small firms are still not better represented in the survey (in terms of their relative numbers) and therefore the survey results cannot be generalised to small firms. There has been very little research in shipping with regards to size of the firm and innovation attributes or characteristics, compared to the literature on size of the firm and innovation outside of shipping, see for example Rothwell and Zegveld (1982) and Rogers (2003) and refer to Rehmatulla et al. (2015) for more examples of these. In shipping both, Wijnolst and Wergelend (2009) and Jenssen and Randoy (2002) only provide a generic overview of the shipping sectors innovation in specific contexts and do not provide details on how the size of the firm influences innovation.

3.2. Respondent demographics

270 companies were contacted by phone and almost 200 companies responded, resulting in a 72% response rate. The remainder responses were received from various other sources e.g. membership databases and third party mailing lists. The survey received 275 responses in total representing almost 20% of the wetbulk, drybulk and container fleet (approximately 5500 ships out of 28,000 ships according to Smith et al., 2014). The response rates and the absolute number of responses received in this survey make it the largest of its kind in shipping. Fig. 2 shows that the responses from companies with medium sized fleets are approximately in proportion to the population but the survey possibly under-represents small firms in the shipping sector. Compared to the data shown in Section 4.1, the responses for large and medium size companies are over-represented in the sample. However, the increased focus on the large and medium sized companies results in higher number of ships being covered. In business surveys this strategy is common due to the difficulty in reaching small companies (Eurostat, 2008).

The following demographic questions asked the respondents to identify the fleet they operate and which company types would best describe their company structure. The questions did not have mutually exclusive choices i.e. had multiple response data. Fig. 3 shows that the majority of the respondents were mainly from the sectors that were of interest for this survey, i.e. tanker, drybulk and container sectors. The primary respondents to the survey were shipowners, shipowner-operators and management companies, as shown in Fig. 4. The survey also had responses from charterers that have ships on long-term time charter and cargo owning companies that own a shipping fleet to move

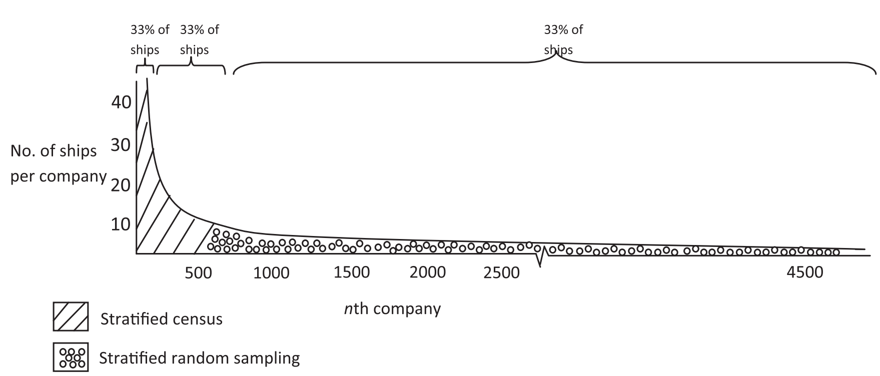

Fig. 1. Population frame and sampling strategy.

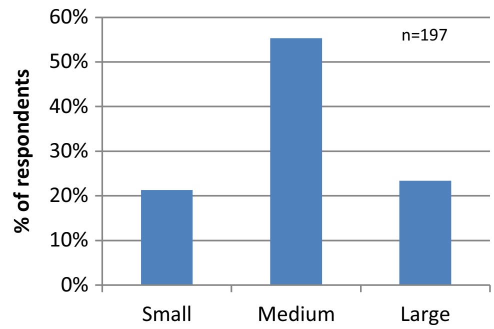

Fig. 2. Respondents by fleet size.[1]

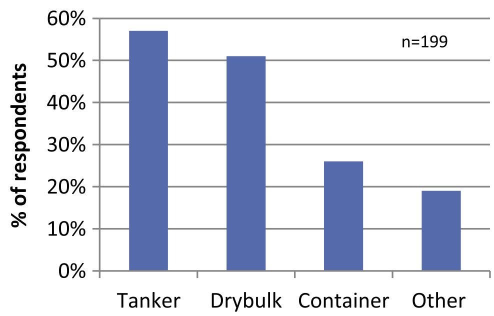

Fig. 3. Respondents by sector.

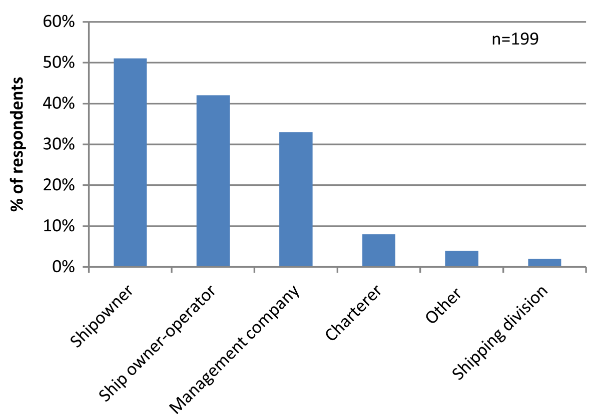

Fig. 4. Respondents by type of shipping company.

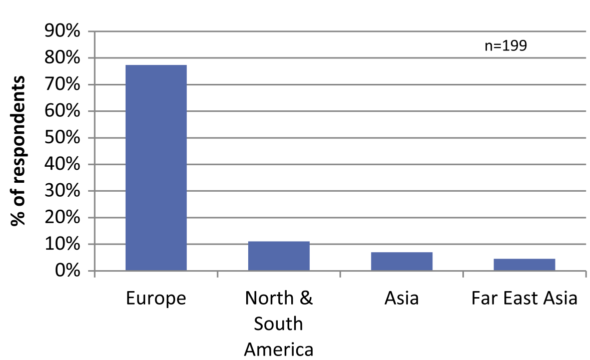

Fig. 5. Geographical distribution of survey respondents.

their own cargoes. Over half of the respondents were from senior level management consisting of technical directors, technical managers and fleet managers. They were followed by technical superintendents (including senior superintendents), sustainability or energy efficiency managers and project managers. Fig. 5 shows the geographical dispersion of the respondents. The majority of the responses were from companies headquartered in the EU, mainly in Greece and Germany. Comparing the responses received and the stratified sampling frame (Table 3) the survey over-represents respondents from EU, despite efforts to obtain responses from other regions, especially the Far East (which includes major shipping hubs e.g. Singapore, Hong Kong, China & Japan).

