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PhD Series 10.2022

Franz Maximilian Buchmann

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CBS PhD School | **PhD Series 10.2022**

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Driving the Green Transition of the Maritime Industry through Clean Technology Adoption and Environmental Policies

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Foreword

This thesis marks the end of my Ph.D. process, a journey of over three years with many ups and downs. In hindsight, it is probably a good thing that I did not know beforehand what (and how many) challenges the process entailed over the three years, as it might have appeared an impossible task to my younger self. Therefore, I consider my biggest accomplishment not to be finishing the Ph.D. project, the thesis, or the research papers, but the simple fact that I did not quit, even when the circumstances seemed grim. This was only possible due to the people I had around me, and here I want to say "thank you" to these great people.

First and foremost, I would like to thank my supervisors. Leonardo (Santiago), words cannot express how grateful and thankful I am for being able to call you my "Doktorvater." Without your experience and guidance, this Ph.D. project would have simply not been possible. I still have the first drafts I gave you to comment on at the beginning of my Ph.D. process and the difference is like day and night compared to this final product. Your eye for detail and academic knowledge helped me become the researcher I am today. However, on top of your academic qualifications, you are a great human being, who truly cares about the people around him and you were always there when I needed you. I will never forget our discussions about research, life, or football, and I will truly miss our weekly meetings. Carsten (Ørts Hansen), thank you for giving me the opportunity to pursue my Ph.D. studies at the Department of Operations Management. You always had an open ear, even during very challenging times, and I could always count on your support so I could grow as a Ph.D. student. Further, your connections to stakeholders and your initiatives in the department made it possible for me to disseminate my research, and to get inspired through dialogues with other people from the field or industry. It was a pleasure having you as my supervisor and manager.

In addition, I would like to thank everyone involved in the Green Shipping Partnership Project. The project gave me the opportunity and support to present my research in the early stages of my Ph.D. studies. The constructive feedback I received and the discussions we had greatly influenced my academic work. I am also grateful for the inclusive environment of the project, which led to fruitful academic collaborations and even friendships. The interesting "beach walk" we had in Vancouver will always remain in my memory. I would also like to thank the discussants and participants of my first and second work-in-progress seminars, who, with their comments, helped

to greatly improve the three research papers. Moving on, I would also like to thank my fellow Ph.D. students (in some cases, Assistant Professors or Senior Researchers by now), who made the process so much more enjoyable. I will miss our infamous table soccer matches and the quirky discussions across the Ph.D. hall-way. Allow me to impart one last piece of advice: never count the times you have rewritten parts of your thesis, it would be far too depressing. A big thanks also to my friends and fellow Ph.D. students in other departments, with whom I completed the majority of my course work.

Last but not least, I would like to express my gratitude to my friends and family at home and in Denmark. You provided invaluable emotional support during the last three years and were understanding if I (again) did not reply to your calls and messages for days. In particular, I would like to express my deepest gratitude to my parents, Andrea and Franz; my grandmother, Gerda; and my partner, Arundhati. I would not be the same person without you, and words cannot describe how grateful I am to have you in my life. Finally, I would like to thank the people who supported me on my way but are not here anymore to witness this moment; this one is also for you.

Abstract

The climate change crisis is arguably the biggest contemporary challenge facing the global community, and reducing emissions is an issue of paramount importance for stakeholders in the maritime industry. The scope of this thesis focuses on two key pillars related to the green transition of international shipping, namely, clean technology adoption and environmental policies. The overarching objective of the Ph.D. thesis is to examine thoroughly the interplay between clean technology adoption and environmental policies to drive the green transition of the maritime industry. The three research papers of this dissertation concomitantly address the overarching objective from both policy and managerial perspectives. The first study (Chapter 2) focuses on the heterogeneous impacts of technology and operational levers on environmental performance in the context of a mandatory environmental policy in the maritime industry. The study develops hypotheses concerning the impact of a key set of levers and empirically tests them with statistical methods. The empirical analysis shows that the relationship between technology and operational levers and environmental performance is complex, and effects can vary across the range of environmental performance. The second study (Chapter 3) examines the impact of an emission trading scheme on the decision to invest in clean technologies in an environment with regulatory and demand uncertainties. The study develops a multi-stage decision model in a stochastic environment and derives analytical results describing the optimal investment policy over time. In addition, the analytical results highlight that an environment with increased uncertainties has a substantial effect on the costs of regulation and the value of actively managing the investment decision. The third study (Chapter 4) focuses on assessing the potential for energy efficiency improvements in ship designs across the different shipping sectors. Departing from the rationale for energy efficiency in marine policies, the study develops a general framework for comparing the energy efficiency of ship designs and derives best-practice benchmarks by applying nonparametric benchmarking methods. The empirical results suggest that the situational contexts for energy efficiency improvements significantly vary across shipping sectors. Based on the results, the study provides policy implications for existing and additional policy measures to foster the green transition of the maritime industry.

