The diffusion of wind propulsion technologies in shipping: an agent-based model.

Abstract

International shipping accounts for around 80% of global trade and is therefore critical to global economy. Carbon emissions from international shipping are expected to increase significantly in line with the global trade. A range of niche technologies developed for ship propulsion provide solutions to reduce shipping CO_2 emissions. However, these technologies face barriers that limit their diffusion. This paper focuses on the Flettner rotor technology through a transition perspective. An agent based model is developed to explore the diffusion of Flettner rotors in time charter drybulk shipping to 2050, under imperfect agent information and split incentives barriers that current shipping models omit. Simulation results are more conservative compared to those models. In the "business as usual" scenario, barriers impact the technology diffusion rate and its timing, even on shipping routes or geographical niches with favourable wind conditions. Further exploration of simulation scenarios reveals that the introduction of carbon pricing, or demonstration project policies, increases technology diffusion and delivers a modest CO_2 emissions reduction to 2050. The carbon pricing and demonstration project policies are found to work in a complementary way that greatly increases the effect of either policy introduced in isolation.

Introduction

Anthropogenic greenhouse gas ('GHG') emissions increase global temperatures, with severe implications for people and ecosystems, if they continue to grow unabated (IPCC, 2014). Carbon dioxide ('CO_2') accounted for 76% of anthropogenic GHG emissions in 2010 and under the Paris Agreement Parties shall implement emission mitigation measures, to limit global temperature increase to less than 2°C above pre-industrial levels (UNFCCC, 2015). CO_2 emissions from international maritime shipping are modest, they represented around 2% of global CO_2 emissions in 2012 (Smith et al., 2014). However, without further mitigation, shipping CO_2 emissions could increase 50-250% by 2050 (Smith et al., 2014), and reach around 10-25% of global emissions as other sectors continue to decarbonise (Kennedy et al., 2011; Cames et al., 2015).

It is imperative, for climate mitigation, that shipping reorients towards a low carbon trajectory. Current emission control policies from the International Maritime Organisation (IMO) include the technical Energy Efficiency Design Index (EEDI) and the operational Ship Energy Efficiency Management Plan (SEEMP) (IMO, 2017). "Business as usual" forecasts to 2050 show shipping CO_2 emissions reductions of 35-40% might be possible from existing policies, however net emissions are expected to continue to rise even under optimistic assumptions (Bazari and Longva, 2011).

Additional policies are required to encourage the diffusion energy efficiency innovations within shipping and drive decarbonisation in line with the 2°C target within the Paris Agreement. Marginal abatement cost curves show that cost-effective energy efficiency innovations might reduce shipping CO_2 emissions (Buhaug et al., 2009; Wang et al., 2010; Eide et al., 2011; Wang and Lutsey, 2013). Ship propulsion technologies such as Flettner rotors, kites, and sails, can complement conventional technologies and achieve large emissions reductions (Traut et al., 2014; Lloyd's Register, 2015; Nelissen et al., 2016). Smith et al. (2013a) suggest 10-60% emissions reductions might be possible, dependent on operational speed, the technology, and wind conditions.

A number of barriers constrains the diffusion of wind propulsion technologies in shipping despite their potential (Rojon and Dieperink, 2014; Rehmatulla et al., 2017a). These barriers include imperfect information around technological performance, and split financial incentives, the most common occurrence of which is in the short-term time charter market (Rehmatulla et al., 2017b). Incentives are split between ship charterers that cover their fuel costs, and shipowners that cover operating, capital, and investment costs of energy efficient technologies. Shipowner incentives to invest in energy efficiency measures and reduce fuel costs for charterers are low. The potential savings passed through to shipowners via higher time charter rates are limited, therefore many energy efficiency investments are uneconomic for shipowners (Ådland et al., 2017).

Policies to remove these barriers and increase the diffusion of wind propulsion in shipping are carbon pricing (Buhaug et al., 2009), and institutional demonstration projects which publish results in the public domain (Rehmatulla et al., 2017b). The question is whether they can work against the barriers documented in the literature (Rehmatulla et al., 2015). It is necessary to understand and assess the effect of policies that aim to remove transition barriers in the shipping sector. This paper aims to address this need, improve the understanding of how barriers affect the shipping transition, and provide relevant policy insights. Insights cannot draw on the experience of historical shipping transitions towards carbon intensive ships (Geels, 2002), because a transition towards a low carbon trajectory is required for which there is scarce experience (Papachristos, 2014). Modelling and simulation is warranted to recalibrate our thinking about alternative, future transition outcomes and their mechanisms (Papachristos, 2018),

A methodological aim for this paper is to demonstrate how the qualitative understanding of barriers in the transition case can be integrated better in a modelling approach that explores wind propulsion in the current shipping transition. The integration of the dynamic impact of barriers will improve the insights and conclusions of a range of detailed, techno-economic models on decarbonisation policies for the shipping sector such as the Global Transport Model ('GloTraM') used within Smith et al. (2016) and Raucci et al. (2017) or the 'generic model' used in Nelissen et al. (2016).

The paper adopts the Multi-Level Perspective ('MLP') to conceptually frame the analysis (Geels, 2004; Geels and Schot, 2007), for two reasons. First, because the MLP has been used in previous exemplary transition cases in shipping (Geels, 2002), and second, because the alternative ship propulsion case exhibits an add-on and hybridization pattern that has been analysed under the MLP already (Geels and Schot, 2007; Mander, 2017). In this pattern, niche-innovations, such as wind propulsion, can develop symbiotic relationships with conventional technologies if they can function as competence-enhancing add-on to solve environmental problems and improve performance. The paper focuses on rotor technology within drybulk shipping because it represents a feasible add-on technology (Nelissen et al., 2016). The nature of the technology favours short-term time charter contracts which are prone to the split incentives barrier (Rehmatulla et al., 2017b).

An agent based model ('ABM') is developed based on this MLP conceptualisation, to explore the diffusion of Flettner rotor technology in the time charter drybulk shipping sector on a route with favourable wind conditions. Simulation results are more conservative compared to those from current shipping models that omit barriers and agent expectation mechanisms. In the "business as usual" scenario, barriers prevent diffusion, even with favourable wind conditions. Barriers are shown to impact both the rate of technology diffusion and its timing. Additional scenarios that introduce carbon pricing, or demonstration project policies, increase technology diffusion, and deliver modest CO_2 emissions reduction by 2050. The combination of carbon pricing and demonstration project policies is found to be complimentary, and greatly increases the benefit of either policy when introduced in isolation.

This paper is structured as follows. Section 2 provides context through a review of the literature on the diffusion of innovations, technological transitions, and barriers to energy efficiency, before critically reviewing existing diffusion modelling within shipping. Research questions are then proposed. Section 3 introduces the theoretical context for modelling, the modelling method, and assumptions. Section 4 outlines results. Section 5 discusses results, addressing research questions and considering findings in the context of the wider shipping literature. Section 7 concludes, summarizing research findings, policy recommendations, limitations within the method, and future research.

Background

Section 2.1 outlines a brief discussion of the extensive diffusion of transitions and niche literature. This is used, in section 2.2 to conceptualize the situation and the barriers that alternative propulsion technologies face in the shipping sector. Section 2.3 provides an overview of modelling techniques and applications in the shipping sector that serves to contextualize the model developed in this paper.

The Multi-Level Perspective

The MLP is a sociotechnical framework that facilitates the analysis of system innovation and system wide technological diffusion (Geels, 2002; 2004; Geels and Schot, 2007; Geels et al., 2016). The framework integrates technological concepts from evolutionary economics (Nelson and Winter, 1982) and wider sociological rules (Rip and Kemp, 1998) that account for social group dynamics that influence system change and inertia.

The core MLP concept is the sociotechnical system, which facilitates analysis of what underlies the activities of actors who reproduce system elements. The actors are embedded in interdependent social groups, each with its own regime (set of rules). The MLP distinguishes between technological, culture, science, markets, industry and policy regimes (Geels and Schot, 2007). The sociotechnical regime refers to the inter-regime alignment and coordination of intergroup activities that generate path dependency and stabilize sociotechnical trajectories a state of system lock-in (Unruh, 2000). The MLP has two additional analytical concepts (Geels, 2004): (i) the landscape at the macro level provides gradients for sociotechnical regime trajectories which represents exogenous factors such as oil prices or economic growth which influence niches and incumbent regimes, and (ii) the niche level where radical innovations incubate and proliferate protected from external influences.

In the MLP framework transition processes unfold when the sociotechnical regime is sufficiently destabilised through reinforcing and disrupting interactions that develop between these three levels by (Geels and Schot, 2007): (i) niche technologies that may develop through learning, price/performance improvements and support from powerful groups, (ii) landscape trends that act on the regime (economic, cultural, demographic and other), (iii) internal regime tensions that can accumulate and create windows of opportunity for innovations in niches, and (iv) external influence from other systems, regimes or niches (Papachristos et al., 2013). The transition is completed when the social and technical aspects of novel innovations become embedded in the new sociotechnical system.