[1] The sample size varies per question due to missing responses for the demographic questions.

4. Results and discussion

This section shows the uptake of different technologies in the categories aforementioned. The Y axes of figures Figs. 6, 10, 14 and 18 show the implementation range in percentage of the total number of ships in which these measures have been implemented by the respondents. So for example, Fig. 6 shows that for bulbous bows, the implementation ranged from 45% to just under 60% of the 2148 ships, i.e. actual implementation of bulbous bows lies between 952 and 1271 ships, these are shown as tables in the Appendix A as well as the total number of respondents per measure. A range (maximum and minimum) is given because the survey question contained categorical variables such as '1–5 ships', '6–10 ships', etc. to minimise respondent burden. The remainder figures show the percentage of responses for each of the category of the response choice and therefore can only be used as an indication of the trends. It is also important to note that the results presented in this paper are aggregate and not controlled for different variables such as size of the firm, sector of the firm and chartering ratio, which are presented in Rehmatulla (2016) Rehmatulla et al. (Submitted).

Fig. 6 shows the implementation of design technologies from the survey. The figure shows that the use of bulbous bows is widespread, eighty of the 275 respondents had implemented it and on average each firm had implemented it between twelve and sixteen ships within its fleet. This suggests that the measure is well diffused within the firms that have adopted the technology, despite the way in which they can reduce fuel consumption can be complex. Bulbous bows have to be considered in conjunction with the variability of the draught and sea conditions. For slower and large ships (with a lower Froude number) the increase in wetted surface area due to a bulbous bow may increase the resistance of a ship (Bertram and Schneekluth, 1998). For certain ships there may be a benefit in not having a bulbous bow (Calleya, 2014). Figs. 7–9 suggest that bulbous bows are being implemented on all three different ship types (focus of this study) and on all ship sizes but much more in the tanker sector and 10,000 DWT to 100,000 DWT size category. The measure has relatively higher implementation in newbuilds compared to existing ships, which can be due to the economics of implementing it at design compared to implementing it during drydocking, where the opportunity costs might outweigh the potential fuel savings (Hill, 2010). Across all the design measures the implementation averaged between 32% and 47% in the respondents' fleet. This finding is similar to that obtained by Faber et al. (2011) but much higher than that suggested by HSH Nordbank (2013).

Fig. 7 shows that most of the design technologies have mainly been implemented in the drybulk and the tanker sector, with the exception of bulbous bows and design speed reduction from a smaller engine being also being taken up in the container sector. The higher uptake of design speed reduction from smaller engine corroborates with that observed in the container sector, which has had the highest implementation of slow steaming (Smith et al., 2014; Rehmatulla, 2014) and where slow steaming is becoming the norm (Maloni et al., 2013). For the total cost and emissions impact of design speed reduction from smaller engines, refer to OCIMF (2011) and Smith et al. (2011).

Fig. 8 suggests that the design measures are implemented in a range of ship sizes, but that some measures are predominantly applied to certain size categories, e.g. shaft line arrangement mainly being

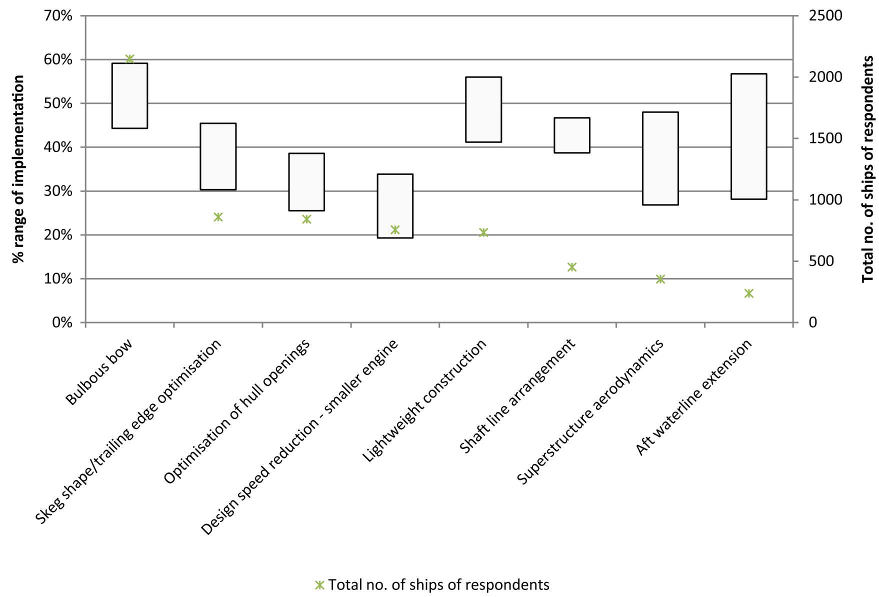

Fig. 6. Implementation of design measures.

applied to smaller ship sizes and optimisation of hull openings applied to medium sized ships. Fig. 9 shows that on average more of the design based measures were implemented in newbuilds, which is understandable given their relevance at the design stage. However, the two most implemented measures coupled with aft waterline extension have around 25–30% implemented as retrofits. According to Wang et al. (2010), both, bulbous bows and aft waterline extension, are also considered as retrofit measures.

Fig. 10 illustrates the implementation of the hydrodynamic measures.[2] The adoption of pre/post-swirl devices is quite high and similar to the design measures the effectiveness of these devices can be dependent on the particular ship that is being used, e.g. a ship with a bad aft-end may be easier to improve. If not evaluated properly, some hydrodynamic devices may even cause an increase in fuel consumption. Fig. 10 also shows that measures which had the highest level of implementation (in absolute terms) actually had lower range of implementation in the sample, for example pre/post-swirl devices, whereas measures which had the lowest level of implementation (in absolute terms), had a higher range of implementation in the fleet of the respondents, for example pods and thrusters. This suggests that for the more popular measures the diffusion within the respondents' fleet is more gradual or on a trial basis. Another explanation for the higher implementation range for pods and thrusters and contra-rotating propellers is that they are applicable or implemented in ship types other than tankers, drybulk and containerships, for example in RoRo and ferries (Wang et al., 2010), where perhaps the market is more acquainted to their performance. Across all hydrodynamic measures the implementation averaged between 24% and 44% in the respondents' fleet, marginally lower than the average implementation range suggested for design measures. This finding is lower compared to that obtained by Rojon and Smith (2014) and DNV GL (2014) but comparable to that suggested by HSH Nordbank (2013) (Fig. 11).