Danish Abstract

Klimakrisen er uden tvivl den største nutidige udfordring, som det globale samfund står over for, og reduktionen af emissioner er et spørgsmål af afgørende betydning for interessenter i den maritime industri. Denne afhandling fokuserer på to nøglesøjler relateret til den grønne omstilling af international skibsfart, nemlig vedtagelse af ren teknologi samt miljøpolitik. Det overordnede formålet med ph.d.-afhandlingen skal er grundigt at undersøge samspillet mellem ren teknologi og vedtagelse og miljøpolitikker for at drive den maritime industris grønne omstilling. De tre forskningsartikler i denne afhandling behandler samlet det overordnede mål fra både et politisk og et forretningsmæssigt perspektiv. Den første artikel (kapitel 2) fokuserer på heterogene indvirkninger af teknologi og operationelle løftestænger på miljøpræstationer i sammenhængen af en obligatorisk miljøpolitik i den maritime industri. Artiklen opstiller hypoteser om virkningen af et sæt af reguleringsmuligheder og tester dem empirisk med statistiske metoder. Den empiriske analyse viser, at forholdet mellem teknologi, operationelle reguleringsmuligheder og miljøpræstationer er kompleks, og virkningerne kan variere på tværs af spektret af miljøpræstationer. Den anden artikel (kapitel 3) undersøger effekten af en emissionshandelsordning på beslutningen om at investere i rene teknologier i et forretningsmiljø med regulerings- og efterspørgselsusikkerhed. Undersøgelsen udvikler en flertrinsbeslutningsmodel i en stokastisk kontekst og udleder analytiske resultater, der beskriver den optimale investeringspolitik over tid. Derudover viser de analytiske resultater at en forretningskontekst med øget usikkerhed har en væsentlig effekt på omkostninger ved regulering og værdien af aktivt at styre investeringsbeslutningen. Den tredje artikel (kapitel 4) fokuserer på at vurdere potentialet for energieffektiviseringsforbedringer i skibsdesign på tværs af forskellige skibsfartssegmenter. Med udgangspunkt i behovet for energieffektivitet i maritim regulering udvikler artiklen en generel ramme for sammenligning af energieffektiviteten af skibsdesign og –afledninger og udleder 'best practice' benchmarks ved at anvende ikke-parametriske benchmarkingmetoder. De empiriske resultater tyder på, at de situationelle sammenhænge for energieffektiviseringer varierer betydeligt på tværs af shippingsektorer. Baseret på resultaterne giver undersøgelsen forslag til reguleringsmulighederne for eksisterende og yderligere politiske foranstaltninger til at fremme den maritime industris grønne omstilling.

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Abbreviations

AE	Auxiliary Engines
AIS	Automatic Identification System
CF	Carbon Conversion Factor
CII	Carbon Intensity Indicator
COP 26	26th UN Climate Change Conference of the Parties
CO_2	Carbon dioxide
CWFR	Clarkson World Fleet Register
CZCS	(Mærsk Mc-Kinney Møller) Center for Zero Carbon Shipping
DAWE	Department of Agriculture, Water, and the Environment
DEA	Data Envelopment Analysis
DGO	Diesel/Gas Oil
DMA	Danish Maritime Authority
DNV	Det Norske Veritas
DWT	Deadweight Tonnage
EC	European Commission
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EIV	Estimted Index Value