Innovation niches

The MLP has already been applied to the maritime transition from sailing ships to steamships (Geels, 2002), and the rise of slow steaming and wind propulsion (Mander, 2017). The emergence of these niches is documented in recent wind technology firm survey data (Rehmatulla et al., 2017b). In both cases, small niches facilitate technology experimentation for these innovations

(Geels, 2004) to address CO_2 emission problems. Niches provide active or passive shielding to "crude and inefficient" innovations from market selection pressures (Rosenberg, 1976; Schot et al., 1994; Kemp et al., 1998; Smith and Raven, 2012).

For example, the geographical position of particular shipping routes provides favorable winds for navigation (Nelissen et al., 2016), and this is a form of passive shielding to wind propulsion technologies (Mander, 2017). Active shielding involves some form of actor network to support demonstration projects that aim to develop and illustrate the utility of new technologies (Raven et al., 2016). This shielding provides the necessary space to articulate actor expectations and achieve convergence, develop the necessary actor networks, and initiate learning processes, to achieve the necessary accumulation that will enable scaling up the niche (Hoogma et al., 2002; Schot and Geels, 2008; Smith and Raven, 2012; Naber et al., 2017).

Actor Expectations

Actor expectations towards innovations form around their function, performance, and market potential, and are critical to gather support for them (Hoogma et al., 2002). The potential of innovations must be credible, relevant, and provide solutions to distinct societal issues (Kemp et al., 1998). Actor expectations may be fragmented initially but the accumulation of information from development experiments facilitates their articulation and convergence, and adds momentum to the innovations. Actor expectations can also be driven by developments that are external to the niche, such as environmental regulations. For example, the role of expectations has already been explored in the transition to alternative fuel vehicles (Budde et al., 2012; Bakker et al., 2014).

Network development

Actor expectations towards a technology determine whether they participate in niche networks as users. The appeal of niche innovations can trigger the formation of actor networks that drive technology development. Networks form and grow through actor expectation alignment that increases niche structuration (Geels, 2004). Network formation facilitates interactions between niche actors that support the niche technology. For example, the network of actor interactions, communication and information sharing enables resource pooling, and access to technology development resources (Rogers, 2003; Schot and Geels, 2008). The role of niche users is important as they provide insights into their requirements, and learning about markets and related barriers (Kemp et al., 1998; Smith and Raven, 2012).

Learning

Learning concerns critical innovation features: technical performance, user requirements and barriers to use, associated infrastructure requirements, environmental impacts, and government policies or regulation (Hoogma et al., 2002). Technology experimentation contributes to learning, niche actors revise their technology expectations, communicate them through their networks, and attract more actors (Rogers, 2003). The recursive process of expectation convergence, network formation, and learning is continuous (Figure 1), and it increases actor alignment and structuration of rules and technology elements in the niche (Schot and Geels, 2007).

The accumulation of innovation momentum from niche experiments shifts from initial exploration and demonstration to full-scale replication once the rules around the technology stabilize to provide the impetus to commercialize the technology (Hetland, 1994; Hoogma, 2000; Schot and Geels, 2007). Innovation niches become market niches which then challenge the incumbent regime as market share increases (Hoogma et al., 2002). However, poor results from niche experiments may drive actor expectations down, and lead to niche extinction as supporters leave the innovation niche or network (Hoogma et al., 2002). Initial poor results can also lead often to an observed boom and bust cycle (Alkemade and Suurs, 2012; van Lente et al., 2013).

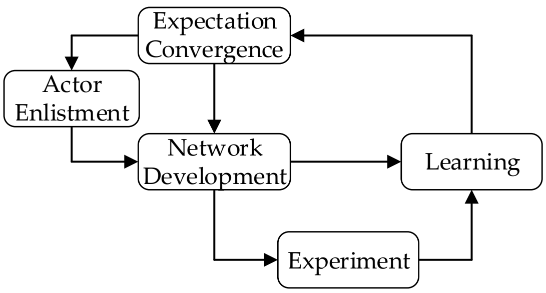


Figure 1 Niche development dynamics (based on Lopolito et al., 2013)

International shipping and barriers to shipping energy efficiency

Innovation barriers are mechanisms that prevent decisions that are energy and economically efficient and thus they prevent cost-effective investments in energy efficient technologies (Sorrell et al., 2004). Barriers to energy efficient innovations generate an energy efficiency gap between the expected energy use and the optimal use (Jaffe and Stavins, 1994). The literature on energy efficiency barriers in shipping is growing but the variety of conceptual frameworks makes cross comparison difficult (Jafarzadeh and Utne, 2014; Johnson et al., 2014; Rojon and Dieperink, 2014; Rehmatulla and Smith, 2015; Johnson and Andersson, 2016; Nelissen et al., 2016; Rehmatulla et al., 2017b).

Common barriers to the diffusion of new technologies in international shipping include imperfect information on technological performance, and split incentives in the short-term time charter market where shipowner investments in energy efficient technologies are not rewarded through charter premiums (Agnolucci et al., 2014; Prakash et al., 2016; Ådland et al., 2017). Other significant barriers include access to capital (Rojon and Dieperink, 2014; Nelissen et al., 2016; Rehmatulla et al., 2017b), technical risk and incompatible infrastructures (Jafarzadeh and Utne, 2014; Nelissen et al., 2016; Rehmatulla et al., 2017b), and economic risks such as uncertain oil prices or lower fleet utilisation (Johnson and Andersson, 2016; Nelissen et al., 2016; Rehmatulla et al., 2017b).

A range of policies to overcome such barriers exists: (i) carbon pricing (Buhaug et al., 2009; IMO, 2010; Nelissen et al., 2016), (ii) demonstration projects for promising technologies, either operated, funded, or supported through public institutions such as the IMO which makes publicly available robust and trusted performance data from full-scale trials (Rojon and Dieperink, 2014; Nelissen et al., 2016; Rehmatulla et al., 2017b), (iii) higher access to capital through public funding (Nelissen et al., 2016), and (iv) introduction of speed limits (Rehmatulla and Smith, 2015; Mander, 2017). The effectiveness of such policies varies as some face practical and distributional considerations including impacts on international trade (IMO, 2010; Vivid Economics, 2010), and on some occasions localised speed limits deliver low emission reductions with high economic costs (Cariou and Cheaitou, 2012).

Modelling the diffusion of energy efficiency innovations within shipping

Modelling work on the diffusion of energy efficient technologies in shipping does not consider in detail these barriers and as a result cannot assess the effectiveness of related policies. A variety of modelling approaches have been used so far on innovation diffusion in shipping industry. Senger and Köhler (2015) explore research and development and shipyard investment decisions, and subsequent technological change on wind propulsion technologies with an agent-based model (ABM) and an evolutionary approach (Safarzynska et al., 2012). The model includes macroeconomic factors such as global demand for shipping, fuel prices, and policies such as emission standards. It facilitates the exploration of global fleet evolution and wind propulsion adoption. However, the model does not distinguish between shipowners and charterers therefore it cannot be used to explore the important split incentives.

Nelissen et al. (2016) develop a dynamic techno-economic model with technological learning effects to explore wind propulsion diffusion. The model accounts for fuel savings and actual cost estimates for wind technologies as investment in wind propulsion is sensitive to capital costs and realised fuel savings. Model results suggest that wind technologies diffusion could be self-sustaining from 2020 onwards without additional support policies or economic incentives. This is relatively optimistic especially when contrasted with the current limited uptake of wind propulsion in shipping (Rehmatulla et al., 2017b). A reason for this is that the model does not include key barriers such as imperfect information or split incentives, as the authors note.

Rehmatulla et al. (2015) develop a heuristic approach to forecast technology diffusion within shipping based on the Bass diffusion model (Bass, 1969). They use actual data to inform their diffusion approach and take explicit account of current industry barriers. Their results show that diffusion is driven more by imitation rather than actor innovation, due to shipping industry's risk-averse nature (Rojon and Dieperink, 2014). Nevertheless, their approach captures innovation technology attributes and associated barriers through coefficients of innovation and imitation that influence diffusion s-curves, thus it is not generative (Epstein and Axtell, 1996; Epstein, 2007). This implies that it cannot account for significant discontinuities in the diffusion process such as the introduction and impact of new policies or changes in the socio-technical landscape. At best their approach can offer a quasi-explanation for the complete lack of wind propulsion diffusion but it cannot completely explain it (Rehmatulla et al., 2017a).

The review of relevant modelling work in shipping leads to certain requirements that modelling work should address. It should distinguish between shipowners and charterers, include key barriers such as imperfect information or split incentives, and follow a generative approach to facilitate understanding and assessment of the effect of relevant policies on adoption of wind propulsion technologies. Such a generative approach is presented in the following sections.

Agent-based modelling

Agent-based modelling was developed for research on complex adaptive systems (Tesfatsion, 2006). They are composed of goal-directed agents that interact and respond to environmental stimuli. Agent interactions produce emergent behavior and system properties that are not prescribed in agent behavior (Epstein and Axtell, 1996; Epstein, 2007). ABM is one of the methods used in sociotechnical transitions research (Safarzyńska and van den Bergh, 2010; Safarzynska et al., 2012; Holtz et al., 2015; Köhler et al, 2017). Such models have certain advantages when it comes to explore the behavior of complex adaptive systems as they: (i) provide explicit and systematic representations that allow experimentation, (ii) generate complex system behavior from underlying mechanisms and processes and thus they facilitate the inference of insights about system behaviour.

