

# The diffusion of energy efficiency technologies in shipping

Nishatabbas Rehmatulla<sup>1</sup>, Solmaz Haji Hosseinloo<sup>1</sup>, Tristan Smith<sup>1</sup> & John Calleya<sup>2</sup>

<sup>1</sup> UCL Energy Institute, Central House, 14 Upper Woburn place, WC1H 0NN, London, UK.

[n.rehmatulla@ucl.ac.uk](mailto:n.rehmatulla@ucl.ac.uk)

<sup>2</sup> UCL Mechanical Engineering Dept., Roberts Building, Torrington Place, WC1E 7JE, London, UK.

## Abstract

Energy efficiency technologies are a key enabler for shipping's transition towards a low carbon future. Numerous energy saving technologies have been suggested but their implementation is not well known. To that end various attempts have been made to assess the uptake of these technical energy efficiency measures in shipping. The research described in this paper goes further than the general level implementation of the measures by assessing the implementation at the ship level (e.g. by ship type and ship size) and at the company level (e.g. type of company and size of company) thus enabling to build an accurate picture of the take-up of these measures. This is done through a survey of over 270 shipping companies, across 30 countries. Thereafter, a framework is developed to reliably forecast uptake of energy efficiency innovations in shipping. The results from the survey suggest the widespread use of bulbous bows, pre/post-swirl devices, engine modifications, lowering design speed and de-rating. The framework developed in the paper could be a suitable way forward to forecast future take-up of energy efficiency technologies in shipping.

## Keywords

Energy efficiency gap, diffusion of innovations, barriers, modelling, survey

## 1 INTRODUCTION

Operational and technical measures can improve the energy efficiency of ships and consequently the carbon intensity and emissions can be lowered. With mounting pressure from emissions regulations and volatile fuel prices, the shipping industry is constantly seeking new ways of improving fuel consumption and reducing emissions at the ship level (e.g. per tonne mile). There is however a disconnect between the improvements being made at the ship level and the absolute CO<sub>2</sub> emissions required from the industry, due to the rising demand for shipping services and potential future emissions regulation. For the purposes of this paper, we will assume that transport demand is out of scope as a 'lever' to reduce emissions and thus we focus only on the transport supply side, improving energy efficiency as a strategy towards low carbon shipping.

Over fifty measures (Buhaug et al. 2009; Wang et al. 2010) have been identified that could result in efficiency gains and they are generally grouped as technical measures (some applicable to new ships and some to existing ships) and operational measures. With so many options on the table, the clear question then is: what is the implementation of these energy efficiency measures and if it's not as expected (based on models or targets) as it is supposed to be, then why? And what does the characterisation of this gap mean for any future uptake of these technologies. The former question refers to the energy efficiency gap (Jaffe & Stavins 1994), which has been suggested in various sectors (Rohdin, Thollander & Solding 2007; Thollander & Ottosson 2008), including shipping (Rehmatulla & Smith 2015; Rehmatulla, Smith & Wrobel 2013; Jafarzadeh & Utne 2014; Johnson, Johansson & Andersson 2014; Rehmatulla & Smith In Press). The latter question revolves around the diffusion of technologies (Rogers 2003), the rate of adoption of different innovations and diffusion networks. Currently there is good data available on which ships are slowing down and by how much, using Satellite Automatic Identification System S-AIS (Smith et al. 2013; Smith et al. 2014), as well as general survey responses on operational efficiency (Rehmatulla 2012; Maddox Consulting 2012). However, operational energy efficiency is only one aspect of efficiency and this research attempts to check whether this is in combination or separate from interventions with technology. This paper provides the first analysis of the implementation of the technical measures, using the survey method. It is hoped that this data would create a baseline of observed implementation which could then be used to compare with the modelled implementation, using GloTraM, and to assess the energy efficiency gap.

## 2 LITERATURE REVIEW

### 2.1 IMPLEMENTATION STUDIES

Several attempts have been made to assess the uptake of technical energy efficiency measures in shipping. The first studies that attempted to gauge the implementation of technical measures and operational energy efficiency measures were Faber, Behrends & Nelissen 2011 and Maddox Consulting 2012. Both these studies had very few responses from shipowners and operators, five and twenty eight, respectively, and the implementation was mainly based on expert judgement of the authors.

HSH Nordbank's (2013) survey of sixty shipping companies within its portfolio, was one of the first studies that attempted to gauge the nature of implementation of technical energy efficiency measures and the impact of policies (at the global level) on the attitude towards implementation at a larger scale. The results show that almost half of the respondents were engaged in either acquiring energy efficient newbuilds or were actively retrofitting their vessels. The sample is not representative, but nevertheless suggests a high degree of technical interventions were taking place. A third of the respondents had retrofitted more than 50% of their fleet and almost 40% had done this for less than 10% of their fleet. A third of the respondents of the survey indicated they planned or had implemented optimisation and modification of the rudder and propeller and another fifth of the respondents had planned or implemented modifications affecting the bow and/or the hull, though the extent and the details of which are not known. For newbuilds the implementation of technical measures was shown to be clearly much higher, e.g. almost two thirds of the respondents had implemented optimised hull openings and engines that were optimised for slow steaming, and over half of the respondents had implemented measures that optimised rudder-propeller combination.

Rojon & Smith (2014) survey of 130 shipowners & operators focuses on the strategies for measuring fuel consumption and in light of this, asks the respondents if they have implemented any technical measures and how they have verified the savings from these interventions. The survey showed almost 80% of the surveyed companies had adopted fuel saving technologies in the past five years, almost half of which include more than one technology at a time. Similar to HSH Nordbank (2013), Rojon & Smith (2014) show that propeller modifications had been implemented by over half of the respondents in the sample, though the implementation of machinery measures and hull coatings was higher than that of propeller modifications. Whilst the data can be broken down by ship type and type of company (i.e. what measures have been implemented in which ship types & by which type of operator), the data is not captured for the size of the ships on which the measures are implemented and whether the measures were retrofitted or for newbuilds.

DNV GL (2014) survey of 85 shipping companies (75 shipowners, operators and management companies) focuses on all the areas covered by HSH Nordbank (2013) and Rojon & Smith (2014) i.e. assesses the drivers for implementing the energy efficiency measures (including policies), monitoring and reporting energy data, as well as obtaining implementation rates for twenty one 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. IMarEST & Colfax (2015) survey of 200 shipping companies (around 80 shipowners, operators and charterers) attempts to gauge the attitudes towards implementation of 'green' practices or measures (which includes SO<sub>x</sub>, NO<sub>x</sub> and ballast water management). The survey looks at the implementation in some detail e.g. whether the company has already implemented, planning to implement or will not implement a particular measure and not a dichotomous level (Tornatzky & 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.