ETS	Emission Trading Scheme
EU	European Union
EU-ETS	European Union Emission Trading Scheme
EU-MRV	European Union Monitoring, Reporting, and Verification
ICS	International Chamber of Shipping
GDP	Gross Domestic Product
GHG	Green House Gas
GT	Gross Tonnage
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied Natural Gas
MACC	Marginal Abatement Cost Curve
MARPOL	International Convention for the Prevention of Pollution from Ships
MBM	Market-based Measure
MDO	Marine Diesel Oil
ME	Main Engines
METS	Maritime Emission Trading Scheme
MGO	Marine Gas Oil
MRV	Monitoring, Reporting, and Verification (System)
NOx	Nitrogen Oxides
OECD	Organisation for Economic Co-operation and Development
OM	Operations Management
QR	Quantile Regression

SDG	Sustainable Development Goal
SEEMP	Ship Energy Efficiency Management Plan
SEM	Standard Error of the Mean
SFOC	Specific Fuel Oil Consumption
SOM	Sustainable Operations Management
SOx	Sulfur Oxides
TRES	Thomson Reuters Eikon Shipping
TW	Transport Work
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention on Climate Change
WBCSD	World Business Council for Sustainable Development
WCED	World Commission on Environment and Development

Chapter 1

Introduction to the Ph.D. project

> *"Mankind is on the horns of a dilemma. For, whether we like it or not, our collective way of life has become unsustainable and we need to do something about it - and soon. The choices we have made about the way we lead our lives have been slowly eating away at the very support system that enables us to live and breathe. This cannot, and should not, go on. We need to make some tough decisions, we need to make them now and we need to act on them as one, with total and undivided commitment — today and in the future."*

This statement was read at World Maritime Day 2009 by the Secretary General of the International Maritime Organization (IMO), Mr. Efthimios E. Mitropoulos, highlighting the area of inquiry of this Ph.D. thesis. The overarching objective is to examine the interplay between clean technology adoption and environmental policies for the decarbonization of the maritime industry. The climate change crisis is arguably the biggest contemporary challenge facing the global community, and reducing emissions is an issue of paramount importance for stakeholders in the maritime industry. The scope of this thesis focuses on two key pillars related to the decarbonization of international shipping, namely, clean technology adoption and environmental policies. While there are other drivers, these two pillars form an integral part of the green transition process, which is discussed in the following sections of the introduction.

At first, section (1.1) gives the reader an introduction to and background of the climate change problem and evidences the role of the maritime industry in this global phenomenon. Section (1.2) outlines the role of environmental policies in the decarbonization of the maritime industry. The implementation of policy measures is a key instrument for policy makers to drive the green transition of international shipping and to meet climate change targets. In section (1.3), the role of clean technology adoption for the green transition is described in the context of the thesis. The majority of marine emissions stems from the global fleet; thus, the adoption and development of cleaner technologies is one of the industry's key levers to meet long-term emission reduction goals. Section (1.4) outlines the overarching objective of the thesis by highlighting the interplay between environmental policies and clean technology adoption for decarbonizing the maritime industry. Finally, the theoretical perspective is laid out and an overview of the three research papers is given.

1.1 Green transition of the maritime industry

Since the Industrial Revolution around 1750, technological and societal developments have facilitated unseen levels of international trade and economic growth and thus have led to drastic improvements in global living standards. Based on DeLong (1998), the global gross domestic product (GDP) per capita grew on average by 0.01% from 1000 BC to 1750; however, since then, it has grown on average by 1.5% per year. To illustrate, the global GDP per capita in 2000 was more than 50 times higher than three millennia before. This global increase in living standards is accompanied by a rapid global population growth of roughly factor 10 since 1750. This economic and population growth did not come without consequences. Today, an ever-increasing number of goods is produced and transported around the globe with human-made devices, like ships, trucks, and airplanes, to be consumed by customers. Maritime transport plays a key role in international trade by transporting roughly 80% global trade volume of physical goods (UNCTAD, 2019). However, these practices led to an unprecedented depletion of finite natural resources, including fossil resources or raw materials, and the pollution of such ecosystems as the ocean and the atmosphere. Humanity's way of living is not only currently having negative impacts on the natural environment in which we are all living, but it is also seriously threatening the livelihood of future generations.