There are clear advantages to the agent-based approach given the focus of this paper. Nevertheless, it should be noted that model results represent alternative futures from which insights can be drawn, rather than accurate predictions (Holtz et al., 2015). Moreover, a range of challenges needs to be addressed in ABM such as no standard modelling techniques, limited model comparability resulting from different theoretical contexts, this highlights the importance of empirical validation (Windrum et al., 2007). The issues noted above will be addressed in the following sections.

Model Development

Model development follows the "Overview, Design concepts, and Details" protocol in a condensed form to describe the ABM (Grimm et al., 2010). The model in this paper draws on the work of Lopolito et al. (2010; 2013). Their approach has clear advantages: (i) it utilises an established theoretical context to structure model processes and agent behaviours, a key issue with agent-based modelling (Windrum et al., 2007); and (ii) it focuses on three key mechanisms (converging expectations, networking, and learning) which improves model transparency and facilitates analysis. The original model used in Lopolito et al. (2010) was obtained from the authors and modified as necessary for this paper to fit the context of rotor propulsion diffusion in shipping and the inclusion of the imperfect information and split financial incentives barriers. Adjustments include expectations and knowledge spillover effects through communication channels or networks (Rogers, 2003).

Agents and their environment

This model will simulate rotor diffusion for 100 shipowners within the 60,000-99,999 deadweight tonnage ('dwt') drybulk shipping sector from 2020-2050. It is assumed that each shipowner owns a single ship and makes investments according to profit maximising behaviour (Raucci et al., 2017). One month is deemed reasonable time interval for shipowner investment decisions. The ships are retrofitted to install rotor technology so the total ship number is kept constant. Three agent types interact with the shipowner in the model: technology providers (n = 2), shipyards (n = 1), and demonstration projects (where n is varied in line with the simulated policy). All agents move and interact within a finite social space (Lopolito et al., 2013). The social space is a wrapped grid of 32 cells by 32 cells forming a torus and provides a mechanism within the model to capture social interactions between shipowners during the course of their business which facilitate the exchange of information through networking. Technological risk is captured through the random generation of grey cells in each period using a risk variable within the model to represent the operational failure of the niche technology. Global environmental factors or socio-technical landscape pressures such as oil and carbon prices are modelled within each shipowner agent's profit function. The model runs over 360 months from 2020-2050, to allow comparison of results with recent shipping models (Nelissen et al., 2016; Raucci et al., 2017).

Agent processes

This model was developed using NetLogo © (Wilensky, 1999). NetLogo simulations run through a schedule of user-defined processes each model period t. This section discusses agent logic and the underlying assumptions made[1].

Process 1: Period setup

In each period technical risk is distributed to the social space, represented through the random generation of grey cells subject to a probability modelled by the $Risk$ variable. It reflects the technical risk attributed to rotor technology as perceived by shipowners and technology providers (Rehmatulla et al., 2017b). Risk includes ship structural integrity and stability, and cargo handling. External risks from shipping market conditions are assumed constant, so all ships are chartered each period. Once technical risk is calculated, shipowner agents 'move' 2.5 cells in a random direction within a two-dimensional social space. This mechanism represents an assumption that shipowners within the dry bulk shipping sector will interact through chance social encounters until they begin to network.

Process 2: Networking between shipowners

The expectations of each shipowner i concern the performance of rotor technology and range from 0 (no interest) to 1 (complete preference). If expectations are greater than threshold value $EX_{support}$, the shipowner shifts from being a regime actor to niche supporter and joins the network of niche supporters which represents the innovation niche (Lopolito et al., 2013). This mechanism accounts for knowledge spill-over effects.

Process 3: Shipowner interaction with technology providers

Technology providers interact with their nearest regime shipowner actor in the social space and increase expectations subject to the TP_{EXincr} parameter, representing the increase in a shipowner's expectations towards the rotor technology from a single interaction with a technology provider. This parameter is not directly observable and is therefore calibrated. Technology providers only increase the expectations of regime shipowner actors. Once a regime shipowner's expectations towards rotor technology are greater than 0.5, the shipowner becomes a niche supporter. The expectations of niche supporters increase through niche experimentation or institutional demonstration projects. This mechanism represents the significance of imperfect information and the need for shipowners to validate technology provider claims (Nelissen et al., 2016; Rehmatulla et al., 2017b).

[1] The model code is available from the authors upon request.

Process 4: Shipowners calculate fuel costs

Shipowner *i* calculates ship fuel cost at time *t* $F_{i,t}$ in millions of dollars ($m) for the period paid by the time charterer, including any carbon pricing costs.

Process 5: Shipowner decision to install rotor technology

The shipowners use the Expected Net Present Value E(NPV) metric to assess the value of investment and whether they will adopt and install rotor technology through interacting with a shipyard (Rehmatulla et al., 2015, Nelissen et al., 2016). The $E(NPV)$ is calculated from the shipowner's expected incremental profits in $m from a chartered ship with rotor technology over the discounted payback period of T months (equation 1) where DR is the discount rate assumed (8.5%) and $E(K_t^n)$ the capital cost of fitting the rotor technology. If $E(NPV)$ given by equation 1is greater than zero the test is passed.

$$E(NPV) = \sum_{t=1}^{T} \frac{E(FPT_{i,t}^n) - E(C^n)}{(1+DR)^t} - E(K_t^n) \qquad (1)$$

Incremental revenues to the shipowner $(FPT_{i,t}^n)$ from adopting the niche technology capture the fuel cost savings from its use that are passed from the charterer to shipowner through an increased charter premium (Ådland et al., 2016; Raucci et al., 2017). The expected incremental revenues $E(FPT_{i,t}^n)$ are a function of the ship's fuel cost each month $F_{i,t}$, the expected percentage fuel saving from rotor technology $E(RE)$, and charterer expectations towards the effectiveness of rotor technology $EX_{C,t}$, calculated as average shipowner expectations for the period. The expected revenues *E(FPT)* are multiplied by shipowners' expectations $EX_{i,t}$ to reflect uncertainty over the technologies performance (Lopolito et al., 2013). The shipowner $E(FPT_{i,t}^n)$ is given by:

$$E(FPT_{i,t}^n) = (F_{i,t} \times E(RE) \times EX_{C,t}) \times EX_{i,t} \qquad (2)$$

To simplify the model, the *expected* percentage fuel savings from rotor technology are assumed constant over the simulation horizon. Charterer expectations represent their perception of rotor technology performance, a factor in setting their premiums (Smith et al., 2013b, p.77). Charterer expectations correspond to the B_tc 'barrier factor' within the Raucci et al. (2017) model. It is assumed that charterers have homogenous expectations and do not participate in niche experiments. Instead they take cues from shipowners' expectations and representations as to the effectiveness or energy efficiency of rotor technology and its reliability. The expected additional maintenance cost to the shipowner $E(C_{i,t}^n)$ from adopting the rotor technology is given by:

$$E(C_{i,t}^n) = C_{i,t}^n \times (2 - EX_{i,t}) \qquad (3)$$

Cost expectations are calculated with a modified version of the Lopolito et al. (2013) formula[2], whereby costs are multiplied by 2 minus the shipowner's expectations. This implies that shipowners with zero expectations will overestimate costs by 100%. The expected revenues and costs capture the importance of performance uncertainty on shipowner investment decisions and are analogous to the imperfect information barrier. Shipowners estimate the capital cost of adopting the rotor technology $E(K_t^n)$ given by:

$$E(K_t^n) = K_t^n \times \left(2 - EX_{i,t}\right) \tag{4}$$

In addition to the discounted payback test outlined above, shipowners also require the rotor technology to generate an operating profit. It is assumed that the drybulk time charter regime is perfectly competitive and therefore regime profits are nil (Ådland et al., 2016) therefore an operating profit from the rotor technology indicates an improvement in profitability for shipowners. The expected operating profit $E(OP)$ depends on the difference between shipowner charter revenues $R_{i,t}^R$ and operational costs $C_{i,t}^R$ when using regime technologies. They are assumed to be constant within the model timeframe. $E(OP)$ depends on expected incremental revenues $E\left(FPT_{i,t}^n\right)$ minus the expected additional maintenance costs $E\left(C_{i,t}^n\right)$ from adopting rotor technology. The expectation mechanisms in equations 2 and 3 are again applied but only to incremental rotor revenues and maintenance costs as regime revenues and costs are not considered uncertain. The operating profit test is passed if the expected operating profit $E(OP)$ from using rotors is greater than regime operating profits.

$$E\left(OP_{i,t}^n\right) = \left(R_{i,t}^R - C_{i,t}^R\right) + E\left(FPT_{i,t}^n\right) - E\left(C_{i,t}^n\right) \tag{5}$$

Process 6: Shipowners determine whether to 'use' rotor technology

The niche supporters that install rotor technology to ships repeat the operating profit condition test in subsequent model periods. Niche supporters can remove and store rotors if their expectations fall due to failed experiments. It is assumed that shipowners leave the equipment necessary to re-install the rotor technology on their ships, so that if the operating profit condition is satisfied and expectations improve in future periods, shipowners can resume their participation in rotor technology niche experiments.