Fig. 13 illustrates the varying degree of implementation of hydrodynamic measures across the different ship types. Most measures have been implemented on tankers and drybulk ships compared to container ships. Contra-rotating propellers though applicable to all ship types have higher implementation in the other ship types and small size ships (Fig. 12). Air lubrication had implementation which ranged 1 – 5 ships of company's fleet, suggesting that the technology is still being trialled predominantly in the drybulk ships, given their higher frictional resistance due to their hull forms. The adoption of air lubrication is promising in that it can provide an additional reduction in fuel consumption to a ship that is hydrodynamically well designed. Some ship design models suggest that the gains may be in the region of 1.0–4.8% over an operating profile depending on the ship that is used (Calleya, 2014). The modelling of air lubrication can be difficult because, although there is much potential for fuel savings, the mechanism for the savings has been unclear.

Fig. 13 shows that on average over two thirds of the hydrodynamic measures were implemented in newbuilds, perhaps suggesting that these devices are sold as a package by the shipyards, to improve energy efficiency, as suggested by HSH Nordbank (2013), although this is difficult to verify because of the lack of information in the EEDI technical files of newly built ships and data reported in IMO, (2014, 2015, 2016). There is however a contrast between the newbuild to retrofit ratio of the hydrodynamic measures and the design measures. Pre/post swirl devices and propeller modifications for example have an equal split between newbuilds and retrofits. A possible explanation for the higher implementation for existing ships (retrofits) could be due to the existing market conditions, resulting in a two tier market for efficient and inefficient ships (Agnolucci et al., 2014). Thus, there is increasing pressure on existing ships to compete directly with more efficient newbuilds. Retrofitting hydrodynamic measures perhaps allows inefficient ships to remain competitive and prevents them from being laid up or being scrapped prematurely.

Data obtained from a technology supplier (method two as explained in Section 4) of pre/post-swirl devices are to some extent comparable to the survey results. The data from the supplier shows a greater proportion of the installations on drybulk ships (58%) compared to tankers (42%) and no implementation on containerships. With regards to ship size the data closely supports the survey results, with smaller ship sizes (under 10,000 DWT) having low implementation, ships in

[2] These were categorised as follows:

- Pre/post swirl devices included boss cap fin, vane wheel, presswork ducts, mews duct and stator fins.
- Propeller/rudder integration included propeller rudder bulb, propeller rudder matching/combination and asymmetric rudder.
- Propeller modifications included advanced blade sections, winglets/Kappel and prop section optimisation.
- Pods/thrusters included wing thrusters, pulling thrusters, wing pod, pulling pod.
- Other hull streamlining includes low profile openings, optimisation of water flow openings.

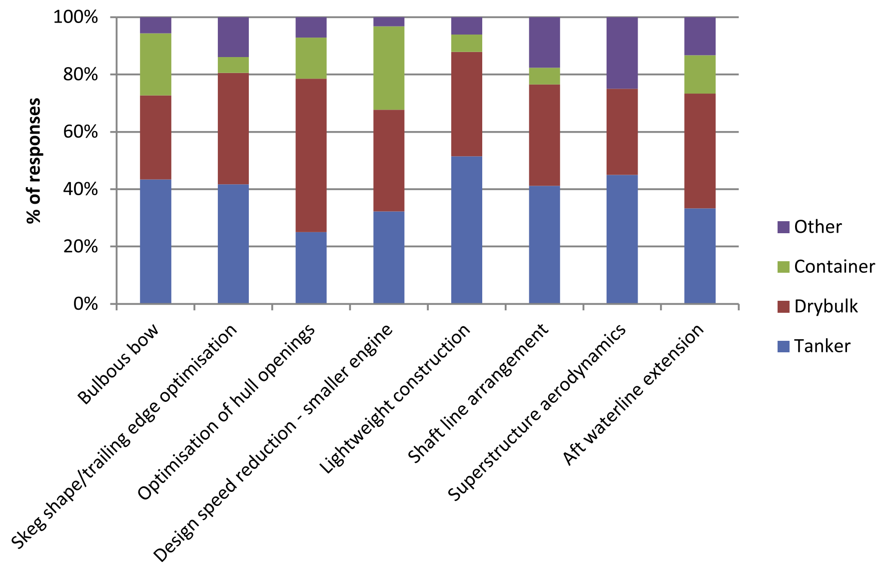

Fig. 7. Implementation of design technologies by ship type.

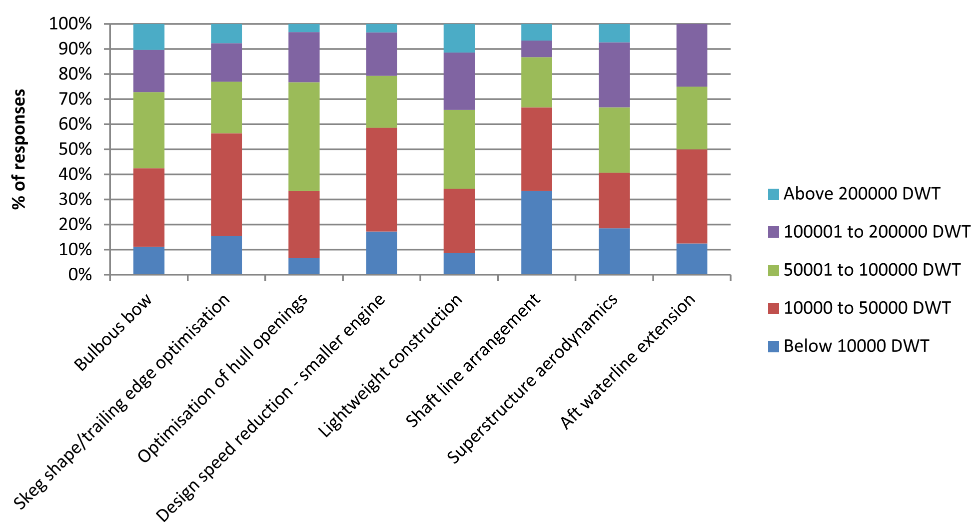

Fig. 8. Implementation of design technologies by ship size.