Table 1: Summary of key findings from previous studies

Study	Year	Sample size	Key finding	Comments
Faber, Behrends & Nelissen	2011	4	40% average implementation across 30 technologies Engine related highest implementation ~ 55% 20% average implementation for alternative energy	Very small sample
Maddox Consulting	2012	25	Average 30% implementation in 7 technical measures	Small sample
HSH Nordbank	2013	60	1/3 retrofitted more than 50% of fleet Hydrodynamic measures prevalent	Sample within portfolio
Rojon & Smith	2014	130	80% had implemented at-least one technology: Machinery, hull coatings, propeller modifications	Aggregate level data
DNV GL	2014	75	75% implementation across 21 measures	Aggregate level data
IMarEST & Colfax	2015	80	High implementation for alternative fuels Lower implementation for other measures	Aggregate level data

## 2.2 THE ENERGY EFFICIENCY GAP AND THE DIFFUSION OF INNOVATIONS MODELS

The literature on implementation suggests moderate level of implementation when measures are taken in aggregate. Looking at certain categories of measures reveals marked differences in implementation of measures, with several of the measures showing very little or no implementation. There could be several reasons for the low levels of implementation. The difference can be mainly explained using two key concepts. First, it is possible that the technology is undergoing a typical product life cycle or diffusing in the system, which specifies that all products will progress over time in non-linear fashion (the S-curve) (Rogers 2003). The diffusion rate is as a result of the attributes of the innovation itself, the communication channels, time and the social system (Rogers 2003). Secondly, there may be barriers which are impeding the progression of the product along the life cycle, leading to an energy efficiency gap, which describes the difference between an ideal range of implementation versus the lower levels observed in practice (Rehmatulla & Smith 2015). The concept of barriers in shipping has been investigated by (Jafarzadeh & Utne 2014; Acciaro, Hoffmann & Eide 2013; Johnson, Johansson & Andersson 2014; Rehmatulla & Smith 2015). With exception of a few (Darley & Beniger 1981; Dieperink, Brand & Vermeulen 2004; Jaffe & Stavins 1994; McMichael & Shipworth 2013) the above two concepts have rarely been empirically studied in tandem.

The earliest diffusion studies began in the early 1940's (Ryan & Gross 1943) and continued to receive increasing attention in the mid to late 21<sup>st</sup> century in various disciplines ranging from sociology (Bowers 1937) to anthropology (Pelto 1973) and from public health (Berelson & Freedman 1964) to marketing (Bass 1969) with an exponential increase in diffusion studies taking place in the early 50's and 90's (Rogers 1976). Diffusion studies covered a wide array of sectors and disciplines, with the best contributions coming from the sociology and marketing disciplines. The Bass model of diffusion and the epidemic models of diffusion, in marketing and management respectively, have enabled researchers to predict the uptake of new products and other innovations. The diffusion model has also been applied in the innovations in the energy sector (Darley & Beniger 1981; Dieperink, Brand & Vermeulen 2004; Kok, McGraw & Quigley 2011), and the renewable energy technologies (Eleftheriadis & Anagnostopoulou 2015). The paper will attempt to provide a first analysis of the use of diffusions of innovation theory and whether it can produce valuable insights for assessing the future take-up of energy efficiency technologies in shipping.

## 2.3 CONCLUSIONS FROM LITERATURE

The following conclusions can be drawn from the foregoing review:

1. The surveys conducted to date to assess the current implementation of technical energy efficiency measures have lacked methodological rigorousness, 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.
2. The sample size has been low, in the region of 50-100, which is not enough to attain statistical significance even if the whole shipping population was deemed homogeneous.
3. Details of implementation have generally been left out for example the exact specification of retrofit & newbuild, ship type and ship size in which the measure has been implemented
4. There is a lack of use of diffusion research in conjunction with barriers research, which can help to characterise the diffusion of energy efficiency technologies in shipping.

### **3 METHODS**

The research questions that the work informing this paper aims to consider include;

1. What is the current rate of implementation of technical energy efficiency measures in shipping and what are details of the implementation of those measures?
2. What is the future uptake of these technologies out to 2050? How can diffusions research or other models help to predict future technological pathways?

The result of the data generated from the above research questions is a better picture of how energy efficiency is being achieved and a generalization of what technologies are being fitted to which ship types/sizes and age and by which type and size of ship owner. Figure 1 shows the framework to answer the research questions.

To answer the first research question a survey was developed, which followed the TDM (Dillman 2009) and the survey procedures developed in (Rehmatulla 2014) and detailed (Rehmatulla & Smith In Press). The survey covered all the technical measures and excluded of operational measures. The unit of analysis or target population were global shipping companies, which were recruited from Clarksons Shipping Information Network (SIN) database of shipowners. A stratified sampling approach was taken so as to represent the different variables of interest to the survey. The sampling frame was stratified by size (small, medium and large), sector (wetbulk, drybulk, containerised and mixed) and region (EU, North & South America, Asia and Far East). The majority of the companies are headquartered in European Union region and the Far East, altogether representing nearly 90% of the census population (Rehmatulla 2015).

270 companies were contacted by phone and almost 200 companies responded, resulting in a 72% response rate, using the sampling frame. The remainder responses were received from various other sources e.g. membership databases and third party mailing lists. In total the survey received 275 responses representing almost 20% of the wetbulk, drybulk and container fleet (28,000 ships according to Third IMO GHG Study). 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. The primary respondents to the survey were shipowners, shipowner-operators and management companies. 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 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. The majority of the responses were from companies headquartered in the EU, mainly in Greece and Germany.

The second research question is answered using a qualitative literature review of the diffusion of innovations studies. The findings from this review are then used to test forecasting of one energy efficiency technology in shipping and develop a framework for future work on this subject.