Process 7: Shipowners calculate realised operating profits for the period

Realised operating profit $OP_{i,t}^n$ is calculated in each period for each shipowner. If a shipowner occupies a grey cell (with probability P represented by the $Risk$ variable) the profit calculation is assumed to exclude $FPT_{i,t}^n$ revenues due rotor technology 'failure', with an associated $Claim$ for

[2] The original formula within Lopolito et al. (2013) is as follows: $E\left(C_{i,t}^n\right) = C_{i,t}^n \times \frac{1}{EX_{i,t}}$

underperformance made by the charterer (Veenstra and Van Dalen, 2011). If rotor technology operates as intended, realised shipowner profits effectively equal $FPT_{i,t}^{n}$ revenues less rotor operating costs. $OP_{i,t}^{n}$ for shipowner *i* in period *t* is given by:

$$OP_{i,t}^{n} = \begin{cases} \left(\left(R_{i,t}^{R} \times (1 - Claim)\right) - C_{i,t}^{R}\right) - C_{i,t}^{n} & with\ probability\ P \\ \left(R_{i,t}^{R} - C_{i,t}^{R}\right) + FPT_{i,t}^{n} - C_{i,t}^{n} & with\ probability\ 1 - P \end{cases} \quad (6)$$

Where:

$$FPT_{i,t}^{n} = \left(F_{i,t} \times RE_{i,t} \times EX_{C,t}\right) \times EX_{i,t} \quad (7)$$

The *actual* fuel efficiency savings from the rotor technology $RE_{i,t}$, calculated as a percentage randomly selected from a gamma distribution with shape parameter $\alpha = 6$ and rate parameter $\beta = 23.7$[3]. Additional data for a route with favourable wind conditions are used from Nelissen et al. (2016). This approach captures the inherent uncertainty of wind propulsion and shipowners' FPT revenues. It reflects a commercial structure whereby FPT revenues are adjusted according to actual wind conditions.

Process 8: Shipowners update knowledge through experiments

Shipowners and their crews learn about the technical performance, user requirements and barriers to use, and infrastructure compatibility of rotor technology through experiments. Each experiment increases knowledge stock KN_i of the shipowner by KN_{incr}. The immediate neighbours in the experimenting shipowner's network also increase their knowledge through spillover effects, to lesser extent, with the percentage spillover determined through the $KN_{spillover}$ parameter.

$$KN_{i,t+1} = KN_{i,t} + KN_{incr} + KN_{spillover}$$

Process 9: Shipowner interactions with institutional demonstration projects

Institutional demonstration projects represent an extended full-scale rotor technology sea-trial that is implemented, funded, or supported by an organisation such as the IMO. It makes project results public to accelerate the increase in expectations and knowledge of rotor technology through documenting actual rotor performance and commercial feasibility (Rojon and Dieperink, 2014; Nelissen et al., 2016; Mander, 2017; Rehmatulla et al., 2017b).

In simulation scenarios that include a demonstration project, it runs from $t = 1$ for a specified number of months. The demonstration agent increases the expectations and knowledge of shipowners within a defined radius subject to the D_{EXincr} and D_{KNincr} parameters. This radius, D_{radius}, is set at 3 which equates to moderate dissemination of demonstration project results

[3] Calculated from data provided by M. Traut from Delft – data from the Nelissen et al. (2016) paper

throughout the non-networked shipping agents. The agent can increase shipowner expectations up to D_{EXmax}, again reflecting the importance of direct experimentation and validation within the niche supporters' network. It is assumed that demonstration projects cannot fail.

Process 10: Update technical risk

Technical risk decreases with accumulated knowledge within the niche supporter network from rotor technology operation, incremental improvements in rotor reliability by technology providers that use shipowner feedback, and greater infrastructure compatibility.

The use of average shipowner knowledge (the first term within the bracket) is a simplification, which represents a balance between external improvements in technical risk driven through the niche's interactions with technology providers and infrastructure owners, and internal niche improvements reflecting an understanding of 'best practice' within the niche. The result is technical risk follows an S-shaped curve, consistent with discussion in Geroski (2000).

Once shipowner's knowledge is updated to reflect both experiments within the niche supporter network and knowledge acquired from demonstration projects, technical risk is given by:

$$Risk_{t+1} = Risk_t - \left(\frac{\frac{1}{n}\sum_{i=1}^{n} KN_i}{100} \times \left(\frac{Risk_t}{Risk_{t=0}} \right) \right) \quad (8)$$

Process 11: Rotor technology capital costs are updated

Capital costs are updated using a 'one-factor learning curve' as summarised within Rubin et al. (2015) and used within Nelissen et al. (2016). The 'one-factor learning curve' assumes that a doubling of installed capacity (or ships using rotor technology) results in a percentage reduction (LR) in the technology's capital cost. LR is set to 10% in line with other shipping models (Nelissen et al., 2016). Demonstration agents are counted as an additional installed unit when calculating installed capacity for the learning curve effect.

Process 12: Shipowners (and charterers) update expectations

Shipowner expectations $EX_{i,t+1}$ are updated through the operating profit (or loss) $OP_{i,t}^{n}$ from participating in experiments through chartering out a ship using rotor technology:

$$EX_{i,t+1} = EX_{i,t} + OP_{i,t}^{n} \quad (9)$$

Immediate neighbours within the shipowner's network will also increase (or decrease) expectations as a result of neighbours' experiments results, reflecting spillover effects (Rogers, 2003), although to a lesser extent determined through the $EX_{spillover}$ parameter. The expectations of shipowners not using rotor technology also experience small random movements reflecting socio-technical landscape variation and industry speculation:

$$EX_{i,t+1} = EX_{i,t} + (V_{i,t} - \frac{1}{2}V_{i,t}) \quad (10)$$

Where $V_{i,t}$ is a random number from 0 to 0.05

Charterer expectations $EX_{C,t+1}$ are recalculated using the updated average shipowner expectations for the start of the next period, representing dynamics within the split incentives barrier:

$$EX_{C,t+1} = \frac{1}{n}\sum_{i=1}^{n} EX_{i,t+1} \quad (11)$$

The model then updates visual outputs and moves to the next period, looping back to Process 1. Figure 2 illustrates how the model processes ('P') interact.

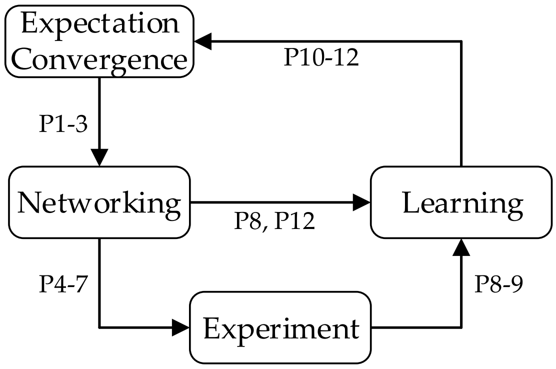


Figure 2 Niche dynamics (adapted from Lopolito et al. (2013)

Parameterisation and empirical validation

Parameterisation and empirical validation ensures that an ABM provides a realistic simplification of the simulated system. The ABM literature identifies the following approaches (See Appendix B for approach descriptions):

Table 1: Approaches to parameterisation and empirical validation

Source	Approaches
Windrum et al. (2007)	• Indirect calibration • Werker-Brenner • History-friendly
Thiele et al. (2014)	• Best-fit • Categorical calibration

The Werker-Brenner approach is preferred due to an emphasis on critical realism which recognises that socio-economic patterns such as technological diffusion are the result of deeper or emergent processes (Werker and Brenner, 2004). This approach offers a powerful methodology to develop rigorous, empirically-grounded simulation models that embody alternative assumptions (Windrum et al., 2007). The model was calibrated and validated using the Werker-Brenner approach (Werker and Brenner, 2004). Parameters for which empirical data were not available, were calibrated against the diffusion curve from Rehmatulla et al. (2015). Figure 3 demonstrates the model can replicate key stylised facts from the diffusion literature (see Appendix B for calibration and validation details).

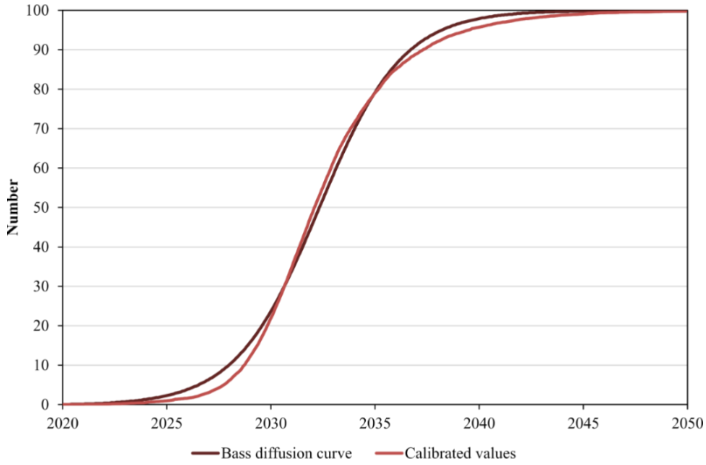


Figure 3 Model calibration Source: Rehmatulla et al. (2015) and author's calculations

Model parameters, initial values, and sources are outlined in Tables 3.

Empirical data has been used where available from the shipping literature for initial parameterisation in accordance with the Werker-Brenner approach (Werker and Brenner, 2004) (see Appendix C for all model parameters).