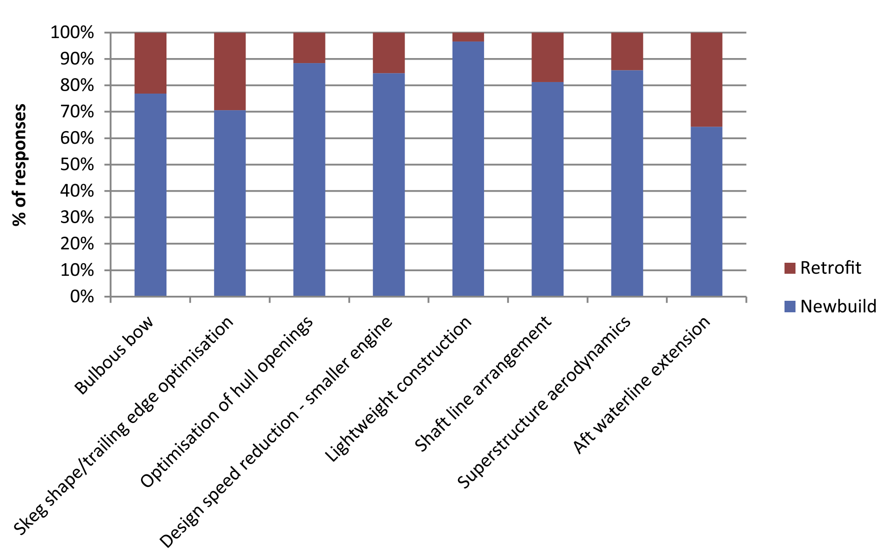

Fig. 9. Implementation of design technologies by newbuild and retrofit.

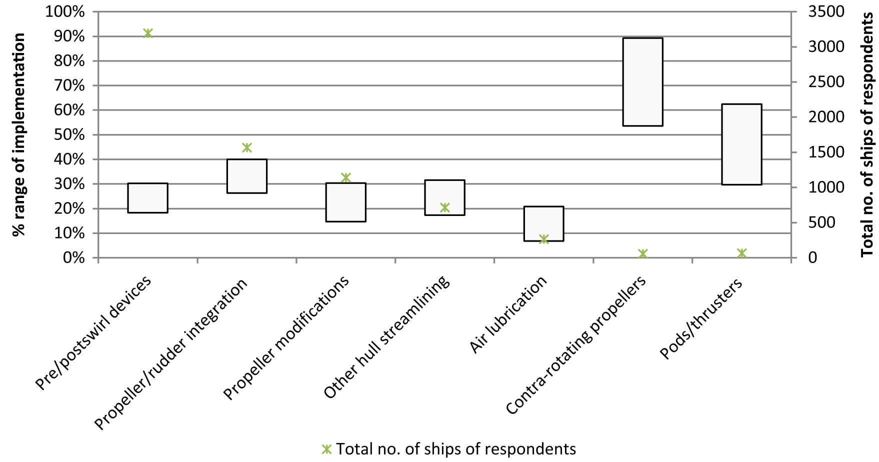

Fig. 10. Implementation of hydrodynamic measures.

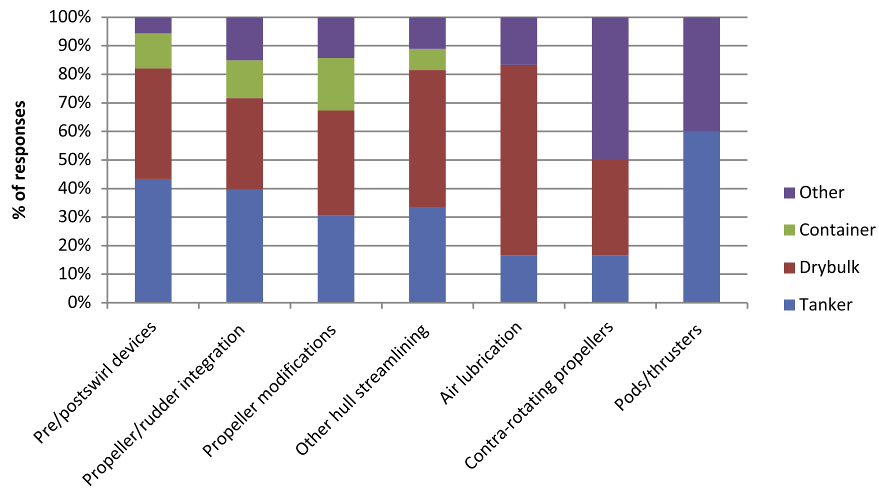

Fig. 11. Implementation of hydrodynamic technologies by ship type.

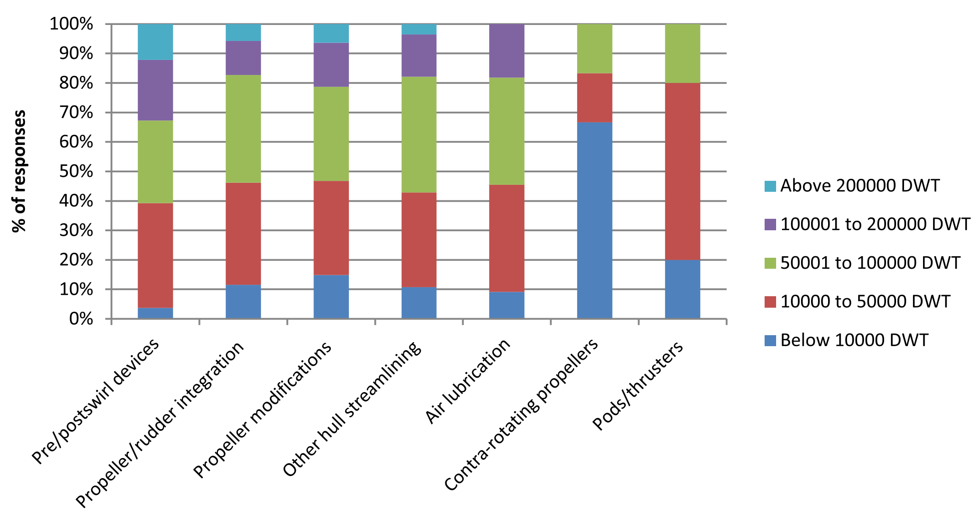

Fig. 12. Implementation of hydrodynamic measures by ship size.

the remaining categories having similar implementation of just over 30% each, and the implementation in the largest ship sizes being under 10%.