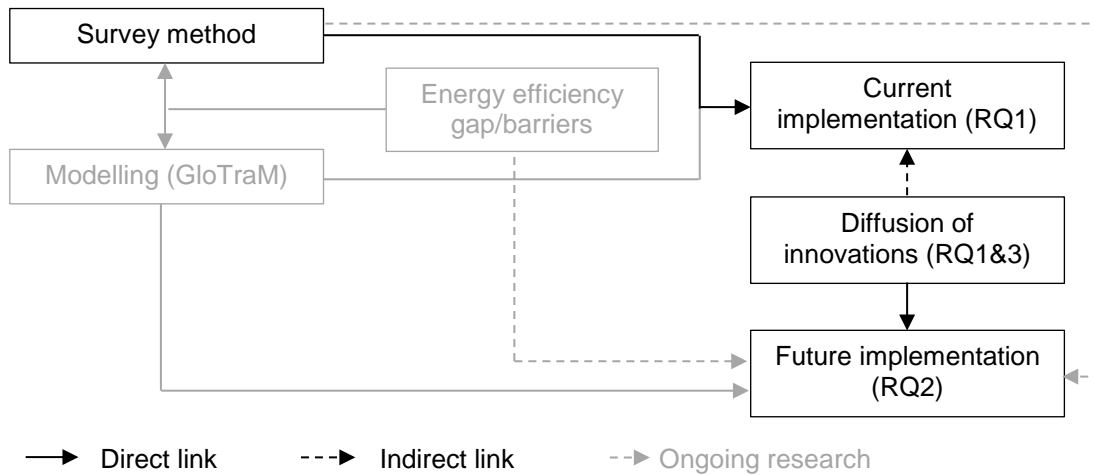


Figure 1: Framework to assess current and future implementation

## 4 RESULTS

### 4.1 CURRENT IMPLEMENTATION

Figure 2 shows the implementation of design technologies from the survey. The figure shows clearly the use of bulbous bows is widespread, almost 80 of the 275 respondents had implemented it and the absolute number (ten to fifteen ships per company) 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. The increased area of the wetted surface due to a bulbous bow increases the frictional resistance; at low speeds this increase is usually greater than the reduction in resistance (Bertram & Schneekluth 1998). This may mean that in some cases, particularly for slower and longer ships that operate at lower Froude numbers, there may be a benefit in not having a bulbous bow (Calleya 2014).

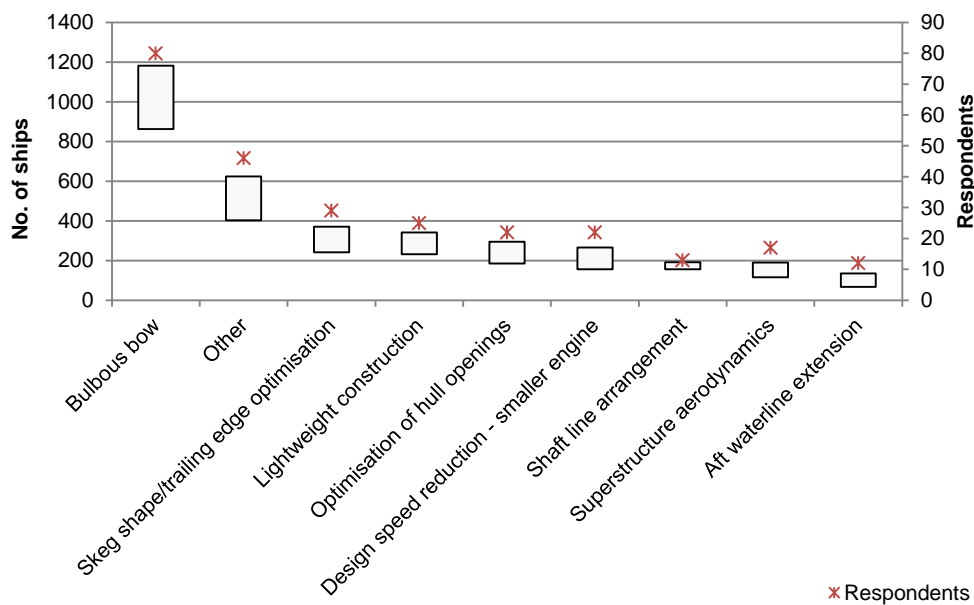


Figure 2: Implementation of design measures

Figure 3 shows that the adoption of pre/post-swirl devices is quite high, as shown in previous studies. Similar to the design measures the effectiveness of these devices can be dependent on the particular

ship that is being used, a ship with a bad aft-end may be easier to improve, this may be related to the ship type or cargo that is being carried. Some hydrodynamic devices may even cause an increase in fuel consumption. The adoption of air lubrication is promising in that it can provide an additional reduction in fuel consumption to one that is hydrodynamically well designed. Some design models suggest that the gains may be in the region of 1.0 to 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.

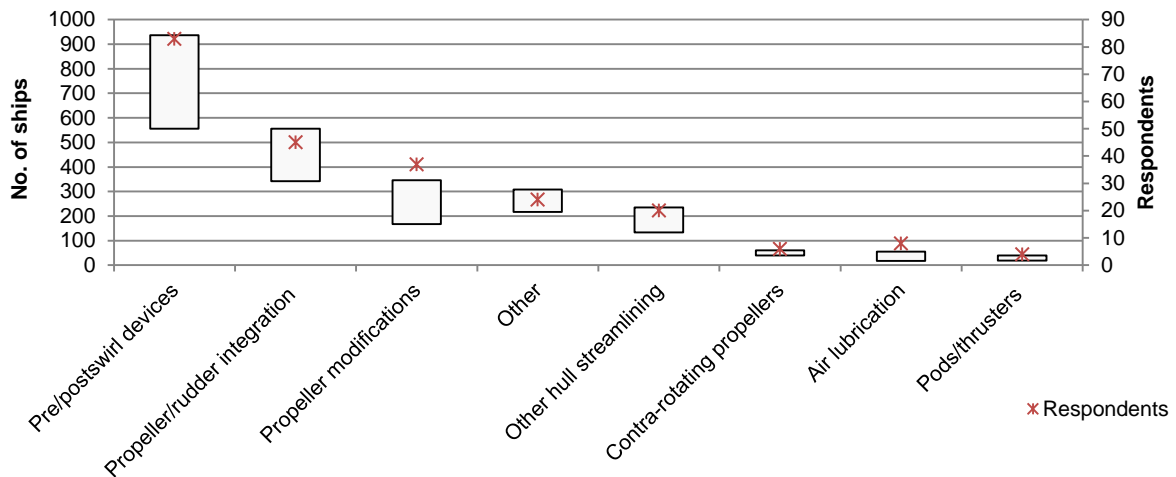


Figure 3: Implementation of hydrodynamic measures<sup>1</sup>

In contrast to Figure 2 and Figure 3, the machinery measures (Figure 4) shows that there several measures that have had high adoption within the companies. The high implementation of energy saving lighting is perhaps due to the relative ease of implementation despite the low level of cost-effectiveness of the technology for the ship types studied. Some of the machinery measures can depend on the operating profiles being considered. For example, diesel electric drive is less likely to be used on some cargo trades where ships operate at a narrow band of speeds. The reduction in fuel consumption from energy-saving lighting is likely to be very small (less than 1%) although the implementation of these is quite high due to the maturity of the technology and ease of implementation.

Speed reduction and engine de-rating are popular strategies to reduce carbon dioxide emissions. Engine upgrades are normally applied as part of a package that includes changes in the turbo charger, pistons and pumps (Buhaug et al. 2009). It is not clear to whether de-rated engines are being fitted or an engine with a lower power is being installed. For an existing ship and without changing the propeller, this will result in a lower 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) specific fuel oil consumption can be decreased and the speed can be lowered. This is a possible retrofit option for existing ships. If the same speed needs to be maintained then the engine would have to be changed. For new ships engine de-rating for a ship with a given design speed would involve installing a more powerful engine than usual and operating it at a lower speed, this would result in a reduction in specific fuel oil consumption 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. The reduction in design speed results in a much larger reduction in fuel consumption and EEDI compared to de-rating.

