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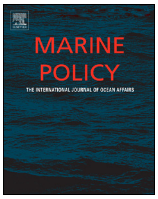

Wind technologies: Opportunities and barriers to a low carbon shipping industry

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ABSTRACT

The abatement potential of wind technologies on ships is estimated to be around 10–60% by various sources. To date there has been minimal uptake of this promising technology, despite a number of commercially available solutions that have been developed to harness this free and abundant energy source. Several barriers have been referred to in the literature that inhibit uptake of energy efficiency measures in shipping. This paper provides a systematic analysis of the viability of wind technology on ships and the barriers to their implementation, both from the perspective of the technology providers and technology users (ship owner–operators), using the survey and the deliberative workshop method. The data generated from these methods is analysed using the qualitative content analysis method. The results show that whilst there is renewed interest in wind power, there are several common economic barriers that are hindering the mass uptake of wind technologies. Our analysis shows that third party capital is a plausible solution to overcoming the cost of capital, split incentives and information barriers that have contributed to inhibiting the uptake of wind technology in the shipping industry.

1. Introduction

The shipping industry is commonly cited as the most energy efficient mode of transport, but this will be a challenge in the future as its current contribution (around 3% of global CO_2 emissions) is expected to increase to around 20–25% of global anthropogenic CO_2 emissions by 2050 due to growth in international trade and other industry sector decarbonisation [1]. Several technical and operational energy efficiency measures have been identified that can be applied to new and existing ships to reduce fuel costs and meet this climate change challenge. Solutions could come from a combination of step-change technologies that provide significant energy and emissions reductions, alternative fuels and operational improvements that provide nominal energy reductions.

Under the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC), greenhouse gas emissions from shipping have been left to the United Nation's International Maritime Organisation (IMO). The IMO introduced the Energy Efficiency Design Index (EEDI), which sets mandatory CO_2 reduction targets for all newly built ships built from 2013 onwards. The reduction targets are tightened every five years up until 2030 to ensure that ship owners order more efficient ships. The amendment also introduced the Ship Energy Efficiency Management Plan (SEEMP) requiring ship owners to have a plan on-board each vessel to improve operational efficiency.

The impact of these policies is estimated to reduce CO_2 emissions by 25% reduction in a business-as-usual scenario by 2050 [2], whereas the reductions required if the industry is to be sustainable are in the region of 80% compared to current levels [3]. Recent reports submitted to the IMO Marine Environment Protection Committee (MEPC) [4,5] showed that the EEDI is only spurring 'mainstream' innovation (e.g. hydrodynamics, hull and propeller appendages) and there has been no uptake at all of innovative measures that yield significant savings, which are necessary to keep shipping's CO_2 emissions in line with either the 1.5 or 2 °C targets (Internationally agreed limits on average global warming above pre-industrial levels) [6].

Wind technologies offer significant savings on existing ships that can allow ship owners to operate competitively with new ships. There are three different technologies through which wind energy can be harnessed for propulsion purposes: Flettner rotors, kites and sails. The fuel savings that can be achieved from these wind-assistance technologies depend on the design of the ship (particularly the rig and hull), the operating speed, and the wind speeds and directions experienced.

Wind speeds vary depending on the route and season. Higher wind speeds allow a ship to harness more wind as power to propel

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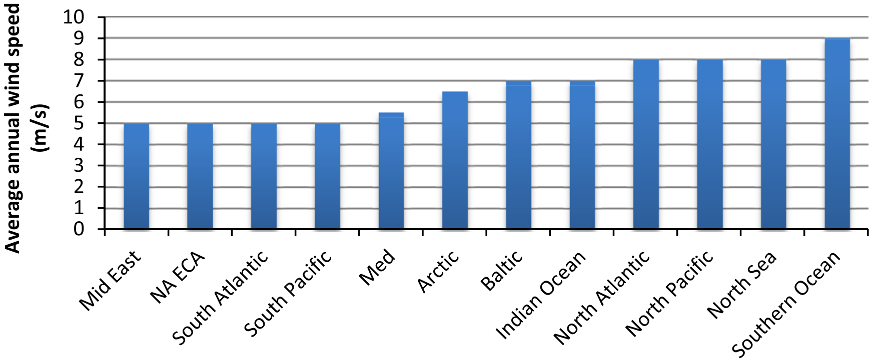

Fig. 1. Estimated average annual wind speed in different sea areas. Data from NASA Surface meteorology and Solar Energy for the period 1983–1993 (http://eosweb.larc.nasa.gov).

the ship and less power from the diesel engine. For many ships, the operating profile and routes taken are variable and can change from one voyage charter to the next, such that there is heterogeneity in the fuel savings for different ship types and some uncertainty in predicting fuel savings. An initial assessment of the viability can be obtained by understanding the average wind speeds for the areas of operation of a particular ship type. (Fig. 1) classifies the average annual wind speeds into different sea regions, ranked from least windy sea region (the Mid-East, North Atlantic Emission Control Area and South Atlantic) to the most windy sea regions (North Pacific, North Sea, and Southern Ocean).

To understand whether wind technology is likely to be viable for a certain ship type, the information about relative wind speeds needs to be matched to activity data that describes ships' movements. (Fig. 2) displays this information for dry bulk carriers in two size ranges, 0–10,000 and 10–35,000 DWT capacities, using data from Smith et al. [7]. The graph shows that in many instances there is a good alignment between the windier sea areas and the areas where there is significant shipping activity (for example, North Pacific, North Atlantic and the Indian Ocean). This implies that at least for these two example ship types and sizes, if a ship operated a sequence of voyages over a year that mirrored the aggregate average activity in different sea regions shown in Fig. 2, there is a good probability of experiencing higher than average wind speeds and a good level of utilisation (fuel cost savings) from wind assistance technology.