In contrast to Fig. 6 and Fig. 10, the machinery measures (Fig. 14) shows that there are several measures (in absolute terms) that have been adopted by the respondents. The most popular energy efficiency measures in this category were engine tuning, energy saving lighting, speed control of pumps and fans, waste heat recovery, common rail technology and design speed reduction through engine derating. Across all twelve machinery measures the implementation averaged between 28% and 44% in the respondents' fleet, similar to the average implementation range suggested for hydrodynamic measures. This finding is considerably lower compared to that obtained by Rojon and Smith (2014), DNV GL (2014) and Faber et al. (2011).

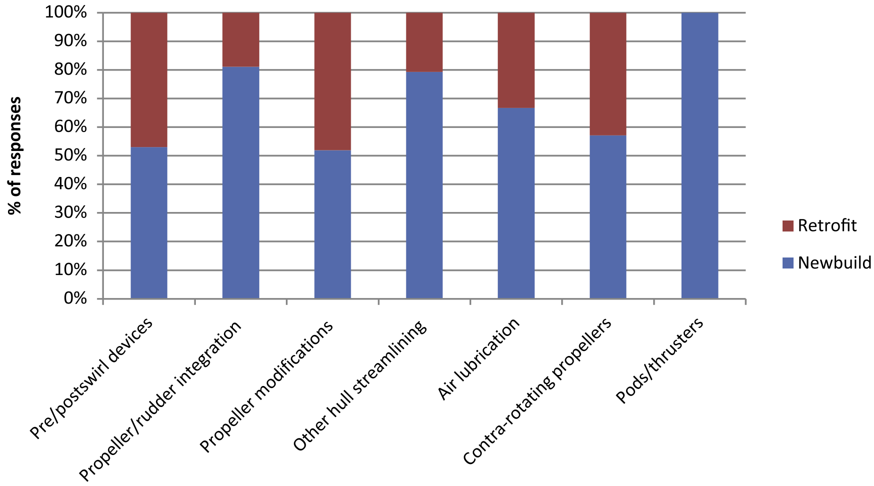

Fig. 13. Implementation of hydrodynamic measures by newbuild and retrofit.

Despite the reduction in fuel consumption from energy-saving lighting on a ship is likely to be very small (less than 1%) (Wang et al., 2010) and thus the typically long-term payback period, yet the energy saving lighting (though strictly not a machinery measure) had one of the highest implementation. This could be due to the ease of implementation and the maturity of the technology. This finding suggests that some measures are perhaps not being implemented using conventional investment appraisal methods (Parker, 2015), although several responses from the survey suggested that payback was the most often used investment appraisal tool, as one large European tanker and drybulk shipowner operator states with regards to engine derating: *"We have made several investigations into the derating the main engine of existing vessels in connection with fitting of new propellers, but this method of saving fuel has shown to have too long payback time, although savings were considerable. The conversion cost has simply been too high"*.

The reduction in fuel consumption through the use of waste heat recovery over an operating profile can be small, but it is widely implemented in the survey sample. The effectiveness of some of the machinery measures can thus depend on the operating profile of the ship that is being considered. For example, diesel electric drive is unlikely to be used on some cargo trades where ships operate at a narrow band of speeds. On average 70% of the machinery energy efficiency measures were implemented in newbuilds (Fig. 17). Further analysis of the top five measures by implementation shows that a large proportion (around 40%) is for ship sizes in the range of 10,000–50,000 DWT (Fig. 16).

Fig. 15 shows the implementation of machinery measures by ship type. With the exception of low loss power distribution, the measures had mostly been implemented in the tanker sector (average 40%), followed by drybulk (average 30%). Combined Diesel Electric Drive and common rail technology had high implementation in the drybulk sector.

Speed reduction through engine de-rating and engine tuning are popular strategies to reduce fuel consumption and deserve further discussion. The survey contained options for fitting 'design speed reduction - smaller engines' and 'design speed reduction – engine derating' but the majority of the respondents selected the latter option which suggests that the respondents are using de-rated engines when considering changes in design speed. De-rated engines, although relatively expensive, are being implemented probably because they have lower Specific Fuel Oil Consumption (SFC). The second IMO GHG study (Buhaug et al., 2009) explains how de-rating and engine upgrades can be used to potentially reduce an engine's SFC by approximately 4.3% and up to 3%, respectively.

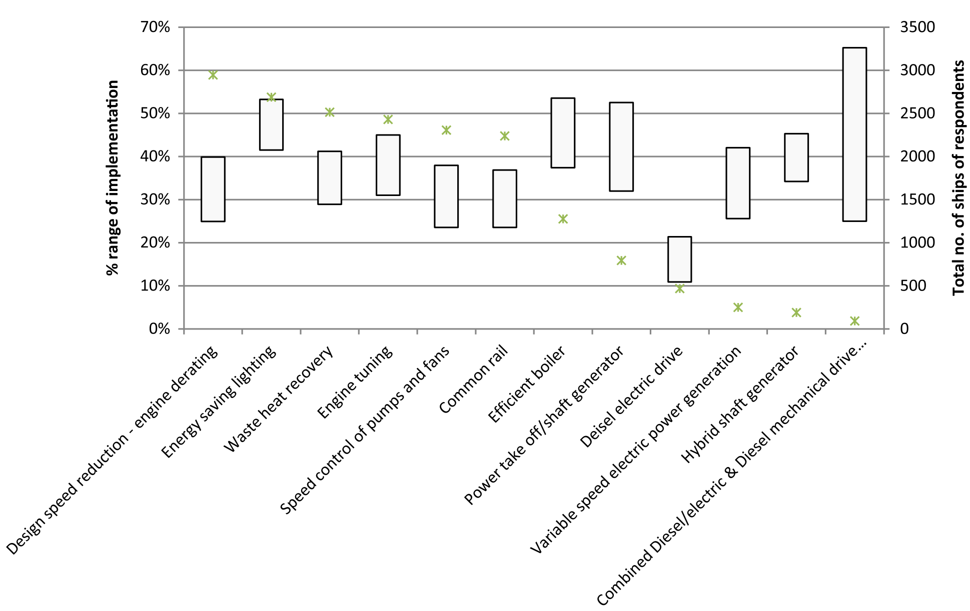

Fig. 14. Implementation of machinery measures.