<sup>1</sup> Pre/post swirl devices includes: boss cap fin, vane wheel, presswork ducts, mews duct, stator fins  
 Propeller/rudder integration includes: propeller rudder bulb, propeller rudder matching/combination, asymmetric rudder  
 Propeller modifications includes: advanced blade sections, winglets/Kappel, prop section optimisation  
 Other hull streamlining includes: low profile openings, optimisation of water flow openings  
 Pods/thrusters includes: wing thrusters, pulling thrusters, wing pod, pulling pod

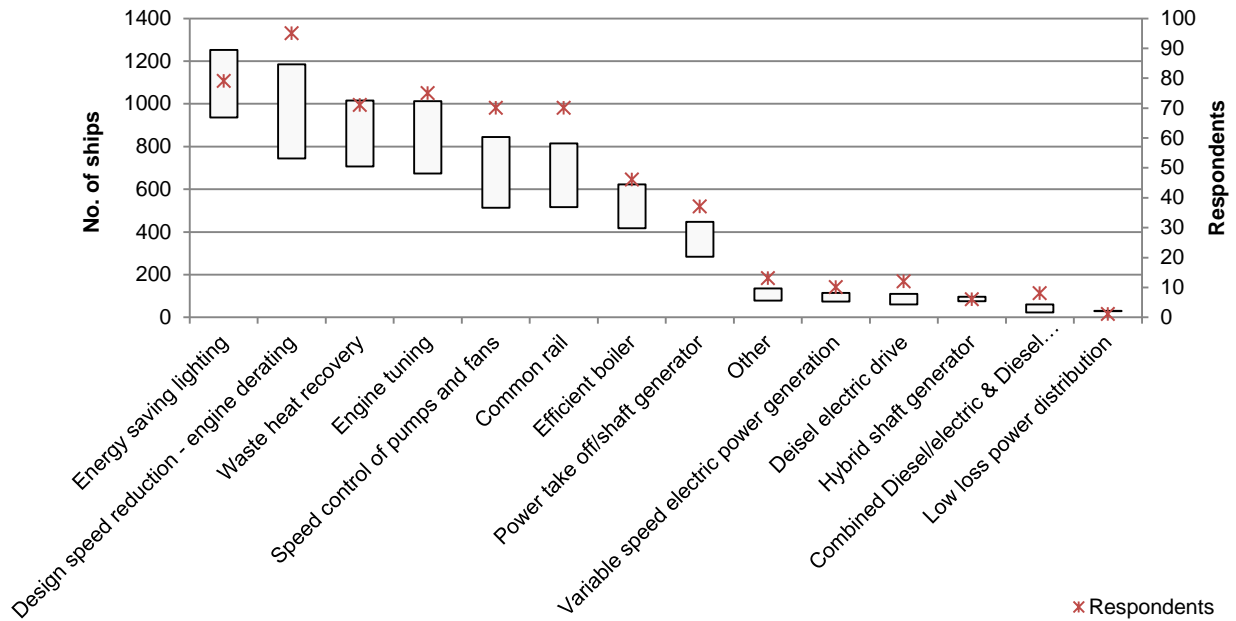


Figure 4: Implementation of machinery measures

Figure 5 shows the implementation of alternative energy sources to Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO). It is difficult to interpret the high usage of batteries and fuel cells from the survey. This may be because batteries are included in most machinery arrangements, which may not be novel. The adoption of fuel cells seems very unlikely. 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 (Calleja, 2014), though the higher savings in this area are unlikely to be cost effective. Wind assisted propulsion has the largest potential in CO<sub>2</sub> emissions, however these technologies have not been adopted by any ships.

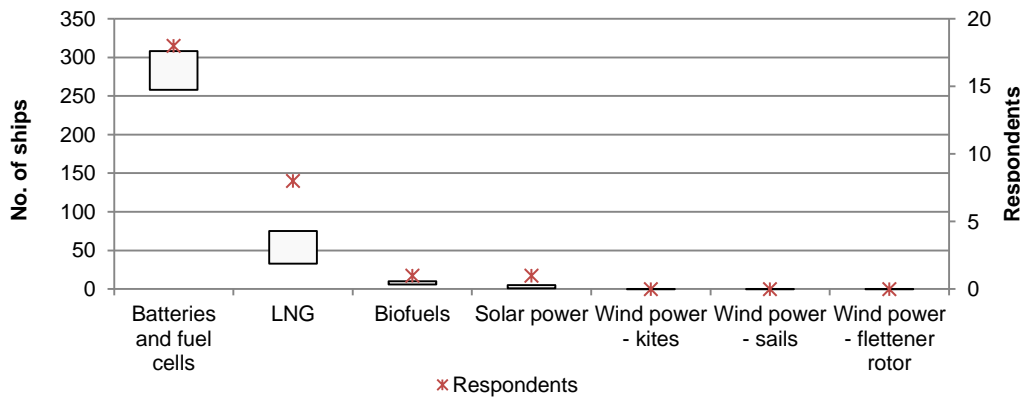


Figure 5: Implementation of alternative sources of energy

#### 4.2 FRAMEWORK FOR FORECASTING ENERGY EFFICIENCY INNOVATIONS UPTAKE

In this section an attempt will be made to synthesise various diffusion forecasting studies with the aim of producing a framework that encapsulates the various factors at play during the diffusion of an innovation and how this framework can be applied to predict future uptake of energy efficiency innovations in shipping. The most important variables to determine the rate of adoption of an innovation (i.e. the speed with which an innovation is adopted, steepness of the adoption curve) are; understanding of the attributes of innovations, types of innovation decisions, communication channels, innovativeness of the adopters and social network of the system (Rogers 2003), though the most important prediction comes from the perception of the attributes of the particular innovation,

which explain almost 50%-85% of the rate of adoption (Rogers 2003). Generally these attributes have been classed as relative advantage, compatibility, complexity, trial-ability and observability (Rogers 1995), though these categories have been suggested as too vague by Tornatzky & Klein (1982) and require further conceptualisation. Various other attributes (over twenty) have been suggested by Moore & Benbasat (1991), Tornatzky & Klein (1982) and Kearns (1992). The adoption of innovation or technologies (or artefacts) is also as a result of wider or systemic technological transitions, defined as the way societal functions are fulfilled (Geels 2002) and composed of the socio-technical landscape (wider technology external factors), socio-technical regimes (the technology itself, users, etc.) and technical niches. Figure 6 shows how our understanding of diffusions of innovation models, technological transitions model and barriers to energy efficiency can be used to explain the qualitative aspects of the rate of adoption and predict the future uptake of a technological innovation.