Whilst this information shows that there is sufficient wind strength for the areas where ships operate, the commercial viability of wind technology requires quantifying the amount of fuel savings that can be achieved. This requires further data on the specifics of ship operation for a given voyage – the typical operating speeds, routes taken, fuel consumption of ships on certain representative voyages and specifics on the savings achieved by the technology. Fuel savings modelled as a simulation show that for that range of speeds, season, and ship designs, the average voyage fuel savings were approximately 10–60% [8]. These results provide encouragement that there is good potential for fuel saving, but further verification needs to be obtained from actual sea trials.

There are a number of technical issues, related to operation and safety, which constrain the types of ships suitable for wind technology. Examples of these considerations include visibility obstruction, cargo handling, air draught constraints, crew safety, crew training, structural integrity, and stability and heel. For example, cargo-handling considerations have prevented containerships from being a market target of wind technology. Careful consideration has been given to all of these issues by the various technology providers with wind-assistance technology offerings and a majority of these issues do not appear to be insurmountable for a large percentage of the shipping market. The clearest proof of this is the class approval that has been achieved by a number of the technology providers.

Despite the viability of wind technology to deliver significant fuel savings in the shipping industry, there are a number of barriers that have prevented its uptake in the sector. In a study of perceptions of Norwegian ship owners on CO_2 abatement technologies, Acciaro, Hoffmann and Eide [9] show that wind technologies score the worst in most barriers categories compared to other technical energy efficiency measures such as cold ironing, waste heat recovery and propeller efficiency devices. The respondents were not familiar with the wind technologies, percieved them as less safe or reliable, and felt they were less effective compared to other technologies [9]. Using technological innovation systems theory, semi-structured interviews and content analysis, Rojon and Dieperink [10] suggest that the key barriers to

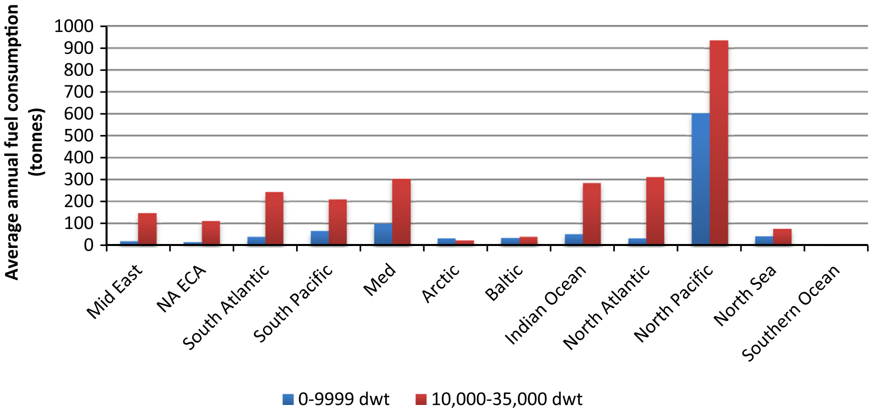

Fig. 2. Average annual fuel consumption in different sea areas. Data from Smith et al. [7].

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the implementation of wind technologies relate to the lack of primary practical knowledge, which stems from a lack of sea trials to test the technology. This was attributed to the risk-averse nature of the industry where "no one wants to be the first to try out the technology, yet everybody wants to be second" [10, p. 398], and lack of financial resources. The existence of barriers that inhibit sufficient levels of investment in energy efficiency measures is the primary reason for considering public policy interventions [11]. Policy makers and regulators at the UK, EU and global levels have yet to improve existing policy or design new policies to incentivise wind propulsion, such as information campaigns, as well as providing public funding to help aid research and development, testing and pilot programs in energy efficiency measures [10].

The two aforementioned studies analysing the barriers to implementation of wind technologies in the shipping industry lack a clear taxonomy of barriers. Barriers to energy efficiency can be classified into three types: regional, sectoral and technology specific [12] and the taxonomy of barriers has varied and has not always been rooted in specific disciplines [13]. This paper evaluates the barriers to the uptake of wind technology in shipping from an economic perspective, and provides a solution to overcome some of these barriers, given the lack of existing policies to address them.

2. Data and methods

The research developed for this paper is part of a joint collaboration project called Shipping Innovation Fast Tracker (ShiFT) between the UCL Energy Institute and Carbon War Room (CWR), which aims to accelerate the mass uptake of 'clean' technology solutions in the shipping industry that deliver 'double-digit' efficiency gains, carbon and other emissions savings. A self-completion questionnaire was designed to collect data using the cross-sectional research design [14]. The survey was supplemented with data generated from a deliberative workshop [15] hosted by CWR and the UCL Energy Institute during the Danish Maritime Days conference in October 2014. The methodology followed in the paper is similar to the research on barriers to innovation in other fields [16,17] and uses the mixed methods research strategy to provide 'complementarity' to the data generated [18,19].

The survey consisted of eight open-ended questions, seeking to gauge the applicability of the technology to shipping, the commercial aspects of the technology and the barriers the providers face. This information was used to identify where the firms are situated in the "valley of death", a situation in which a technology fails to reach the market due to the inability to advance from demonstration to commercialisation [20]. Fig. 3 shows the various phases the wind technology firm has to pass through to reach the market and achieve a positive cash flow. The "valley of death" corresponds to phase two, where the cash flow is significantly negative as the firm obtains classification, patents, and invests more to perform sea trials to prove the fuel savings in real operating conditions.