Table 2 Selected Reference Baseline scenario parameters

Parameter	Value	Description	Source
$Risk_t$	0.25	Risk of a technical failure.	Author's assumption; required information not available.
$EX_{i,t}$ $seeded$	0.75	Expectations towards rotors for 5 niche supporters seeded at $t = 0$	See note 1.
$EX_{i,t}$ $regime$	0.175	Expectations towards rotors of the regime actors at $t = 0$	See note 1.
$EX_{support}$	0.5	Expectations threshold at which niche actors become niche supporters.	Author's assumption; consistent with Lopolito et al. (2013) approach.
TP_{EXincr}	0.15	Increase in shipowner expectations from technology provider interaction.	Calibrated.
$Fcons_i$	560	Fuel consumption in mt per month.	2009-2011 mean fuel consumption for 60,000-99,999dwt bulk carrier from Smith et al. (2014) excluding boom periods (Ådland et al., 2016).
$Fprice_t$	400-800	LSHFO price in $/mt.	See Figure 4.
$Fcarbon$	3.114	CO_2 emitted in mt per mt of fuel consumed.	Smith et al. (2014).

DP_{hurdle}	60	Discounted payback hurdle assumption (months).	Nelissen et al. (2016).
C^n	0.0125	Rotor technology maintenance cost in \$m per month.	Technology provider data reported in Rehmatulla et al. (2017b).
K^n	2	Rotor technology initial capital cost in \$m; 3 rotors (Nelissen et al., 2016).	Author's assumption; balanced view of available data; see Figure 3.
$E(RE)$	0.25	Expected rotor fuel savings; Long Beach to Shanghai route, regular voyage speeds	Nelissen et al. (2016); simulation data for a 90,000dwt bulk carrier.
DR	0.085	Shipowner discount rate.	Nelissen et al. (2016).
$R_{i,t}^R$	0.304	Regime time charter rate per month in \$m.	Raucci et al. (2017); \$10,000/day.
$C_{i,t}^R$	0.304	Perfectly competitive drybulk regime.	Ådland et al. (2016).
$Claim$	0.25	Proportion of charter revenues claimed by charterer for technical failure.	Author's assumption reflecting 25% time lost during the month.
$RE_{i,t}$	0.08-0.52	Actual fuel savings from using rotor technology on the Long Beach to Shanghai route.	Nelissen et al. (2016) data used to calculate random figure each period.
LR	0.1	Rotor capital cost learning rate.	Nelissen et al. (2016).
$EX_{spillover}$	0.075	Shipowner expectations spillover to network neighbours as proportion of OP profit (or loss) for month.	Calibrated.

Note 1
Author's assumption; limited data is available on actual shipowner expectations towards rotor technology. Assuming seeded niche supporters expectations are high (0.75), regime actor expectations are set to provide an average charterer expectation of 20% at t=0, reflecting a small increment on the 14% charter premium for an energy efficient Panamax drybulk vessel in Ådland et al. (2016). The increment assumes improving sentiments towards energy efficiency to 2020. The resulting low regime expectations (0.175) seem reasonable given the risk-averse nature of the industry (Rojon and Dieperink, 2014) and limited rotor technology implementation (Rehmatulla et al., 2017b).

3.6 Scenarios

Table 3 presents the parameters that were used to model policy scenarios. These parameters relate to the two policies examined within this paper: a carbon price and a demonstration project.

Table 3 Selected policy parameters

Parameter	Value	Description	Source
$Cprice_t$	0-200	Carbon price in \$/mtCO_2.	Raucci et al. (2017).
D_{EXincr}	0.0025	Increase in shipowner expectations from demonstration project.	Calibrated.
D_{EXmax}	0.75	Limit to expectations increase from demonstration project.	Author assumption (see Section 3.4.9.)
D_{period}	180	Demonstration project duration in months.	Author assumption. equivalent to short investment horizon (15 years)

in Raucci et al. (2017).

Table 4 presents model scenarios, identifying research questions addressed, and the values for carbon price and the number of demonstration projects, the two assumptions varied between scenarios. The Reference Baseline scenario represents a true "without-policy" baseline (Strachan, 2011) excluding possible interactions with the EEDI and SEEMP which are outside the model scope. In addition to the scenarios outlined above, sensitivities are run on carbon price, the number and duration of demonstration projects, and the shipping route (wind conditions).

Table 4 Simulation scenarios

No.	Scenarios	Research question(s)	Carbon price	Demonstration Project(s)
1	Reference Baseline	1		
2	\$50/mtCO_2	2a	\$50/mtCO_2	
3	Demonstration Project	2b		1 project (180 months)
4	Combined Policies	2c	\$50/mtCO_2	1 project (180 months)

Model results

Section 4.1 outlines results for each model scenario. Section 4.2 presents results for carbon price and demonstration project sensitivities. Full discussion and analysis of results is presented in Section 5. Each set of results reflects the average for 100 shipowners over 100 model runs using a random seed from 1 to 100 (see Appendix B). Figure 4 shows how the numbers of users, supporters, and strong supporters change over time under each scenario. Figure 5 compares user numbers between scenarios. Figure 6 demonstrates how user numbers change under different fuel price assumptions. Figures 7 and 8 (left) present results for average shipowner expectations, technical risk, and average shipowner profit.

Figure 8 (right) presents the 'estimated reduction in total CO_2 emissions' metric for each scenario, which shows the proportion of CO_2 emissions from the 100 simulated ships during the 2020-2050 model timeframe that is prevented using rotor technology. The 'theoretical maximum' represents the reduction in CO_2 emissions that could be achieved if all 100 simulated shipowners used rotor technology from t=0 on the Long Beach to Shanghai route from Nelissen et al. (2016).