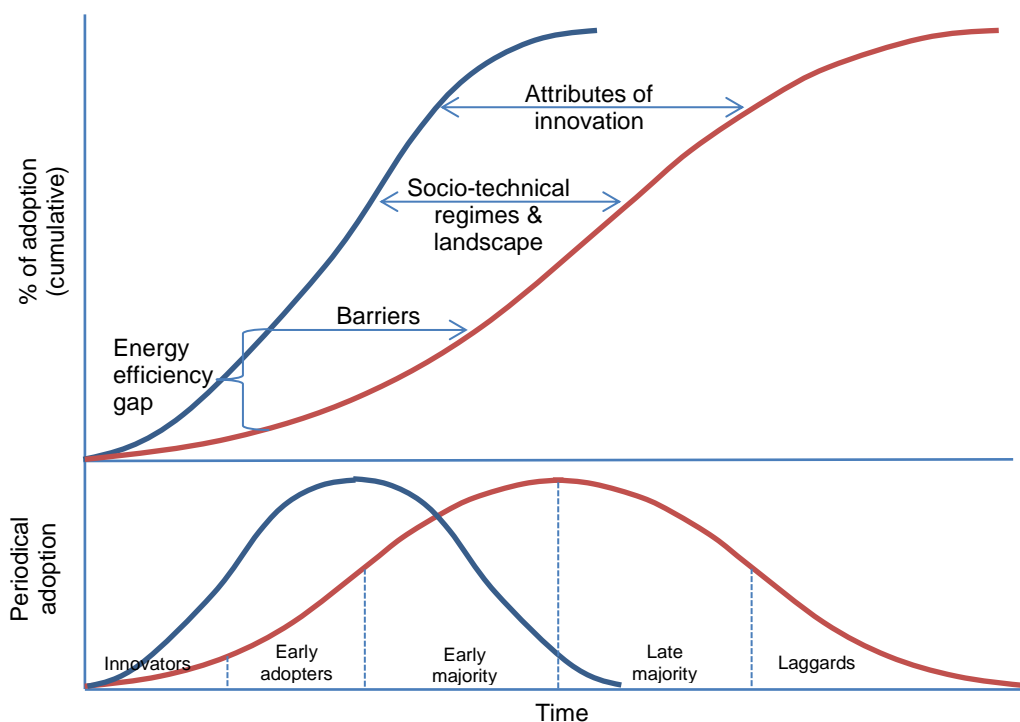


Figure 6: Framework for assessing factors and predicting the rate of adoption of an innovation

Currently there is a good understanding on the subject of barriers to implementation of energy efficiency technologies in shipping (Jafarzadeh & Utne 2014; Acciaro, Hoffmann & Eide 2013; Rehmatulla & Smith In Press). However, in order to be able model and predict future uptake of energy efficiency technologies in shipping, future work needs to focus or translate the vast expanse of diffusions of innovations literature as well as the growing literature on technological transitions. The problem, however, with using diffusions of innovations literature is that majority of the studies are postdiction (ex-post) studies of individual choices. Relatively few studies have predicted the rate of adoption of innovations in the future e.g. (Bass 1969) and focused on the organisation, and extremely limited studies focus on the 'prediction' of energy efficiency innovations adoption, for generalist studies on this subject refer to (Darley & Beniger 1981; Dieperink, Brand & Vermeulen 2004; Beise & Rennings 2005; Kok, McGraw & Quigley 2011). An ideal research design would thus measure attributes of innovation at  $t_1$  in order to predict the rate of adoption for some future time  $t_2$  (Rogers 2003; Tornatzky & Klein 1982).

The Bass diffusion model is one such predictive model that attempts to forecast the adoption of a new product and is perhaps the most widely utilised theoretical model (Rogers 2003). The model proposes that individuals are influenced by a desire to innovate (coefficient of innovation  $p$ ) and by a need to imitate others (coefficient of imitation  $q$ ), with the probability that a potential adopter adopts at time  $t$  is driven by  $p+qF(t)$ , where  $F(t)$  is the proportion of adopters at time  $t$  (Meade & Islam 2006). The general conclusions from numerous studies e.g. (Teng, Grover & Guttler 2002; den Bulte &



Stremersch 2004) that used the Bass Forecasting Model find very low coefficients of innovation (internal influence), suggesting that imitation (external influence) is the main driver for adoption. Several studies have applied and extended (Rogers 1962) and the Bass Forecasting Model (Bass 1969) to predict uptake of innovations, in a global setting (Talukdar, Sudhir & Ainslie 2002; Lee 1990; Mahajan, Muller & Wind 2000), studying multiple innovations at a time, impact of marketing mix variables (e.g. price and promotion) (Bass, Krishnan & Jain 1994) and over multiple generations of innovations (Norton & Bass 1987; Mahajan & Muller 1996; Islam & Meade 1996), all of which can be useful in context of predicting the diffusion of various energy efficiency innovations in the international shipping sector. Meade & Islam (2006) provide a review of the eight basic models and subsequent modifications to these. Rogers (1962) argues that populations are heterogeneous in their innovation characteristics, based on a normal distribution; innovators, the first to adopt the innovation (2.5% of adopters) are followed by early adopters (13.5%), followed by early majority (34%), followed by a late majority (34%) and laggards (16%). Some of the findings in the diffusions literature can be directly linked with barriers to energy efficiency literature, for example in the case of heterogeneity it has been found that early adoption in firms is related to the size of the organisation, larger organisations adopt the technology earlier (Libertore & Bream 1997) and Baptista (1999) shows that geographical location affects the rate of diffusion.

Using the insights from the above, forecasts for uptake of energy innovations in shipping can be made. Sultan, Farley & Lehman (1990)'s meta-analysis of diffusion models suggests that the coefficient of innovation remains fairly stable whereas the coefficient of imitation is variable but averages 0.38 across the 213 applications studied. den Bulte (2000) meta-analysis study of over 1500 sets of  $p$  and  $q$  provides a good starting point to estimate diffusion with a 90% confidence interval for different products and regions. In the following example as a starting point, we use a global market to represent international shipping and assume currently 50,000<sup>2</sup> merchant ships (Smith et al. 2014) as the total potential market that will adopt the innovation (Wetbulk, drybulk, container, RORO, vehicle carriers). Table 2 shows the parameters which have been used to predict the adoptions of pre/post swirl devices. A  $p$  of 0.003 for scenario A, which is in line with previous research and  $q$  of 0.5, as there is very little research on this coefficient for energy efficiency measures and previous research shows that higher  $q$  also reflects waiting till it has become clear what technology will survive (den Bulte 2000). Figure 7 shows the diffusion of one type of pre/post swirl device and Figure 8 compares this with a sample of observed values for the Mewis Duct (MD) from Becker Marine Systems and the Wake Equalizing Duct (WED) from Schneekluth<sup>3</sup>, manufacturers of pre/post swirl devices, with large market shares in this area of innovation. The sample observed values (actual installations since 2010) are similar to scenario C shown in Figure 8, suggesting attitudes that represent low levels of innovation and a high level of imitation within the shipping industry.