Rojon and Dieperink [10] suggest that technology providers acting in isolation create 'confusion rather than conviction' in the technology, there is a lack of knowledge exchange platforms and weak interaction between stakeholders within and outside the system. Hence, an active stakeholder network was established as part of the Shipping Innovation Fast Tracker to accelerate the dissemination of information about wind technology. The workshop aimed to bring together the key stakeholders that would create conditions for collaboration and enable the implementation of the wind technologies. The workshop invited key members of the shipping community and was attended by four wind technology providers, nine ship owners, two third-party financing organisations, a classification society, a ship owner association and a national ship registry. An initial assessment of the viability of wind technology was presented by UCL in terms of its technical and commercial potential. This was followed by specific presentations from the technology providers where the ship owners and classification societies engaged, voicing their concerns about each of the technology. This discussion provided information for which to assess the barriers to uptake in the sector.

The qualitative data generated from the open-ended questions and the deliberative workshop was analysed using the qualitative content analysis method [21]. Category construction and a coding frame are key stages in the use of content analysis [22,23] and can be derived from previous research, data or theories [24]. To classify energy efficiency barriers in wind technology for shipping, a framework of energy efficiency barriers in the shipping industry developed in Rehmatulla [13] was used, as well as drawing from other sources such as Sorrell et al. [25] and Thollander and Ottosson [26]. Emphasis is given to the examine each unit of analysis using the main economic barrier categories (see Fig. 4). The unit of analysis for the qualitative content analysis of the survey and deliberative workshop data are 'themes', which is the most useful unit in qualitative analysis because it provides context [27].

2.1. Classification of the wind technology firms

Six firms were selected based on their overall score derived from the responses in the questionnaire. The technologies provided by the selected firms included variations of the Flettner

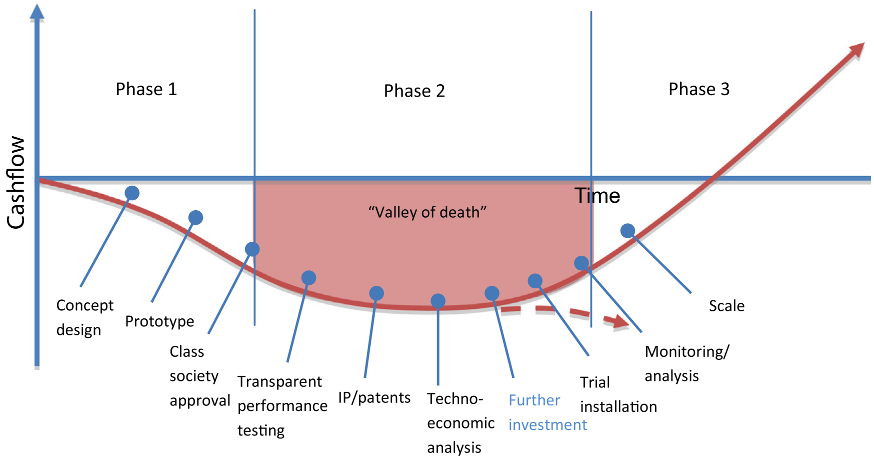

Fig. 3. Valley of death for technology providers in shipping.

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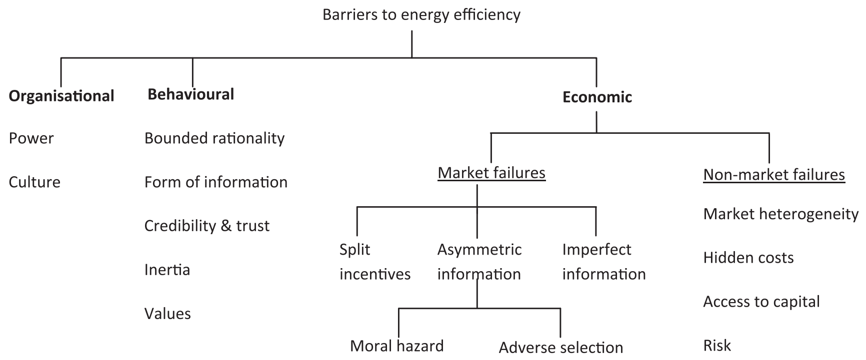

Fig. 4. Classification of barriers to energy efficiency.

Table 1
Survey responses of wind technology firms.

	Saving potential 10% or more	Class approved	Independent testing	Patent approved	Techno-economic analysis, business plan and investment package	Pitched to shipowners	Trials in shipping	VOD phase (refer to Fig. 3)
Company 1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	3
Company 2	Yes	Yes	Yes	Yes	Yes	Yes	No	2
Company 3	Yes	Pending	Yes	Pending	Yes	Yes	Yes	2
Company 4	Yes	Yes	Yes	No	Yes	Yes	Yes	2
Company 5	Yes	Pending	Yes	Yes	Yes	Yes	No	2
Company 6	Yes	Pending	Yes	Pending	Yes	Yes	No	2

rotor and sails.[1] Table 1 shows that the selected companies have gained class approval and their technologies are patented, placing them in the second phase of the 'valley of death'. Crucially, the table suggests most have conducted techno-economic analysis of their technology and have engaged with ship owners or operators but only half have secured commitments for trials.

Following the selection based on the survey, the selected wind technology providers and ship owners were invited to the deliberative workshop to further discuss the implementation, concerns of ship owners and hurdles faced by the technology firms. Some of the providers also presented the business case for their wind technology. Table 2 shows an example of the parameters that one technology provider presented for demonstrating that their wind technology is commercially viable with a payback of just over two years. The survey asked the technology firms if they had pitched their technology to ship owners and operators and inquired about the practical aspects and concerns raised by ship owners about installing the technology which is discussed in the following section.

Table 2
An example of a business case presented by one wind technology provider.