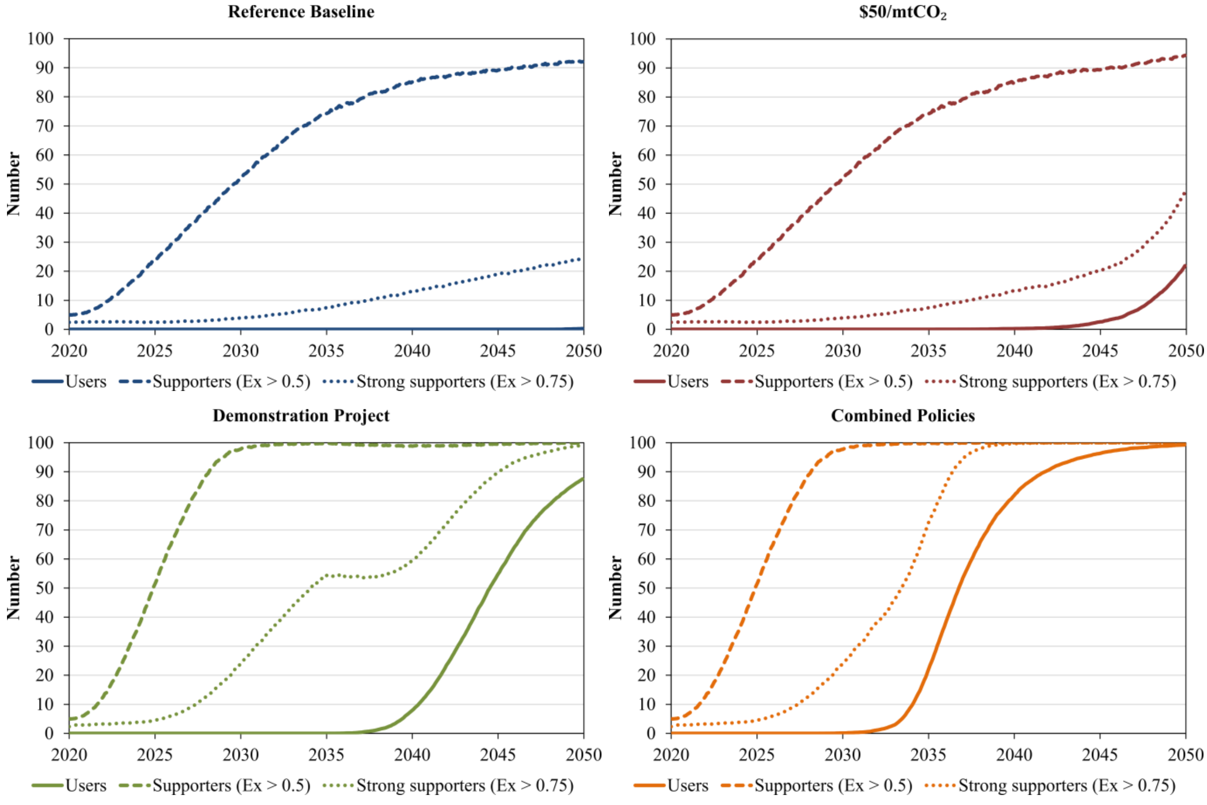


Figure 4 Users, supporters, and strong supporters under scenarios in Table 4

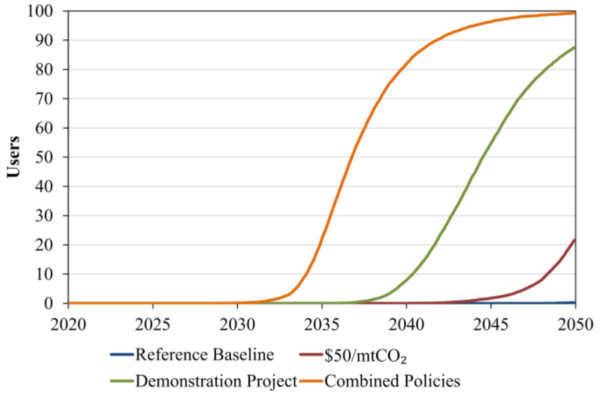
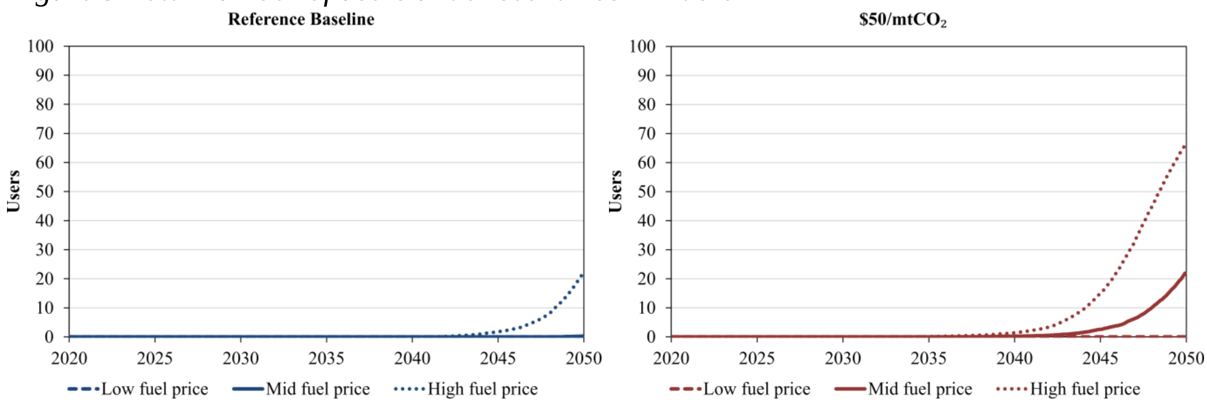


Figure 5 Total number of users under scenarios in Table 4



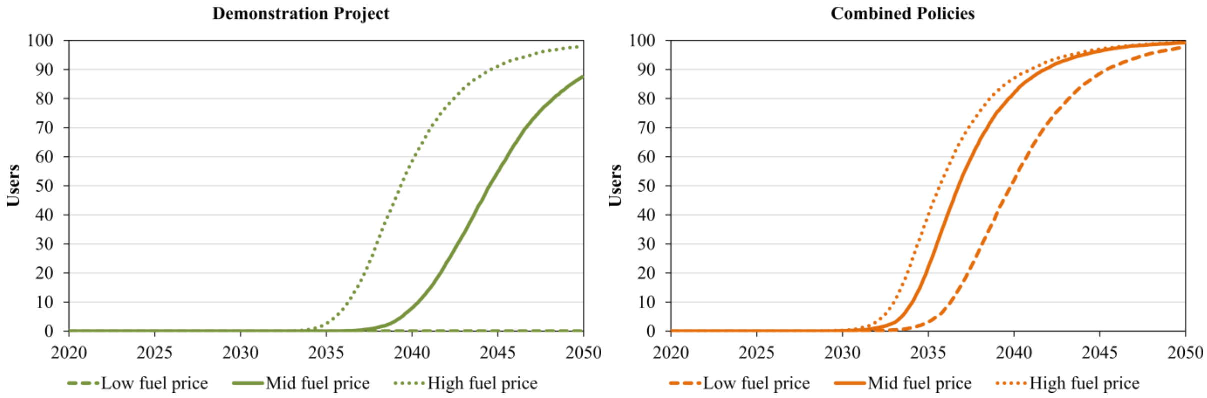


Figure 6 Users under different fuel price assumptions for scenarios in Table 4

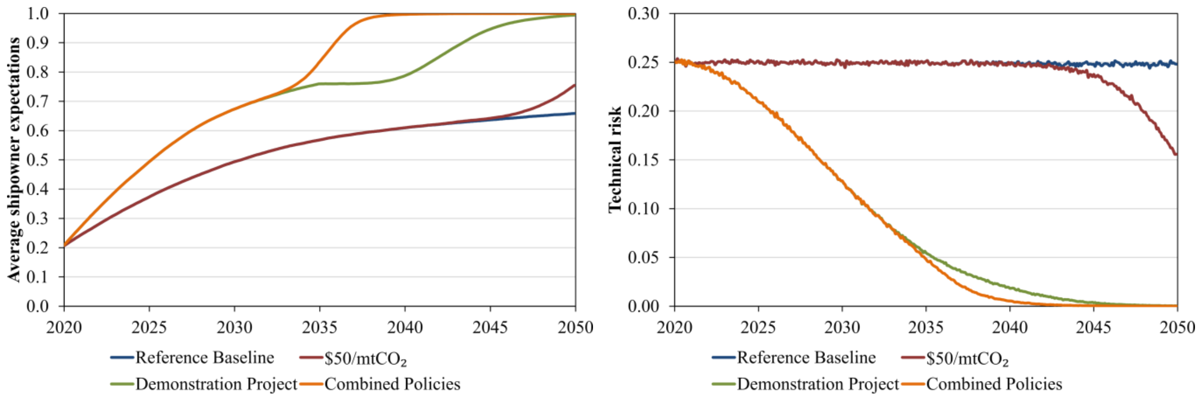


Figure 7 Average shipowner expectations per scenario (left), technical risk per scenario (right)

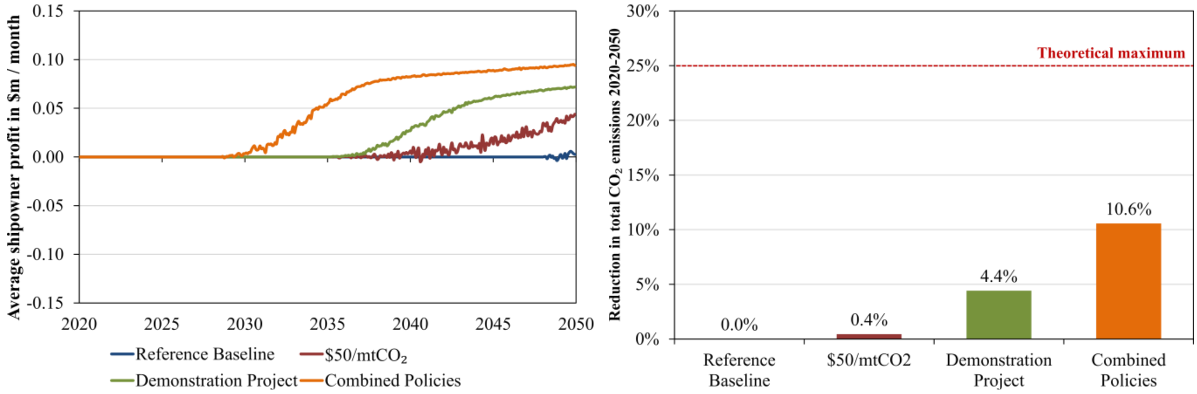


Figure 8 Average shipowner profit (left), estimated reduction in total CO_2 emissions (right)

4.2 Sensitivity analysis

Figure 9 (left) shows CO_2 emissions reductions from different combinations of carbon price and the number of demonstration projects. Figure 9 (right) shows the impact of varying the duration of a demonstration project, rather than the absolute number. The first demonstration project delivers significant, incremental reductions in CO_2 emissions for the carbon price range of \$50-200/mtCO_2 (Figure 9, left). The incremental impact of both carbon pricing and demonstration projects diminishes as the carbon price or number of demonstration projects is increased. This is consistent with results in Eide et al. (2011) where incremental CO_2 emissions savings diminish for abatement costs greater than \$100/mtCO_2. Instead of many demonstration projects, a focus on a few well-designed ones might prove most effective as it minimises the risk of failure and improves their feasibility given their cost (Nelissen et al., 2016).

The demonstration project duration has a significant impact on CO_2 reduction at carbon prices below \$100/mtCO_2 (Figure 9, right). Information and learning spillover effects are assumed to be gradual in the model, so longer demonstration project duration enables greater effect and greater emission reduction.