The diffusion of innovations theory (attributes of innovations, adopter types, and forecasting models) along with barriers to energy efficiency and technological transition concepts can help to shed light on the typical adoption patterns of energy efficiency technologies in shipping. Given the findings presented in 4.2 a number of questions arise with regards to the framework and that require further work and analyses, these are:

1. How can the diffusion of innovations be incorporated in GloTram, which currently models technology takeup using a profit maximisation function of the shipowner?
2. It was clear from the results presented earlier that current and future uptake technologies is not in line with the ambitions required to meet future targets. What can be done now to improve uptake of energy efficiency technologies in the future?
3. Which measures have the highest potential to meet the CO<sub>2</sub> reductions required and what can we say about their adoption rates.

Table 2: Estimated parameters for innovation in shipping

	$p$ (coefficient of innovation)	$q$ (coefficient of imitation)
Scenario A	0.003	0.5
Scenario B	0.002	0.5
Scenario C	0.001	0.5

<sup>2</sup> This assumes no new fleet added or scrapped for the period

<sup>3</sup> Data available from manufacturer websites

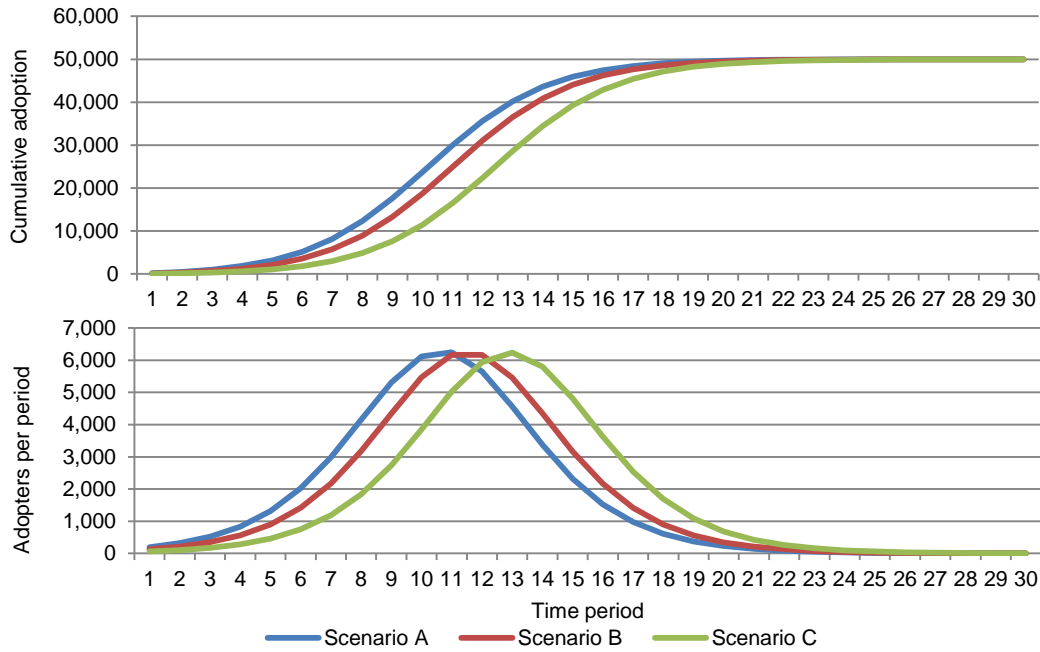


Figure 7: Adoption per period and cumulative adoptions estimates for pre/post swirl devices

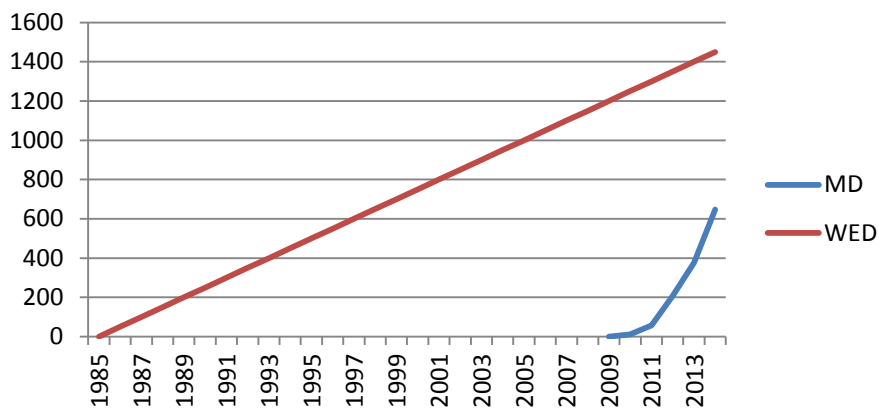


Figure 8: Sample observed actual values for pre/post swirl devices from two manufacturers<sup>4</sup>

## 5 CONCLUDING REMARKS

The paper presented the first analysis of implementation of technical energy efficiency measures using the survey method, which was the most extensive survey of the industry on this subject. The findings show implementation ranges at the ship level for four categories of measures. The survey has helped to confirm some preconceptions such as the use of widespread use bulbous bows, pre/post-swirl devices, engine modifications, lowering design speed and de-rating. The uptake of various other energy efficiency technologies, particularly alternative fuels is low despite their high potential for reducing CO<sub>2</sub> emissions. These aforementioned findings suggest further work in a number of areas:

- There is a need to generalize the sample survey (which covers around 5000 ships) findings to the general population using inferential statistics i.e. the possible ranges that might be expected in the different strata of the population.

<sup>4</sup> Data for WED comes from only two time periods, 1985 and 2015.

- Further analysis of the relationships & correlations with chartering ratio, size and sector of the firm to assess the impact of barriers, such as split incentives, on the implementation of technologies and therefore revisit the energy efficiency gap proposition.
- Expand the framework for diffusion of innovations in shipping so that both qualitative aspects (adopter attributes, innovation attributes, etc.) and quantitative models (to forecast future technological pathways), both of which require further work, can be used in tandem to understand barriers and inform policy.
- There is a need to align the modelling to better reflect the shipowner's decisions on investment in energy efficiency technologies, which may not be purely on an economic basis. After work has been completed on the framework for diffusion, it should be incorporated in the modelling.

## ACKNOWLEDGEMENTS

The authors would like to thank the organisations that helped to disseminate the online survey to their members. The authors would also like to thank all the 275 participants to the survey who gave their valuable time to take part in the survey, making this study one of the first to receive a high response rate in relation to this subject. This research is part of a larger project, Shipping in Changing Climates, funded by the Engineering and Physical Sciences Research Council UK (EP/K039253/1).