Ship type	Oil tanker	Units
Deadweight	75,000	Tonnes
Main engine power	13,000	kW
Propulsion efficiency	0.6	
Service propulsion power	10,500 (81% MCR)	kW
Service speed	16	Knots
Time at sea per year	7008	Hours
Main engine fuel consumption	190	Grams per kWh
Bunker fuel cost (HFO)	600	USD/ton
Total delivery price	2,050,000	USD
Maintenance p.a.	150,000	USD
Average net power	1411	kW
Fuel saving %	13.4	%
Fuel consumption p.a.	13,981	Tonnes
Fuel cost p.a.	8,389,000	USD
Potential savings	1,128,000	USD
Payback	2.1	Years

3. Barriers to implementation of wind technologies

This section of the paper provides an overview of the generic barriers to implementation of energy efficient technology and contextualises these for wind technologies using the findings from the survey, commentary from the deliberative workshop and secondary data sources.

3.1. Categorizing energy efficiency barriers

Despite the substantial abatement potential at negative costs, several studies across different sectors have empirically shown that cost-effective energy efficiency measures are not always implemented [28–32]. The implementation gap, also known as the 'energy efficiency gap' [33] refers to the difference between the actual lower levels of implementation of energy efficiency measures and the higher level that would appear to be cost-effective from the investing entity's point of view based on techno-economic analysis [11]. A plausible explanation for the gap can be explained by energy efficiency barriers, which may be defined as postulated mechanisms that inhibit investment in technologies that are both energy efficient and economically efficient [25].

Barriers to energy efficiency may be divided into three main categories: economic, organizational, and behavioural [34]. Fig. 4 shows the taxonomy of energy efficiency barriers. The aim is to determine which perspective would provide the most plausible account of lack of action, whilst keeping in mind that these perspectives are often linked and overlap [35,36]. This paper uses the economic perspective to understand the lack of implementation, as this perspective is the most developed and well defined [25]. The use of this perspective is grounded on well-established economic theory such as agency theory [37–39], which is needed to explain the complex stakeholder relationships and the "complex

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[1] More details of the technology companies selected and their technologies can be found in www.lowcarbonshipping.co.uk.

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and poorly characterised" barriers in shipping [40, p. 286]. For a discussion of behavioural and organizational barriers see Rojon [41].

Economic barriers can be divided into non-market and market failures [11]. A market failure occurs when the market is not allocating resources efficiently. Allocative efficiency is the state of the economy in which goods are produced up to the point where the last unit of production provides a marginal valuation to consumers which equals the marginal cost of production. This occurs when markets are perfectly competitive, a strong assumption for many markets, though the tramp shipping market has been characterized as close to this ideal [42]. When a market fails to allocate resources efficiently, there is said to be a market failure. Market failures particularly relevant to preventing the uptake of energy efficient technology occur because of split incentives, imperfect information, and asymmetric information. Split incentives arise because of contractual or organizational arrangements, while the latter two barriers are associated with informational problems.

Non-market failures can be defined as obstacles that are not due to a failure in the market but are economic costs faced by a firm such as limited access to capital, capital costs, hidden costs, risk, and heterogeneity [11]. Some barriers may be easier to address with public policies than others [43]. For example, if firms lack access to capital, then a policy that provides funding for a technology would help to foster the diffusion of the technology.

Analysis from leading industry experts and recognized bodies [44–48], has so far shown substantial unrealised abatement potential in shipping using options that often appear to be cost-negative at current fuel prices. Various empirical studies Acciaro, Hoffmann and Eide [9] Rehmatulla [13] Johnson, Johansson and Andersson [49] Jafarzadeh and Utne [50] and other industry literature Faber, Behrends and Nelissen [48] and Maddox Consulting [51] have also suggested the existence of the aforementioned barriers in shipping.

3.2. *Market failures*

As discussed in Section 3.1, a market failure occurs when the market is not allocating resources efficiently. Market failures particularly relevant to preventing the uptake of energy efficient technology occur because of split incentives, imperfect information, and asymmetric information. All of these market failure barriers pertain to wind technology.

3.2.1. *Imperfect Information*

There is a shortage of publicly available information on an average ship's fuel consumption in real operating conditions that is detailed, transparent and audited [52]. There are several reasons that can be attributed to this informational deficiency. First, measuring a ship's performance in real operating conditions is difficult due to the large amount of factors explaining the fuel consumption and the difficulty of isolating their marginal effect. These factors include draught, weather conditions, hull and machinery condition and the crew, some of which are highly variable over time, making the analysis of performance trends difficult even for the same ship.

Second, there is an array of bespoke measurement and analysis techniques used across the industry, some of which are varying in quality. Historically, fuel consumption measurement has been in the form of low frequency data collected every twenty four hours in a noon report. There is large uncertainty in this data [53]. Due to poor economic conditions, increased environmental regulation and increased environmental awareness, the industry has shifted towards better data collection methods such as continuous monitoring systems. Still, this process will be gradual as the uptake is generally limited by installation costs [53].

In addition to the challenges in measuring a ship's performance, it has also been difficult to measure the performance of new fuel-efficient technologies. This is because the tests have been constrained to hypothetical conditions only (e.g. sea trials for a newly built vessel or in a tank test), and therefore has not given investors much confidence in a technology's actual abilities on the less-predictable ocean. The advent of sophisticated monitoring systems has provided a data source that, with rigorous deployment and processing, allows for the calculation of fuel savings with a manageable level of uncertainty. The cost of the advanced monitoring systems varies on average between $20,000 to $200,000 depending on the number of parameters being monitored and how information is presented [54,55]. This can therefore represent between 1% and 10% of the typical cost of installation of the wind technology. One of the wind technology companies who attended the workshop discussed their intention to install such equipment on a ship for a limited period in the sea trials at their own cost.