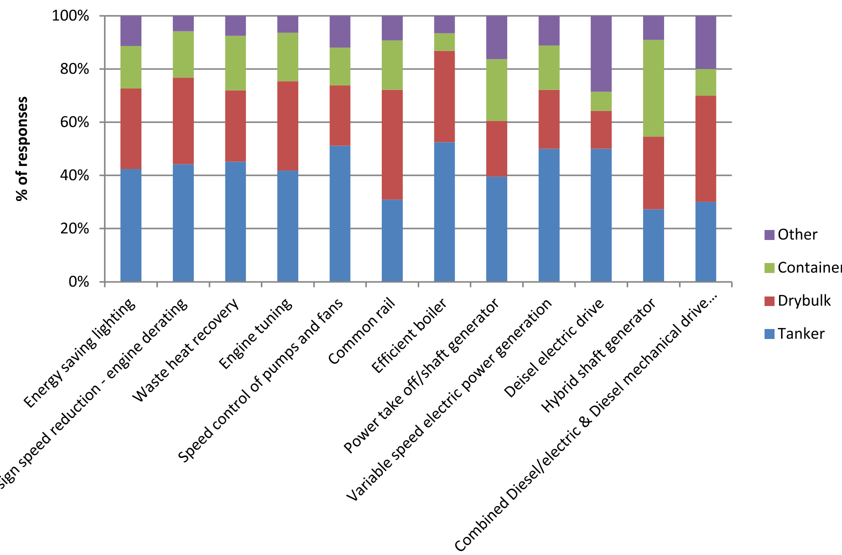

Fig. 15. Implementation of machinery measures by ship type.

Engine upgrades are normally applied as part of a package that includes changes in the turbo charger, pistons and pumps (Buhaug et al., 2009). Any substantial changes to the engine, as mentioned above, for new or existing ships have to meet NOx requirements and will have to have their EEDI verified.

De-rating is when an engine is operated at its normal maximum cylinder pressure for the design continuous service rating, but at a lower mean effective pressure and shaft speed. For an existing ship and without changing the propeller, this will result in a lower ship speed, but when applied to new buildings the propeller can be optimised to absorb this horsepower at a lower than normal shaft speed (Woodyard, 2003). The de-rating of existing ships, yields two outcomes, the engine's SFC can be decreased and the speed can be lowered. This is a possible retrofit option for existing ships. For new ships engine de-rating for a ship with a given design speed ship would involve installing a more powerful engine than usual and operating it at a lower speed, this would result in a reduction in SFC and a potential increase in propeller efficiency. The design speed could remain the same. Note that de-rating is captured in the Energy Efficiency Design Index (EEDI) equation because the de-rated engine power is used.

In order to reduce fuel consumption and the EEDI, smaller engines with a lower design speed can be installed, however installing a smaller engine is not the same as de-rating, which would offer further reductions. It is likely that in order to reduce build costs ship yards may be installing smaller engine rather than de-rating a larger engine, as shown in Fig. 9. The reduction in design speed results in a much larger reduction in fuel consumption and EEDI compared to de-rating. The bias towards higher investment in machinery technologies that may have a similar payback period to other technologies that are not being adopted may be due to the availability of engine technologies and the bundling together of technologies by engine manufacturers. This phenomenon is referred to as 'gold-plating' in the barriers to energy efficiency literature, where consumers purchase more features (in this case more energy efficiency measures) than desired (Golove and Eto, 1996) (Figs. 16 and 17).

Fig. 18 shows implementation of alternative fuel solutions by the respondents. A small number of ships are using LNG and a very small number of ships are using biofuels and solar power. The reduction in fuel consumption from using solar power for propulsion could be between 0% and 3.7% depending on the ship (Calleya, 2014), though the higher savings in this area are unlikely to be cost effective. Wind assisted propulsion has one of the largest potential in CO_2 emissions (Rehmatulla and Smith, 2017). However, these technologies have not been adopted by any ships covered in the survey due to the technical risks involved, the capital costs and informational problems (Rehmatulla and Smith, 2015b), though to date there have been some full scale implementation of the Flettner rotors on board a roro and a multi-purpose vessel. Similarly, the implementation of LNG, biofuels and solar power has been mainly in other sectors[3] (as shown in Fig. 19). The implementation of LNG has been applied to a range of ship sizes in contrast to biofuels and solar power (Fig. 20) and this has mainly been taken up for newly built ships, whereas biofuels and solar power have been implemented in existing ships. The results for the implementation of LNG fuelled ships corroborates with data collected and analysed from Clarksons World Fleet Register and other sources, for the tanker and containerships ships currently in operation, but under-represents drybulk ships that have been built with dual fuel engines (Baresic, 2016). The implementation of LNG is most likely driven by regulations relating to local air pollutants, as explained in Section 4, but its climate impact remains uncertain or under investigation, see for example Anderson et al. (2015) and Thomson et al. (2015) (Fig. 21).

5. Concluding remarks

The paper attempts to gauge the implementation of over thirty energy efficiency and CO_2 emission reduction technologies using a cross-sectional survey. The methodology employed in this paper, for example, the sampling frame, sampling strategy and execution of the survey using Tailored Design Methods, goes far beyond similar studies that have attempted to assess the implementation of technical energy efficiency or CO_2 emission reduction measures in shipping. As a direct consequence of this, the study received the highest response rate and the highest number of responses. This enables the study to generalise to a greater extent some of the findings than could have been done previously. In general the study finds lower levels of implementation for the different categories of energy efficiency and CO_2 reducing technologies than previously suggested in literature.

The results show that whilst there is a good spread of implementation across the different measures, only a few measures in each of the categories are implemented by a large proportion of ship owners. For design related technologies, the use of bulbous bows had the highest implementation. For hydrodynamic measures, the use of pre/post swirl devices had the highest implementation. For machinery measures, a

[3] The number of responses received for this question is low and therefore caution should be taken when interpreting these results.