## REFERENCES

- Acciaro, M, Hoffmann, P & Eide, M 2013, 'The energy efficiency gap in maritime transport', *Journal of Shipping and Ocean Engineering*, vol 3, no. 12, pp. 1-10.
- Agnolucci, P, Smith, T & Rehmatulla, N 2014, 'Energy efficiency and time charter rates: Some evidence quantifying the extent of split incentive problem in the panamax drybulk market', *Transportation Research Part A: Policy and Practice*, vol 66, pp. 173-184.
- Baptista, R 1999, 'Do innovations diffuse faster within geographical clusters', *International Journal of the Economics of Business*, vol 6, pp. 107-129.
- Bass, F 1969, 'A new product growth model for consumer durables', *Management Science*, vol 13, no. 5, pp. 215-227.
- Bass, F, Krishnan, T & Jain, D 1994, 'Why the Bass model fits without decision variables', *Marketing Science*, vol 13, no. 3, pp. 203-223.
- Beise, M & Rennings, K 2005, 'Lead markets and regulation: a framework for analyzing the international diffusion of environmental innovations', *Ecological Economics*, vol 52, no. 1, pp. 5-17.
- Berelson, B & Freedman, R 1964, 'A study in fertility control', *Scientific American*, vol 210, no. 5, pp. 29-37.
- Bertram, V & Schneekluth, H 1998, *Ship Design for Efficiency and Economy*, 2nd edn, Butterworth-Heinemann, Oxford.
- Bower, J & Christiansen, C 1995, 'Disruptive technologies: Catching the wave', *Harvard Business Review*, vol 73, pp. 43-53.
- Bowers, R 1937, 'The direction of intra-societal diffusion', *American Sociological Review*, vol 2, pp. 826-836.
- Buhaug, Ø, Eyring, V, Corbett, J, Faber, J, Hanayama, S, Lee, S, Lee, D, Linstad, H, Markowska, A, Mjelde, A, Nelissen, D, Nilsen, J, Palsson, C, Wanqing, W, Winebrake, J & Yoshida, K 2009, *Second IMO GHG study - Update of the 2000 IMO GHG study*, viewed 06 November 2012, <[http://www.imo.org/blast/blastDataHelper.asp?data\\_id=27795&filename=GHGStudyFINAL.pdf](http://www.imo.org/blast/blastDataHelper.asp?data_id=27795&filename=GHGStudyFINAL.pdf)>.
- Calleya, J 2014, 'Ship Design Decision Support for a Carbon Dioxide Constrained Future (unpublished PhD thesis)', Department of Mechanical Engineering, UCL, London.

- Calleya, J, Pawling, R, Smith, T & Greig, A 2012, 'Ship design and evaluation for a GHG constrained future', *The Environmentally Friendly Ship*, 28 - 29 February, Royal Institution of Naval Architects, London.
- Darley, J & Beniger, J 1981, 'Diffusion of energy-conserving innovations', *Journal of Social Issues*, vol 37, no. 2, pp. 150-171.
- den Bulte, V 2000, *Technical Report: Want to know how diffusion speed varies across countries and products? Try using a Bass model*, viewed 20 October 2015, <<http://www3.nd.edu/~busiforc/handouts/Other%20Articles/Bass%20model.pdf>>.
- den Bulte, V & Stremersch, S 2004, 'Social contagion and income heterogeneity in new product diffusion: A meta-analytic test', *Marketing Science*, vol 23, pp. 530– 544.
- Dieperink, C, Brand, I & Vermeulen, W 2004, 'Diffusion of energy-saving innovations in industry and the built environment: Dutch studies as inputs for a more integrated analytical framework', *Energy Policy*, vol 32, no. 6, pp. 773-784.
- Dillman, D 2009, *Internet, mail and mixed mode surveys The Tailored Design Method*, 3rd edn, John Wiley & Sons, New Jersey.
- DNV GL 2014, *Energy Management Study*, viewed 9 June 2014, <[http://www.dnvgl-source.com/assets/documents/src/dnv\\_gl\\_brochure\\_energy\\_management\\_study\\_2014\\_05\\_web.pdf](http://www.dnvgl-source.com/assets/documents/src/dnv_gl_brochure_energy_management_study_2014_05_web.pdf)>
- Eleftheriadis, I & Anagnostopoulou, E 2015, 'Identifying barriers in the diffusion of renewable energy sources', *Energy Policy*, vol 80, pp. 153-164.
- Faber, J, Behrends, B & Nelissen, D 2011, *Analysis of marginal abatement cost curves*, viewed 05 December 2011, <[http://www.cedelft.eu/publicatie/analysis\\_of\\_ghg\\_marginal\\_abatement\\_cost\\_curves/1155?PHPSES\\_SID=9ec0891a1418473f9020106cba2e3441](http://www.cedelft.eu/publicatie/analysis_of_ghg_marginal_abatement_cost_curves/1155?PHPSES_SID=9ec0891a1418473f9020106cba2e3441)>.
- Geels, F 2002, 'Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study', *Research Policy*, vol 31, pp. 1257-1274.
- HSH Nordbank 2013, *Expert market survey: Eco-Shipping*, viewed 20 January 2014, <[https://www.hsh-nordbank.com/media/pdf/marktberichte/branchenstudien/shipping/20131217\\_Market\\_Survey\\_Eco\\_Shipping.pdf](https://www.hsh-nordbank.com/media/pdf/marktberichte/branchenstudien/shipping/20131217_Market_Survey_Eco_Shipping.pdf)>.
- IMarEST & Colfax 2015, *Making the green agenda pay*, viewed 27 March 2015, <<http://www.imarest.org/all-docman-documents/representation/green-agenda/551-making-the-green-agenda-pay/file>>.
- Islam, T & Meade, N 1996, 'Forecasting the development of the market for business telephones in the UK', *Journal of the Operational Research Society*, vol 47, pp. 906-918.
- Jafarzadeh, S & Utne, I 2014, 'A framework to bridge the energy efficiency gap in shipping', *Energy*, vol Online first, pp. 1-10.
- Jaffe, A & Stavins, R 1994, 'The energy-efficiency gap What does it mean?', *Energy Policy*, vol 22, no. 10, pp. 804-810.
- Johnson, H, Johansson, M & Andersson, K 2014, 'Barriers to improving energy efficiency in short sea shipping: an action research case study', *Journal of Cleaner Production*, vol 66, pp. 317-327.
- Kearns 1992, 'Innovations in local government: A sociocognitive network approach', *Knowledge and Policy*, vol 5, no. 2, pp. 45-67.
- Kok, N, McGraw, M & Quigley, J 2011, 'The Diffusion of Energy Efficiency in Building', *The American Economic Review*, vol 101, no. 3, pp. 77-82.