3.2.2. *Asymmetric information*

In some cases, ship owners may have the incentive to misrepresent the fuel efficiency of their fleet to a potential customer. This could occur in the time charter market, where a charterer hires a ship from a ship owner. The ship owner must provide a fuel consumption and speed curve, providing the charterer with information about the daily fuel consumption at different operating speeds under some assumptions about weather conditions. If the charterer does not measure the fuel consumption, then it has limited power to claim damages for a misstated fuel consumption curve [56]. This asymmetric information leads charterers to have mistrust in the efficiency claims by the ship owner, including those of a ship fitted with wind technology. The advent of continuous monitoring equipment may act as a deterrent for this behaviour [57].

3.2.3. *Split incentives*

Another possible barrier to the implementation of wind technology are the split incentives that have been suggested to be prevalent in shipping due to the contractual arrangements between the charterer and ship owner [58,47,48,13]. Whilst there are many forms of split incentives [59], the split incentive arising in the time charter is the most common form, where fuel costs are borne by charterers (in addition to the daily charter rate) and capital and maintenance costs are borne by the ship owner or operator. This represents a type of principal-agent problem which also arises in the building sector between a tenant and landlord [35,60–62].

The degree of the split incentive in each market segment depends on the size of the time charter market, the length of the contracts and whether charterers are willing to reward owners for their investments in energy efficiency or clean technologies. Estimates from an analysis of fixtures in 2011 [13] shows the size of the time charter market varies in each sector. In the tanker sector, the majority (around 90%) of ships are traded on the voyage charter (spot) market, while in the dry bulk sector time charter contracts could account for as much as 60% of the ships, suggesting that this type of barrier is a larger problem in the dry bulk sector.

Also important is the typical length of a single time-charter contract, which provides information about whether the energy efficiency or wind technology investment can be paid back in the duration of the contract from the fuel savings, if the charterer were to invest. Long-term charters enable a charterer to have a longer investment in the ship. Cargill (a dry bulk charterer) installed Skysail (wind technology) and Shell (a tanker charterer) installed air lubrication, both being long-term time chartered vessels and requiring structural changes to the owners' vessels. Whilst the

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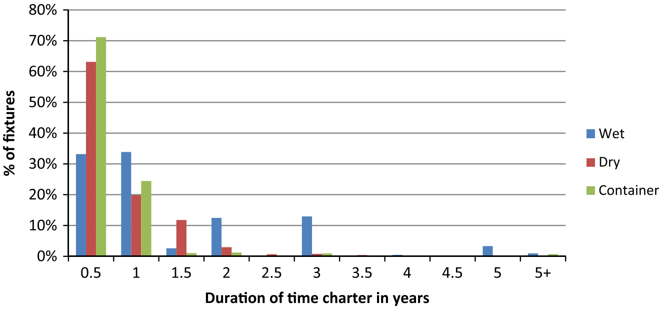

Fig. 5. Time charter fixture duration by sector. Data from Clarksons Shipping Information Network (SIN).

technology is less attractive to the container sector, charterers in this sector have also been driving changes that require structural changes to the ships. An example is Maersk's funding of bulbous bow retrofits to the ships that it has time chartered [63].

Fig. 5 shows that time charter contracts in the dry bulk sector are typically too short to cover the payback period of wind technologies because about 60% are less than six months in length, whereas the average payback of wind technology is much longer. Contracts in the time charter market for wet bulk are slightly longer, with only about 30% less than six months. Overall, 90% of time charters are for a duration of less than two years, therefore it does not permit the majority of charterers to payback an investment in wind technologies.

The third factor leading to a split incentive is whether owners who invest in more energy efficient ships are being rewarded in terms of higher rates. The extent to which the fuel cost savings are passed back to the owner–operator through higher charter rates will create direct incentives for ship owners and operators to implement wind technology. Agnolucci, Smith and Rehmatulla [64] show that on average only 40% of the financial savings delivered by energy efficiency accrue to the ship owner for the period 2008–2012 in the dry bulk Panamax sector. The incomplete pass-through of savings through higher rates has also been suggested by Smith et al. [65], Riise and Rødde [66] and Parker and Prakash [67] and has been referred anecdotally by Faber, Behrends and Nelissen [48], Maddox Consulting [51] and Lloyds List [68].

Whilst charterers may not be directly rewarding energy efficient ships with higher charter rates, a ship's higher fuel efficiency may improve the likelihood of winning a charter, leading to better utilisation rates. This is a key factor in an oversupplied market, where ships have to ballast further in search of employment. Increasingly, leading demand-side stakeholders (e.g. retailers, charterers, ports and banks) are using public information about a ship's design efficiency (a proxy for a ship's fuel efficiency in real operating conditions). As part of the Clean Cargo Working Group,[2] retailers such as IKEA and Wal-Mart are collaborating with leading container shippers to reduce their carbon footprints and taking fuel efficiency into consideration in their tendering process.

In the wet bulk and dry bulk charter market, charterers are beginning to factor energy efficiency into their commercial decision-making. This was evidenced in the workshop by one participant who mentioned, “it is the charterer that is positioned to drive change. Perhaps instead of a ship owner, it will be the charterer who is most likely to win the race to be first, not second”. Exemplifying this trend, Cargill, Huntsman and UNIPEC UK publicly announced in October 2012 that they would no longer charter the least efficient ships in the fleet using RightShip and the Carbon War Room's A to G GHG Emissions Rating. Currently, nearly 25% of the dry bulk and wet bulk market uses the A to G GHG Emissions rating [69] as policy when choosing which vessels to charter. As a result, many of these companies are actively not sending their cargoes on F or G rated vessels (the most inefficient in the fleet), for example, Cargill has a no F or G policy [70].

Other industry stakeholders, including ports and banks, have begun to embed energy efficiency information into their commercial operations. Ports, such as Prince Rupert and Metro Vancouver, are now offering discounts to more efficient vessels. Leading shipping banks such as the KfW IPEX Bank and HSH Nordbank are using energy-efficiency data in making investment and financing decisions. This data is an important part of their risk assessment and return analysis, with inefficient vessels viewed as riskier investments, which is factored into their credit-approval processes for vessel purchases, loan assessments for retrofit projects, and resale or scrapping decisions.