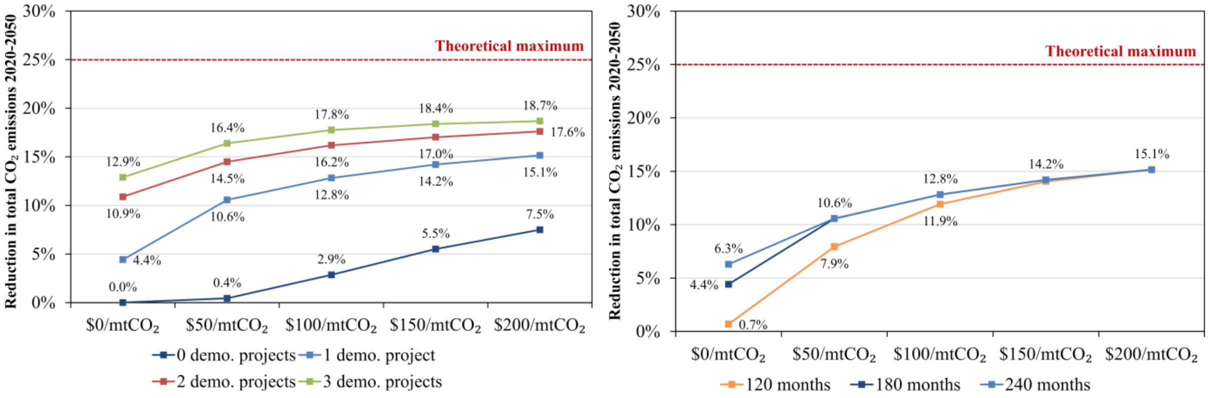


Figure 9 Emission reduction sensitivity to carbon price and number of demonstration projects (left), Emission reduction sensitivity to carbon price and demonstration project duration (right).

Figure 10 (left) shows sensitivity of emission reduction in a shipping route with much lower wind potential e.g. Rotterdam to Shanghai from Nelissen et al. (2016). The expected fuel savings from rotor technology on this alternative route are 10% rather than 25%. Figure 10 (right) shows an estimate for the carbon price required to pass the discounted payback test within the model given average shipowner expectations, using both the expected fuel savings on the more favourable Long Beach to Shanghai route (25%) and the much lower expected fuel savings on the Rotterdam to Shanghai route (10%). This sensitivity demonstrates how sharing learnings from a favourable geographical niche might reduce capital costs on routes with poor wind conditions and increase rotor technology feasibility.

Figure 10 (left) shows the importance of wind conditions in driving rotor diffusion, using wind condition data for the Rotterdam to Shanghai route from Nelissen et al. (2016) with much lower average percentage fuel savings at 10% (compared to 25% average fuel savings for previous results in Figure 9). A combination of high carbon prices (e.g. \$200/mtCO_2) and multiple demonstration projects is required to achieve modest reductions in total CO_2 emissions (3.5-4.7%). These results are in agreement with literature suggesting that wind favourable routes are critical for the diffusion of wind technologies, representing passive protective spaces in which technological experimentation and learning can occur, reducing barriers and costs (Senger and Köhler, 2015; Mander, 2017).

Further analysis (Figure 10, right) shows the estimated shipowner expectations required at each carbon price to pass the model's discounted payback test, calculated using a simple Discounted Cash Flow model (assuming charterer expectations equal shipowner expectations). The results suggest that the carbon price required to facilitate rotor diffusion on a route with poor wind would not be feasible from a political and economic perspective. However, if lessons from experiments in niches with favourable wind conditions can be applied to less favourable routes, then the technical risk and capital cost involved will be reduced, the agent expectations will improve, and this will lower the level of carbon prices required, thus making diffusion more feasible from a political point of view.

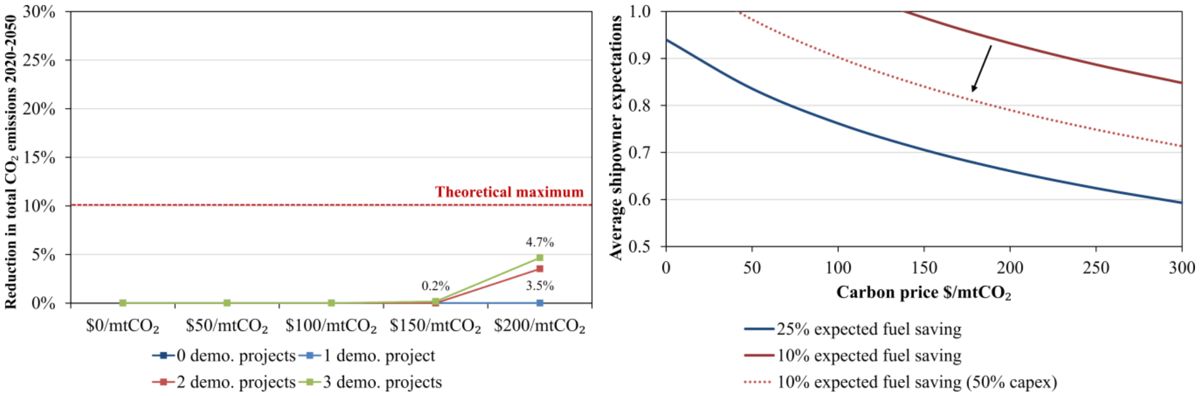


Figure 10 Sensitivities on route with poor wind conditions (left), Average shipowner expectations and the discounted payback test (right)

Figure 11 builds on discussion from Section 5.1.1 and the concept of an expectations threshold. It compares these results with those obtained from "switching off" the split incentives barrier. Without the split incentives barrier, diffusion occurs immediately from 2020. With the barrier in place, no diffusion occurs until 2030 i.e. once the expectations exceed the threshold value. This suggests barriers act to change the rate and timing of diffusion, an important additional insight which builds on the insights in Rehmatulla et al. (2015).

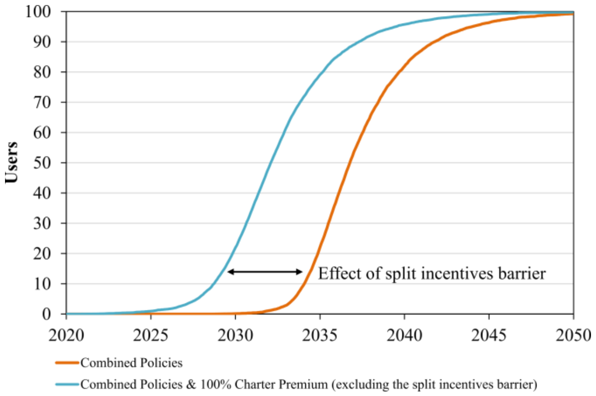


Figure 11 The delaying effect of barriers on diffusion

Discussion

Imperfect information and split incentives barriers can prevent rotor diffusion in the population of shipowners for the model horizon considered, even in routes with favourable wind conditions. The interaction of technology providers with shipowners drives the latter's expectations. However, once they reach 0.5, further increase requires experimentation, or chance socio-technical landscape variation such as an increase in fuel prices making the rotor technology more attractive to shipowners and charterers. Low fuel costs, expectations, and limited charter premiums lead shipowners to perceive rotor technology as uneconomic. Adoption is low and this keeps capital costs high as learning is limited.

Shipowner expectations gradually increase with landscape variation, but they remain too low for even strong rotor technology supporters to experiment. Shipowners underestimate expected rotor technology profits due to imperfect information and charter premiums remain limited due to split incentives. These barriers prevent diffusion because they block the positive feedback loop between experiments, learning, and expectations (Figure 1). This result contrasts with the Bass diffusion model and framework in Rehmatulla et al. (2015) which suggest that barriers act through slowing the rate of diffusion, rather than blocking or preventing diffusion.

The results in this paper are more conservative than those of Nelissen et al. (2016) which, holding the size of the bulker fleet constant at 2020 levels, forecast that perhaps 80% of bulk carriers might use wind propulsion in 2030 under similar assumptions, considering all routes. The difference between the results in this paper and Nelissen et al. (2016) appears attributable to the almost immediate diffusion of the wind propulsion technologies within the Nelissen et al. (2016) model[4]. demonstrates that the omission of barrier and expectation mechanisms from techno-economic models can generate optimistic diffusion forecasts.

[4] Diffusion rates under the Nelissen et al. (2016) model are more consistent with those presented below once barriers are removed from the model within this paper (see Figure 11).

The introduction of a low carbon price (\$50/mtCO_2) increases fuel price and results in limited diffusion, where 22% of shipowners use rotor technology in 2050 (Figure 4). This late and gradual diffusion reduces total CO_2 emissions by 0.4% relative to the "business as usual" scenario. This result is sensitive to fuel prices and demonstrates why shipowners identify fuel price uncertainty as a significant barrier to investment (Rehmatulla et al., 2017b). For example, if fuel prices remain flat at \$400/mt, rotor technology remains uneconomic even for strong supporters.

The average shipowner expectation levels are similar between the Reference Baseline and \$50/mtCO_2 scenarios until experimentation commences around 2040. Then, rising prices and the additional carbon price support drives shipowner with above average expectations to see rotor technology as economic. They install rotor technology and trigger the positive feedback between experimentation, learning, and shipowner expectations that is supported by learning effects that reduce capital costs. Experiments provide information about technology performance and reduce imperfect information. This increases shipowner expectations and improves expected rotor technology profits, increasing charterer expectations as it reduces the split incentives barrier. The expectations growth rate increases (Figure 7, left) as learning reduces technical risk (Figure 7, right) which further increases shipowner profits (Figure 8, left) and performance improvements from experiments. Falling barriers drive rotor diffusion amongst "early adopters" and further improves rotor economic performance through continuous positive feedback.

It is assumed that carbon price influences shipowner expectations through improvements in rotor economic performance and increased participation in experiments, rather than changing shipowner expectations through socio-technical landscape pressures, a plausible additional mechanism. The \$50/mtCO_2 carbon price improves rotor economics even when the percentage of fuel cost savings passed to the shipowner is kept constant, through increasing charterer fuel costs. Keeping the fuel pass-through percentage constant, higher charterer fuel costs will result in shipowners receiving a higher charter rate, making rotor technology more economically viable for shipowners. This demonstrates a reduction in the split incentives barrier whilst the imperfect information barrier remains constant.