- Lee, C 1990, 'Determinants of national innovativeness and international market segmentation', *International Marketing Review*, vol 7, no. 5, pp. 39-49.
- Libertore, M & Bream, D 1997, 'Adoption and implementation of digital-imaging technology in the banking and insurance industries', *IEEE Transactions on Engineering Management*, vol 44, pp. 367-377.
- Maddox Consulting 2012, *Analysis of market barriers to cost effective GHG emission reductions in the maritime transport sector*, viewed 12 December 2012, <[http://bookshop.europa.eu/en/analysis-of-market-barriers-to-cost-effective-ghg-emission-reductions-in-the-maritime-transport-sector-pbML3213436/?pgid=y8dIS7GUWMDSR0EAIMEUUsWb0000a\\_8LQxNb;sid=27eLfRnKx26Lbkvc5PAV2nvv3GSNrrsJp-c=?CatalogCategoryID=IPKep2lx.>](http://bookshop.europa.eu/en/analysis-of-market-barriers-to-cost-effective-ghg-emission-reductions-in-the-maritime-transport-sector-pbML3213436/?pgid=y8dIS7GUWMDSR0EAIMEUUsWb0000a_8LQxNb;sid=27eLfRnKx26Lbkvc5PAV2nvv3GSNrrsJp-c=?CatalogCategoryID=IPKep2lx.>).
- Mahajan, V & Muller, E 1996, 'Timing, diffusion, and substitution of successive generations of technological innovations: The IBM mainframe case', *Technological Forecasting and Social Change*, vol 51, pp. 109-132.
- Mahajan, V, Muller, E & Wind, Y 2000, *New-Product Diffusion Models*, Kluwer Academic, Dordrecht.
- McMichael, M & Shipworth, D 2013, 'The value of social networks in the diffusion of energy efficiency innovations in UK households', *Energy Policy*, vol 53, pp. 159–168.
- Meade, N & Islam, T 2001, *Forecasting the diffusion of innovations*, Kluwer Academic Publishers.
- Meade, N & Islam, T 2006, 'Modelling and forecasting the diffusion of innovation - A 25 year review', *International Journal of Forecasting*, vol 22, pp. 519-545.
- Moore, G & Benbasat, I 1991, 'Development of an instrument to measure the perceptions of adopting information technology innovation', *Information Systems Research*, vol 2, no. 3, pp. 192-220.
- Norton, J & Bass, F 1987, 'A diffusion theory model of adoption and substitution for successive generations of high-technology products', *Management Science*, vol 33, pp. 1069-1086.
- Pelto, P 1973, *The snowmobile revolution: Technology and social change in the arctic*, Melno Park, California.
- Rehmatulla, N 2014, 'Market failures and barriers affecting energy efficient operations in shipping (unpublished PhD thesis)', UCL Energy Institute, University College London (UCL), London.
- Rehmatulla, N 2015, 'Assessing the implementation of energy efficiency measures in shipping: Survey report', UCL Energy Institute, London.
- Rehmatulla, N & Smith, T 2015, 'Barriers to energy efficiency in shipping: A triangulated approach to investigate the principal agent problem in shipping', *Energy Policy*, vol 84, pp. 44-57.
- Rehmatulla, N & Smith, T In Press, 'Barriers to energy efficient and low carbon shipping', *Ocean Engineering*.
- Rehmatulla, N, Smith, T & Wrobel, P 2013, 'Implementation barriers to Low Carbon Shipping', *Low Carbon Shipping Conference*, 9 - 10 September, UCL, London.
- Rogers, E 1962, *Diffusion of Innovations*, Free Press, New York.
- Rogers, E 1976, 'New product adoption and diffusion', *Journal of Consumer Research*, vol 2, pp. 290-301.
- Rogers, E 1995, *Diffusions of Innovations*, 4th edn, Free Press, New York.
- Rogers, E 2003, *Diffusion of Innovations*, 5th edn, Free Press, New York.
- Rohdin, P, Thollander, P & Solding, P 2007, 'Barriers to and drivers for energy efficiency in the Swedish foundry industry', *Energy Policy*, vol 35, pp. 672-677.

Rojon, I & Smith, T 2014, *On the attitudes and opportunities of fuel consumption monitoring and measurement within the shipping industry and the identification and validation of energy efficiency and performance intervention*, viewed 24 February 2014, <[http://www.bartlett.ucl.ac.uk/energy/news/documents/Report-On\\_the\\_attitudes\\_and\\_opportunities\\_for\\_fuel\\_consumption\\_monitoring.pdf](http://www.bartlett.ucl.ac.uk/energy/news/documents/Report-On_the_attitudes_and_opportunities_for_fuel_consumption_monitoring.pdf)>.

Ryan, B & Gross, N 1943, 'The diffusion of hybrid seed corn in two Iowa communities', *Rural Sociology*, vol 8, pp. 15-24.

Smith, T, Jalkanen, J, Anderson, B, Corbett, J, Faber, J, Hanayama, S, O'Keefe, E, Parker, S, Johansson, L, Aldous, L, Raucci, C, Traut, M, Ettinger, S, Nelissen, D, Lee, D, Ng, S, Agarwal, A, Winebrake, J, Hoen, M, Chesworth, S, et al. 2014, *Third IMO GHG study 2014*, International Maritime Organisation, London, <<http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Greenhouse-Gas-Studies-2014.aspx>>.

Smith, T, O'Keefe, E, Aldous, L & Agnolucci, P 2013, *Assessment of shipping's efficiency using satellite AIS data*, viewed 15 April 2013, <[http://www.theicct.org/sites/default/files/publications/UCL\\_ship\\_efficiency\\_forICCT\\_2013.pdf](http://www.theicct.org/sites/default/files/publications/UCL_ship_efficiency_forICCT_2013.pdf)>.

Smith, T, O'Keefe, E & Haji, S 2013, 'GloTraM method', UCL Energy Institute, London.

Smith, T, O'Keefe, E, Haji, S & Agnolucci, P 2013, 'GloTram external factors', UCL Energy Institute, London.

Stopford, M 2009, *Maritime economics*, 3rd edn, Routledge, London.

Sultan, F, Farley, J & Lehman, D 1990, 'A meta-analysis of applications of diffusion models', *Journal of Marketing Research*, vol 27, pp. 70– 77.

Talukdar, D, Sudhir, K & Ainslie, A 2002, 'Investigating new product diffusion across products and countries', *Marketing Science*, vol 21, no. 1, pp. 97-114.

Teng, T, Grover, V & Guttler, W 2002, 'Information technology innovations: General diffusion patterns and its relationships to innovation characteristics', *IEEE Transactions on Engineering Management*, vol 49, pp. 13-27.

Thollander, P & Ottosson, M 2008, 'An energy-efficient Swedish pulp and paper industry - exploring barriers to and driving forces for cost-effective energy efficiency investments', *Energy Efficiency*, vol 1, no. 1, pp. 21-34.

Tornatzky, L & Klein, K 1982, 'Innovation characteristics and innovation adoption-implementation: A meta-analysis of findings', *IEEE Transactions of Engineering Management*, vol 28, no. 1, pp. 28-43.

Woodyard, D 2003, *Pounders Marine Diesel Engines and Gas Turbines*, 8th edn, Elsevier Butterworth-Heinemann, Oxford.