Finally, the voyage and time charter parties that have traditionally existed in shipping, may need to be reviewed to enable the implementation of wind technologies. In the voyage charter, the ship owner has an obligation to proceed with reasonable despatch and without unjustifiable deviation under the ‘utmost despatch’ and ‘deviation’ clauses [71]. Content analysis of charter parties by Rehmatulla [13] suggests that most often used standard voyage charter parties in the wet bulk and dry bulk sectors, do not allow any deviation ‘except for saving life or property’ and contain clauses that restrict slower speeds. Both of these clauses could have an adverse impact on the ability to fully utilise the potential of wind technologies. “To take full advantage of the opportunity of wind systems, the vessel should be allowed to change course to chase the wind (using high-quality software systems to do so), which may need to be reflected in the charter party,” stated one ship owner in the oil tanker sector at the workshop.

3.3. Non-market failures

The survey of technology companies and the discussion in the workshop suggested that most of the non-market failures discussed in Section 3.1 are plausible explanations for the lack of uptake from ship owners and operators. This section identifies how non-market failures may also be contributing to the low uptake of wind technologies.

3.3.1. Risk

Risk in context of energy efficiency can be classified as external risk (overall economic trends, fuel price, policy and regulation) and technical risk (technical performance and unreliability of the technology) [25]. Both of these risks were cited as the largest risk factors in both the survey and the deliberative workshop.

One of the technical challenges cited in the introduction is maintaining the stability of the ship in rough weather. This was the most cited technical risk by the wind technology providers. According to one wind technology provider, “heavy winds mean large forces at the base of the wind system and the danger of ripping apart the mast during a storm. In case of extreme weather conditions, such as above 200 knots winds, the system will be turned off.” The role of classification societies in ensuring this concern is addressed is pivotal, and, according to another technology provider, “We are in conversation with class societies to confirm that stability is not an issue and that no countermeasures are required.”

The primary concerns of ship owners during the workshop were issues related to structural integrity, cargo handling and stability of the ship in adverse weather conditions, which aligned with those stated by the technology providers in the survey. The following technical concerns are briefly discussed below by level

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[2] A global carrier–shipper initiative dedicated to environmental performance improvement in marine container transport through measurement, evaluation, and reporting.

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of importance:

- Structural integrity – the forces exerted by the technologies on the ship's hull, particularly at the interface between the rig and the hull, need to be taken into consideration.
- Cargo handling – wind assistance technologies can obstruct cargo loading and unloading, depending on the mechanisms used for these operations and the structure associated with the technology. Port crane operations can also cause damage to the wind structure),
- Stability and heel – the large forces created by the rigs can produce heeling forces which may need to be catered for both at the Service Limit State (standard operation) and the Ultimate Limit State (extreme weather conditions).
- Visibility obstruction – many of the technologies produce obstructions to lines of sight both in operation and when stored. These issues need to be checked against rules for safety in operation.
- Air draught constraints – bridges and equivalent structures can impose air draught limits that need to be considered and either impose limits to the height of the installation, added complexity to allow for a folding/collapsible rig, or constraints on area of operation.
- Crew safety – moving parts associated with wind assistance technologies could present hazards to crew.
- Crew training – operation of wind assistance technologies could impose additional training requirements and work load for the crew.

To address the primary concerns relating to structural integrity, cargo handling and stability, some wind technology companies have developed a retractable version of their technology. For non-retractable versions, it is possible that the non-retractable version “requires additional precautions to avoid structural damages by port cranes.” One wind technology provider offers an insurance package to accommodate for possible damages during port operations.

One of the major external risk barriers is the uncertainty about the fuel price. A higher fuel price provides more of an incentive for shipping companies to invest in energy efficient technology. This was apparent from the number of eco-ships being ordered in 2011 due to the escalation in the fuel price [72]. The drop in bunker fuel prices in 2014 has had an impact on ship owners’ interest in wind technology, as the lower price means that the payback is longer.

3.3.2. Access and costs of capital

Restricted access to capital markets is often considered to be an important barrier to investing in energy efficiency. Investments may not be profitable because companies face a high price for capital. As a result, only investments yielding an expected return that exceeds this (high) hurdle rate will be realised [73]. Wang et al. [47] in their modelling suggest a range between $0.7 m and $1.2 m for Flettner rotors and between $0.5 m and $3.6 m for towing kites of different sizes but this may not reflect the actual cost. (Table 2) shows the cost of one Flettner rotor unit as documented in the survey by a technology provider is just over $2 m, twice of that assumed in the modelling.

The shipping industry's culture has been historically conservative and risk averse [10,74], which means that shipping companies are reticent to be the first mover of adoption of unproven technologies. According to one wind technology provider, “everyone would install the system today if it were already proven on a commercial scale. This is the typical chicken-and-egg issue.” Another technology provider also cited being the first mover as a primary concern of ship owners. Because of this, clean tech companies developing wind technologies have to rely on alternative methods to finance investment in trials. One provider stated “we are developing a package for the first commercial installation where we plan to subsidize part of the expenses to make it more attractive for the first client.” The economic downturn of 2009 put a constraint on liquidity given poor economic conditions, which led traditional shipping banks to decrease their loan books on shipping finance and as a result are less willing to participate in loans to retrofit ships.

Currently, third party financing is gaining traction in shipping, however investors are only willing to finance technologies that are proven and mature [75]. As a result, wind tech companies have to rely on their own equity or public funding.