The introduction of a 180 month institutional demonstration project is more effective than a carbon price, as it generates earlier and stronger diffusion in 2035, and 88% of shipowners use rotor technology in 2050 (Figure 4). This results in a 4.4% CO_2 emissions reduction in 2050 (relative to the "business as usual" scenario) which is still moderate compared to the 25% theoretical maximum, and it is sensitive to fuel prices (Figure 6).

The demonstration project drives shipowner expectations up to 0.75 rather than the 0.5 maximum for technology providers (Figure 6, left). Most shipowners become niche supporters within 10 years. When the demonstration project stops in 2035, the average shipowner expectations remain flat as experimentation has not commenced. Increased expectations reduce the impact of barriers and increase expected shipowner profits from rotor technology. However, with average shipowner expectations around 0.75, an exogenous fuel price increase is required for the installation of rotor technology to make economic sense. Such fuel price increases represent 'windows of opportunity' for the niche innovation to increase its market share (Schot and Geels, 2008). This emphasizes the importance that carbon prices or economic support have for rotor diffusion until experimentation begins and positive feedbacks further reduce barriers. Without this support a demonstration project might be much less effective (Figure 5) through delayed positive feedback or reliance on economic support from factors outside the control of policy makers such as socio-technical landscape in the form of rising oil prices.

These results assume that the institutionalized demonstration projects cannot fail. It is assumed there are useful learnings each period from an active demonstration project, increasing shipowner expectations, and that catastrophic failure, such as the loss of a vessel and/or life cannot happen. Significant, publicized failure might damage irreparably industry expectations. As technical risk is reduced from 2020 through knowledge imparted from the demonstration project (Figure 7, right), the rising fuel prices encourage innovators to install the rotor technology, experiment results are more positive, driving a faster increase in shipowner expectations and rotor diffusion when compared to the \$50/mtCO_2 scenario. These findings suggest that diffusion might accelerate if influential shipowner innovators are encouraged to experiment with rotor technology earlier through direct public funding (Nelissen et al., 2016) and then publish their results. However, corporate interests and market competition might mean this approach is implausible.

The combination of the carbon price and demonstration project policies is much more effective in overcoming barriers, with strong rotor diffusion from 2030, that reaches almost 100% of shipowners in 2050 (Figure 4), and reduces CO_2 emissions by 10.6% (Figure 8, right). The reduction in total CO_2 emissions provides a clear performance metric for different policy combinations. The combined policies have a much more significant impact with a 10.6% CO_2 emission reduction to 2050, more than double than when the two policies are implemented separately (4.8%). The combination of policies is also more robust to lower fuel prices. If fuel prices remain flat at \$400/mt, the initial rotor diffusion occurs 5 years later and CO_2 emission reductions decrease to 8.1%. However, diffusion levels still approach 100% in 2050, in stark contrast to what either policy achieves when it is introduced alone.

The \$50/mtCO_2 carbon price reduces the threshold of shipowner expectations for rotor technology installation. The demonstration project increases the percentage of fuel cost savings passed to the shipowner and further reduces this threshold. In addition, the demonstration project accelerates expectations growth. Their combined effect is that shipowner experimentation occurs earlier. The reduced technical risk from the demonstration project (Figure 7, right) and the carbon price's economic support result in much higher, initial realised rotor profits (Figure 8, left), improved experiment results that accelerate positive feedback, and reduce barriers more quickly (Figure 12). Diffusion occurs earlier and at a faster rate.

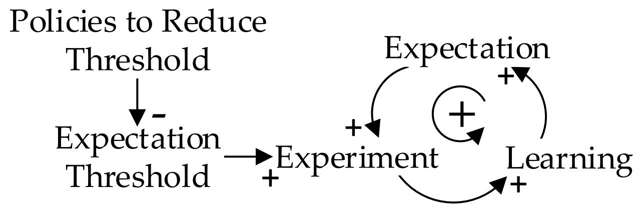


Figure 12 Dynamics of shipowner experimentation

These results show that the combination of policies is significantly more effective and robust in increasing rotor diffusion and reducing CO_2 emissions than the introduction of either policy in isolation. This result is in agreement with similar but more general conclusions from the wider energy literature (Grubb, 2014). Such policy combinations may also be equally effective for other energy efficiency technologies, other shipping sectors, and perhaps other industries, depending on technology attributes and compatibility (Rogers, 2003; Rehmatulla et al., 2015).

Limitations and future research

The model in this paper uses assumptions and a narrow focus to provide transparent and tractable results. They should therefore be considered in the context of these assumptions, providing insights rather than precise projections. Key model assumptions, such as those around charterer expectations and the split incentives barrier or the demonstration project's impact have been modelled in a simple and transparent manner to ensure the model and its results remained tractable. Building of this initial foundation, further modelling of more detailed mechanics for dynamic charterer expectations or demonstration projects could be pursued to provide further insight.

The model reflects limited industry heterogeneity, which can be a possible barrier in shipping (Rehmatulla et al., 2017b). The model could be expanded to reflect different company and fleet sizes new ships, access to capital, or different shipping routes. Moreover, technical change within the incumbent regime could be modelled to include 'sailing ship effects (Ward, 1967).

The model does not account for any potential rebound effects (Berkhout et al., 2000). The existence of not of such effects is not a settled matter. Rebound effects could arise from from improvements in ship energy efficiency, with charterers using energy efficiency as a competitive advantage (Rehmatulla and Smith, 2015). Other studies dismiss the rebound effect within shipping (Buhaug et al. (2009).

The paper aimed to demonstrate the importance of mechanisms and barriers and the benefit of integrating them into techno-economic models that explore the transition of the shipping sector to alternative propulsion technologies. Future research should consider how these mechanisms might be integrated with existing techno-economic models on the importance of demonstration projects for wind propulsion diffusion, and explore the design of such projects to maximise effectiveness and minimise the risk of failure. Moreover, the effect of factors that influence expectations was found to be instrumental. Complementary research could include the development of an 'expectations' metric for shipping actors using survey data.

Further model development would extend its application to the diffusion of other energy efficiency technologies, or sectors within shipping. It could explore multiple competing wind propulsion technologies and assess whether certain technologies can emerge as a "dominant design", or whether several technologies emerge per application domain. More broadly it could be modified and applied to other industries that face similar issues to shipping such as aviation (Schäfer et al., 2016).

Conclusions

The results in this paper indicate that additional policies are required, in niches with favourable wind conditions, to overcome the imperfect information and split incentives barriers that prevent rotor diffusion in drybulk shipping during the 2020-2050 model timeframe. This result is in agreement with literature on key barriers within shipping industry (Nelissen et al., 2016; Rehmatulla et al., 2017b). The model demonstrates that if these barriers are omitted from shipping techno-economic models then they may overestimate the potential for decarbonisation in the sector.

A \$50/mtCO_2 carbon price policy has limited impact on rotor diffusion, reducing CO_2 emissions from simulated shipowners by 0.4% to 2050. The demonstration project is more effective, with earlier, stronger rotor diffusion and 4.4% CO_2 emissions reduction by 2050. In both policy cases, the role of fuel prices is instrumental. High or rising fuel prices are important for wind propulsion diffusion (Rojon and Dieperink, 2014; Mander, 2017; Rehmatulla et al., 2017b).

The combination of the \$50/mtCO_2 carbon price and the demonstration project is much more effective than either policy introduced in isolation with rotor diffusion approaching 100% in 2050. It reduces CO_2 emissions by 10.6%, more than double compared to the two policies implemented separately (4.8%), or than a \$200/mtCO_2 carbon price in isolation (7.5%). The combination of policies is also much more robust to low fuel prices, consistent with recommendations for energy policy design (Grubb, 2014). Furthermore, barriers are shown to impact both the rate *and* timing of rotor diffusion.

Sensitivity analysis shows that carbon price or the number of demonstration projects face diminishing returns in CO_2 emissions. The greatest reduction occurs from the initial demonstration project combined with a politically and economically feasible carbon price of \$50/mtCO_2. A carbon price above \$100/mtCO_2 in combination with multiple demonstration projects has limited benefit. Under low carbon prices, reducing the duration of the demonstration project reduces significantly the diffusion and emissions reductions. High carbon prices combined with multiple demonstration projects are required for even limited diffusion to occur on routes with poor wind conditions. This suggests that a cost-effective approach would be to focus initially on more favourable routes or protected innovation niches might be more cost-effective.

Initial demonstration projects should focus on routes with favourable wind conditions to increase learning and diffusion rates, and reduce the necessary carbon price support. Shipowners that operate on less favourable routes will benefit from learning, reduced barriers and costs, and sufficient improvement in rotor economics to diffuse globally.

Shipping is heterogeneous and separate demonstration projects might be required for each sector and technology pairing. For example, kites within the container sector or sails within the tanker sector. Learnings might not be transferrable across sectors. The diminishing returns to demonstration project numbers suggest that focus should be placed on the design of a few realistic experiments with industry consultation to meet their expectations and reduce possible experimental failures.