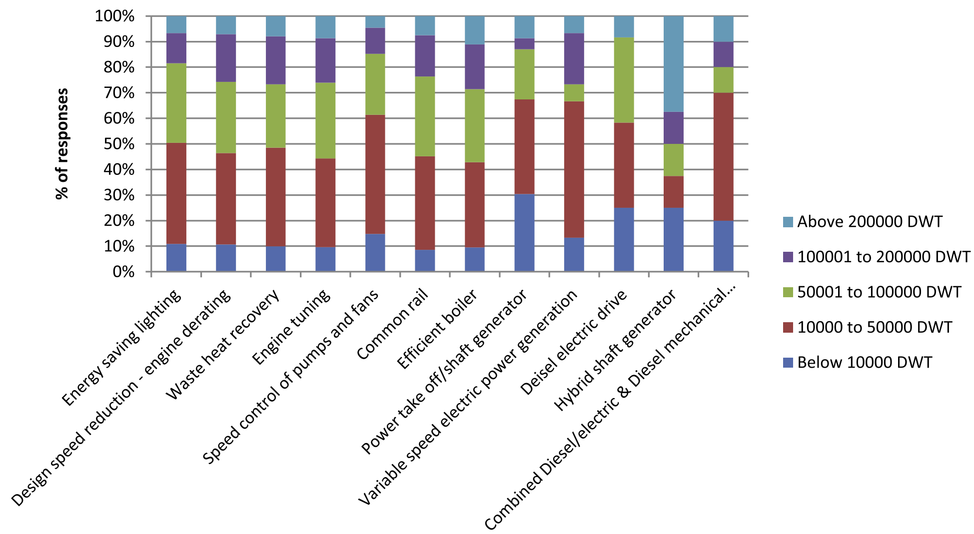

Fig. 16. Implementation of machinery measures by ship size.

larger range of options were being implemented compared to other categories of measures. Engine tuning and engine derating as well as waste heat recovery had the highest implementation. The current use of alternative fuels and renewable energy sources is low.

Secondly, whilst it is not the primary purpose of this paper to consider the energy efficiency gains of the measures, the aforementioned measures with high implementation seem to be those that have small energy efficiency gains at the ship level. Fuel consumption reductions, for example, from air lubrication and Flettner rotors at the ship level have recently been confirmed to be significant, but these technologies have very low implementation compared to measures that were observed to have high implementation. Similarly, the uptake of alternative fuels to HFO is also poor despite their high potential for reducing CO_2 emissions.

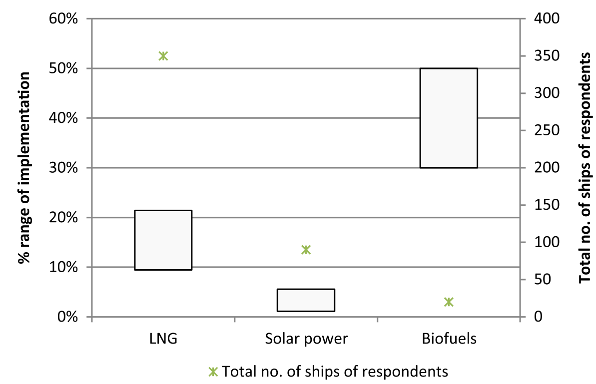

Fig. 18. Implementation of alternative sources of energy.

5.1. Policy implications

It is important to have a holistic view of emissions from shipping in context of global emissions and how these might evolve in the future. The current share of emissions from shipping at around 2% of global CO_2 emissions may increase to around 17% of CO_2 emissions. This is despite the EEDI and SEEMP regulations and driven mainly due to the rising demand for shipping and the reduction in emissions from other sectors after the Paris Agreement. There is increasing pressure on the IMO to deliver on emissions reductions that are going to be in line with what has been agreed in the Paris Agreement. This will require much more take-up of energy efficiency and CO_2 reducing technologies than currently stimulated by the EEDI and market conditions e.g. fuel prices.

The impact of the EEDI regulations has been weak due to two main reasons; the lack of information disclosure which fails to garner the social and market pressure resulting from information disclosure, and

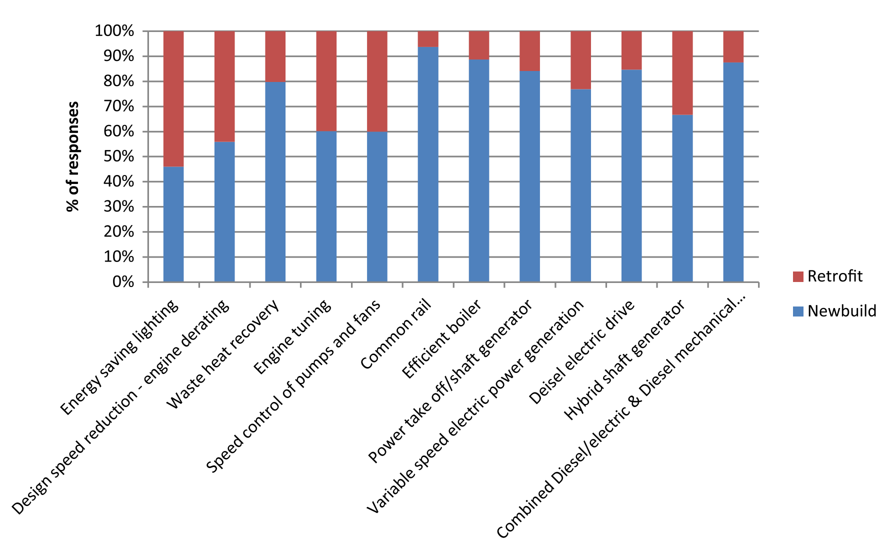

Fig. 17. Implementation of machinery measures by newbuild and retrofit.

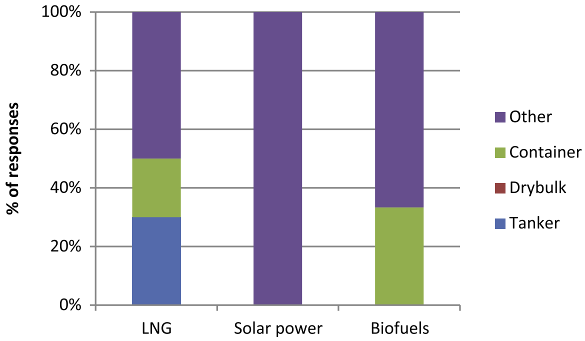

Fig. 19. Implementation of alternative sources by ship type.