3.3.3. Hidden costs

Hidden costs are costs that are not included in the purchase price or payback model provided by the technology firm, but that are envisaged by the investing firm. These include overhead costs related to the investment, the cost of collecting and analysing information, and production disruptions. For wind technology, these include hidden installation costs, the potential to reduce the cargo space, and production disruptions. Production disruptions could occur during installation and operation. To install wind technology on a ship, the operations have to be temporarily suspended. This disruption could potentially be a high opportunity cost, especially when the market is experiencing a boom.

Another concern that a wind technology provider mentioned was “whether installing our wind system would in any way compromise the typical sailing and routing patterns of (the customer's) vessels.” The route sailed using a diesel powered ship may not be the most optimal route sailed using a ship with wind technology, because the wind might be more favourable if the ship took an alternative route. If most of the voyages take longer in order to take full advantage of the wind, then the alternative value of making fewer paid trips per year will likely outweigh the savings in fuel. This opportunity cost is one explanation for the lack of take-up in the industry.

Another hidden cost is the installation cost. According to one wind technology provider, “the installation of our system requires some deck reinforcement to overcome the moment (force) at the base generated by the wind. This reinforcement does not require superstructures and is not something that we foresee as an engineering challenge. Structure-wise our system's installation can be accommodated on a ship deck in a similar fashion as a deck crane and without additional investments.” Other responses that suggested not all costs have been factored into the payback analysis were, “it is possible that the current version (non-retractable) of our wind system requires additional precautions to avoid structural damages by port cranes.”

The workshop revealed that ship owners were concerned that the wind technology might take up additional space, reducing the amount of cargo space. The revenue lost from forgone cargo must be offset by additional fuel savings; thus a payback model which does not account for this opportunity cost would be overstating the payback period.

In their techno-economic or investment appraisal analysis, all of the wind technology providers suggested that the investment cost of their technology would be paid back within five years (with some even indicating shorter payback periods). However, the aforementioned hidden costs such as opportunity costs are not included in these models and would likely lengthen the payback period.

3.3.4. Heterogeneity

Although a technology may be cost-effective on average for a class of users taken in aggregate, the class (e.g. size of ship, company size, specific routes), itself, consists of a distribution of

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heterogeneous owners and operators: some could economically purchase additional efficiency, while others will find the new level of efficiency not cost-effective [76]. The dry bulk and wet bulk shipping sectors are heterogeneous due to the differences in ship sizes, commodities or cargoes, ownership and contracting practices [77]. These sectors have been among the key sectors targeted by wind technology companies based on responses from the survey and workshop.

Barriers due to heterogeneity in the shipping industry include company size and ship type. The wide scale adoption of wind technology requires not only installing wind technology on thousands of ships, but also reaching out to thousands of shipping companies. Analysis of ship ownership in 2012 shows that companies in the dry bulk and oil tanker sectors, which are being targeted as early wind tech adopters, own on average just over four ships, while ownership in the oil tanker sector is just under three on average. This low average ownership places an administrative burden on wind technology companies and banks to finance their cost because of the low economies of scale.

The market segments in shipping are also heterogeneous. The survey responses reflected the heterogeneity in the market by stating the way cargo is handled differently. For example, “most typical concerns on the customer side are related to availability of deck space for the wind system and cargo handling restrictions related to them,” but these “concerns only apply to dry bulk ships, while tankers typically do not involve the use of port cranes.” Other technical considerations apply only to certain ship types. **“**When designing a wind system, height limitations are taken into consideration. A natural limit will be the height of the ship’s tallest point, which in case of a mid-size dry bulk is typically above 20 m, so in line with the size of wind system we are considering in our calculations.”

Another dimension of heterogeneity are the routes of operation. One wind technology provider who has been in a discussion with a tanker company said they found the routes of operation to be in the less windy regions, making the payback longer than for other market segments like the dry bulk sector.

4. Third-party financing solutions to overcome barriers to implementation

Third-party-financing models have been used in the buildings and renewable energy sectors to overcome the capital cost barrier discussed in Section 3.1. These sectors have also overcome split-incentives issues, and incorporated measurement and verification technology into the package that is financed. Currently, these finance models, such as Property Assessed Clean Energy Financing (PACE), on-bill financing [62] offer new sources of capital for proven retrofits, but in theory could also be used to finance wind technologies.

The “Self-Financing Fuel-Saving Mechanism” (SFFSM) for shipping was inspired by the Energy Service Company (ESCO) model that has been successful at accelerating energy efficiency retrofits in the buildings sector. The financing model facilitates the adoption of fuel-efficiency technologies for either long-term time-chartered ships or owner-operated ships. The financing model secures the upfront capital investment cost of fuel-efficient retrofit technologies from a third party financier. Financiers recoup their return from the fuel-cost savings generated by the gains in fuel efficiency afforded by the technologies.

The mechanism requires a baseline fuel consumption to be established for the ship. (Fig. 6) shows the method, developed by one of the authors to quantify fuel savings from the installed technology. Before the technology is installed on the ship, data is collected using noon report and/or continuous monitoring equipment. Over time, the ship’s hull deteriorates due to fouling as can be seen from the increase in fuel consumption before the ship goes into dry-dock. When the ship is dry-docked, the technology is installed and a downward step change in fuel consumption occurs. To estimate the counterfactual fuel consumption, multivariate regression analysis is used, which also accounts for the trend in deterioration of the ship’s fuel efficiency after the first dry-dock and before the second dry-docking.

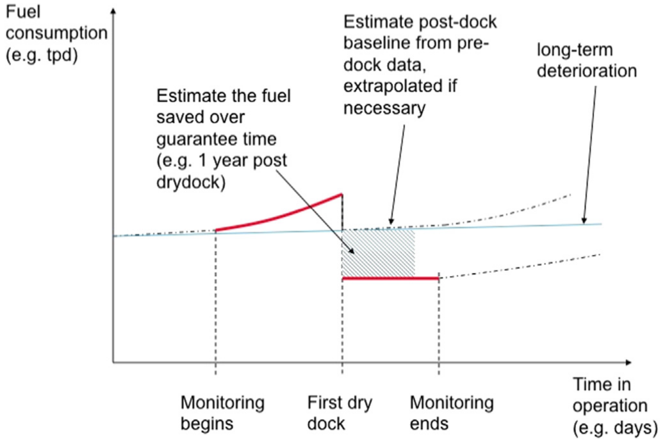

Fig. 6. Monitoring and measurement to calculate fuel savings.
Source: Stulgis et al. [75].

4.1. Impact on economic barriers

The financing model offers the shipping industry a method for overcoming some of the market and non-market failures barriers discussed in Section 3; namely, access to and cost of capital, split-incentives and imperfect information.

4.1.1. Access to and cost of capital

Lack of access to capital is addressed by collaborating with third-party financiers, based on findings that most traditional banks are currently hesitant to fund fuel-efficiency retrofit projects on a large scale. Third-party financing firms are mainly attracted by the short paybacks of these retrofits, especially in light of the performance guarantees provided by the technology vendors under the financing model. A practical example of this is Carbon War Room's partnership with EfficientShip Finance (ESF), a specialist advisory and investment firm focused on fuel efficiency retrofits for shipping. ESF invests in a bundle of technologies delivering 10–15% fuel savings, and is repaid by sharing the bunker fuel savings or increased charter hire achieved by the solutions implemented. Independent performance monitoring is used to track the achieved results and trends over time and to ensure continuous results. In addition to taking on the capital investment, ESF takes on the risk of the technologies that may not meet the estimated fuel savings, as well as the uncertainty in fuel prices. At present, ESF only invests in technologies that have proven fuel saving gains on a minimum number of ships, but will consider financing wind technologies once they have been sea trialled. The company has found that bundling technologies to achieve savings greater than 10% provides ship owners with greater negotiation power than a ship that is only 5% more fuel efficient than the benchmark ship of the same type and size because of the margin of error in measuring fuel consumption on ships.

This example illustrates that once there is high-quality data and proven returns for wind technologies, the companies may see their options for third-party finance expand. Public funding (for example a grant, which might not require a high certainty of

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financial return on investment) for trialling wind technologies on commercial vessels, could provide the type of capital that would enable wind technology companies to test their technologies, and collect valuable data [10]. If the data demonstrates rigorously and robustly that a profitable and attractive business case can be made, and this information can be placed into the public domain, technology companies should be much more successful in securing interested ship owners and investors.

An alternative to the use of public funding to trial the technology is to explore whether computational models could be used to provide the quality and reliability of performance analysis required for investors to have confidence to invest. Such computational modelling could build on existing work [8], and would need further validation of any performance analysis (which could be done through simulation of existing ship's performance on specific voyages), as well as the development of costing analysis, but could be a lower cost route to market than a full-scale trial.

4.1.2. *Split incentives*

The SFFSM tackles the split incentive issue created in the time charter market and discussed in Section 3.3 by its ability to serve vessels on long-term charters. In this case, the mechanism could be set up with the charterer who would invest in the technology and pay back the cost through the fuel savings.

4.1.3. *Informational problems*

To overcome a lack of data regarding the performance of fuel-efficiency technologies, technology providers working with the SFFSM must be able to guarantee that their respective technologies will deliver a certain percentage of fuel savings when installed as part of a bundle of retrofits. Accurately verifying those fuel savings once the technologies are installed is fundamental to the financing model, and, as explained in the previous subsection, this requires that advanced new 'continuous monitoring equipment' be installed onto each retrofitted vessel. Imperfect information about a ship's performance in real operating conditions can also be overcome with continuous monitoring equipment and the establishment of a credible baseline. This information can be used to improve the negotiation power of ship owners and also diminish the mistrust by charterers' about fuel efficiency claims as a result of asymmetric information.

5. Concluding remarks

This paper contains a review of the economic barriers, namely the market and non-market failures, in order to understand the implementation barriers to wind technologies in the shipping sector. Ship owners and operators are most concerned with the technical risks involved, the hidden costs of the technology, and the cost of an unproven technology. This points towards the existence of non-market failures suggesting that ship owners and operators are being rational in their decision making to withhold investment in wind technologies. Informational problems about ships' fuel efficiency in real operating conditions have contributed to the lack of trust in the fuel efficiency claims made by technology providers. Further exacerbating the implementation is the heterogeneity of the shipping sector and split incentives, which requires careful consideration of the sectors, size of the firms operating in the sectors and their exposure to different types of charter arrangements. The paper suggests that innovative financing solutions could be used to overcome the two key market failures (imperfect information and split incentives) and some non-market failures (access to capital).

Given that the innovative financing solution only tackles some of the economic barriers, further work would be beneficial in a number of areas. For example, understanding the ship and wind technology interface through physics, naval architecture and marine engineering is necessary in order to further de-risk the technology. Further work to solve additional barriers not addressed by the financing solution could be to better understand the heterogeneity of the market including exposure of other ship types to split incentives, improving our understanding of operational efficiencies in the sectors and the different type of charters.

On the issue of informational barriers, direct funding from national, supra national (e.g. EU) or international sources (e.g. IMO), specifically for trialling wind technologies on commercial vessels, could be an important enabler of wind technology take-up, by producing rigorous and robust measurements of performance from full-scale trials which are then placed into the public domain. If the data demonstrates a profitable and attractive business case, technology companies will be much more successful in securing interested ship owners and investors. As an alternative or in parallel to full-scale trials, further effort could be placed in computational modelling of performance, and validation of these computational models to assist with investment decisions.

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