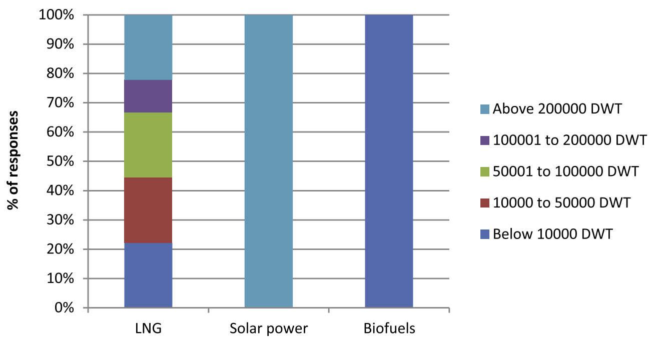

Fig. 20. Implementation of alternative sources by ship size.

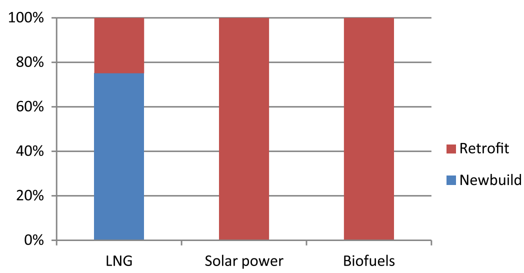

Fig. 21. Implementation of alternative sources by newbuild and retrofit.

secondly, the stringency of the regulation has been weak, with existing analysis showing many newbuild ships achieving reduction targets for phase two and three (2020 and 2025). Furthermore, despite the anonymity of the data, the data captured and reported by the IMO does not show which technologies have been used to meet the reduction targets. The lack of stringency means, that at best, only incremental energy efficiency technologies will be deployed. Implementation of incremental energy efficiency technologies, as shown in the survey, although necessary, is not enough to achieve decarbonisation of the sector (Smith et al., 2016). Moreover the implementation of some energy efficiency measures may be hindered due to market failures, such as lack of information and split incentives[4] as suggested in Rehmatulla and Smith (2015b).

Going beyond a certain emissions reduction target, at the ship level, would require use of alternative fuels with lower carbon content e.g. biofuels and synthetic fuels. The implementation of such step-change technologies is impacted by non-market failures, such as access to capital and different forms of risks, as suggested in Rehmatulla and Smith (2015a). A long-term target or objective seems to be lacking, which affects both, the regulations (e.g. stringency, transparency) and the market (which require incentives and clear direction of travel or certainty). A review of the EEDI stringency levels, have only recently been proposed and a long-term CO_2 emissions objective has also been tabled for discussion at the IMO. The findings of this study provide important background and context for the IMO and to that end an information paper has already been submitted to the 69th session of the Marine Environment Protection Committee and a further information paper on technology potentials being submitted to the 71st session.

5.2. Limitations and further work

There are a number of areas where further work can be beneficial. Despite efforts to make the survey as representative of the whole shipping sector and reduce sampling error, the survey over-represents firms headquartered in the European region and under-represents firms located in East Asia and the Far East. Secondly, small size firms (with 10 ships and under) are under-represented relative to their proportion in the sector. The implication of this is that the results and key findings above cannot represent small firms and companies located in East of Asia and Far East. Future surveys could therefore focus on these two strata. To address geographical under-representation the survey can be administered in different languages as well use a local focal point to administer it using the Tailored Design Method.

The survey data can benefit from further analysis by controlling for multiple variables at the same time, for example, for a particular measure one can control for the ship type, and then observe the different ship sizes within that ship type. In order to continue to evaluate the implementation, a longitudinal study may be deployed, to observe any changes in the level of implementation of the measures. Using other methods to validate the findings as outlined in Section 4 is also an important area for further improving the confidence of the results. This work has already begun, for example data from technology providers has already proved useful in this paper. Further work could also assess the diffusion of technologies at the firm level, and better understand the innovation decision making process from knowledge to implementation and confirmation, as well as barriers to implementation of technologies that have significant potential to reduce CO_2 emissions.

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Appendix A

Design	Aft	Skeg shape/	Optimisation	Shaft line	Bulbous	Lightweight	Design speed	Superstructure

[4] See also Agnolucci et al. (2014), Prakash et al. (2016) and Adland et al. (2017)

measures	waterline extension	trailing edge optimisation	of hull openings	arrangement	bow	construction	reduction - smaller engine	aerodynamics
Minimum	67	261	215	175	952	302	146	95
Maximum	135	391	325	211	1271	411	256	170
Respondents	12	29	22	13	80	25	22	17
Total no. of ships of respondents	238	860	842	452	2148	734	756	354
Min %	28%	30%	26%	39%	44%	41%	19%	27%
Max %	57%	45%	39%	47%	59%	56%	34%	48%

Hydrodynamic measures	Pre/postswirl devices	Propeller/ rudder integration	Propeller modifications	Other hull streamlining	Contra-rotating propellers	Air lubrication	Pods/ thrusters
Minimum	586	412	167	124	30	18	19
Maximum	966	626	346	225	50	55	40
Respondents	83	45	37	20	6	8	4
Total no. of ships of respondents	3194	1566	1140	714	56	264	64
Min %	18%	26%	15%	17%	54%	7%	30%
Max %	30%	40%	30%	32%	89%	21%	63%

Machinery measures	Energy saving lighting	Design speed reduction - engine derating	Waste heat recovery	Engine tuning	Speed control of pumps and fans	Common rail	Efficient boiler	Power take off/ shaft generator	Variable speed electric power generation	Deisel electric drive	Hybrid shaft generator	Combined Diesel/ electric & Diesel mechanical drive (CODED)
Minimum	1115	734	726	753	543	526	477	254	64	51	65	23
Maximum	1431	1175	1035	1093	875	825	683	417	105	100	86	60
Respondents	79	95	71	75	70	70	46	37	10	12	6	8
Total no. of ships of respon- dents	2688	2946	2514	2430	2306	2238	1276	794	250	468	190	92
Min %	41%	25%	29%	31%	24%	24%	37%	32%	26%	11%	34%	25%
Max %	53%	40%	41%	45%	38%	37%	54%	53%	42%	21%	45%	65%

Alternative energy	LNG	Solar power	Biofuels	Wind power - kites	Wind power - sails	Wind power - Flettner rotor
Minimum	33	1	6	0	0	0
Maximum	75	5	10	0	0	0
Respondents	8	1	1	0	0	0
Total no. of ships of respondents	350	90	20	0	0	0
Min %	9%	1%	30%	0	0	0
Max %	21%	6%	50%	0	0	0

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