The issues of endangering the natural environment being the foundation for life on earth and promoting intergenerational inequalities are inextricably linked to the concepts of sustainability and sustainable development. While these terms are often used rather vaguely and can encompass a multitude of topics, the most common definition is from the Brudtland report in 1987 defining sustainable development as *"the development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (WCED, 1987). In general, sustainable development comprises three pillars: economy, society, and environment. One way to conceptualize the relationship between the three pillars is through the notion of carrying capacity, illustrated in Figure (1.1), representing the natural environment's potential for the neutralization of human disruption (Cato, 2009). Through this lens, external environmental limits set the boundaries for society and the economy (Danilov-Danil'yan et al., 2009). Thus, any development exceeding the critical thresholds, where this potential is exhausted, cannot be considered sustainable development. The most prominent ambition to put sustainable development into practice is the 17 Sustainable Development Goals (SDGs) adopted in 2015 as part of the United Nations' (UN) 2030 Agenda for Sustainable Development, which set out a 15-year plan to achieve the goals (UN, 2015). Through the formalization of the SDGs, sustainable development and environmental issues in particular are now the focus of policy makers worldwide.

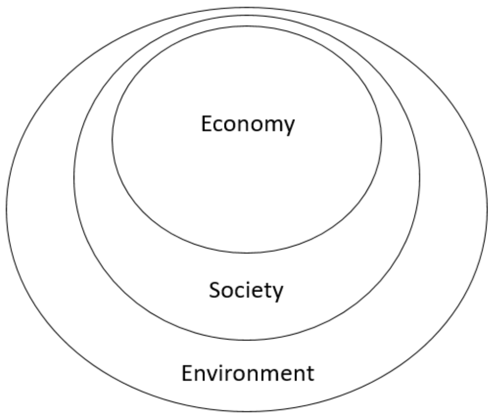

Figure 1.1: Relationship between the three pillars of sustainability, where the environment sets the boundaries for both society and economy (Source: Cato, 2009).

One of the Earth's systems that is impacted negatively by unsustainable human activities is the pollution of the atmosphere, which is targeted by multiple SDGs and will be referred to for simplicity as air pollution in this thesis. In the maritime context, the primary pollutants are greenhouse gases (GHGs), including carbon dioxide or methane, sulfur and nitrogen oxides (NO_x and SO_x), and other kinds of particles. While all these pollutants have direct or indirect adverse effects on human health, ecosystems, and the climate, there are structural differences in the effects between the pollutants. To illustrate, some of the main impacts of NO_x and SO_x emissions relate to the acidification and eutrophication of ecosystems and fostering of respiratory diseases in coastal areas through reducing air quality (Salo et al., 2016). These effects are in general localized around the areas where the pollution occurs and can be, for example, addressed by limiting the content of these pollutants in the fuel used onboard. One key impact of GHG emissions is warming the Earth's atmosphere, leading to climate change. Hence, the adverse effects of GHG emissions are a global problem not limited to certain regions. Further, carbon dioxide has a half-life of 120 years, so emissions today have a long-lasting impact on the natural environment and the livelihood of future generations. Due to the unique global scale and intertemporal nature of the problem, the scope of the thesis is mostly concerned with air pollution related to GHG emissions, with a special focus on carbon, which is the main pollutant in the maritime context.

A main driver of the climate change crisis, addressed by SDG 13, which aims to *"take urgent action to combat climate change and its impacts"* is the release of carbon dioxide and other GHGs through human activities, which has disastrous consequences for the natural environment in general and global supply chains. The so-called greenhouse effect describes the natural mechanism of warming the Earth's surface and in turn facilitating life on Earth. However, the release of carbon dioxide and other GHGs increases their concentration in the atmosphere, enhancing the greenhouse effect and leading to rising temperatures on Earth (DAWE, 2021). It is estimated that about half of the total carbon emissions attributable to human activities in the period from 1750 to 2010 occurred in the last 40 years. In these years, carbon emissions from fuel combustion and other industrial activities accounted for roughly 78% of total GHG emissions globally (IPCC, 2014). The maritime industry is no exception to this global trend. In the period from 1990 to 2019, the total CO_2 emissions of international shipping increased by 97% (Crippa et al., 2020). Further, in line with global increasing trajectories, marine emissions are projected to be 90–130% of the 2008 (baseline) emissions in 2050 depending on economic and energy developments (Faber et al., 2020). If these trends are not halted, it is projected that the global mean surface temperature could increase from 3.7 to 4.8 degree Celsius compared to pre-industrial levels (IPCC, 2014). The consequences, including, inter alia, more extreme weather events and rising sea levels, would dramatically affect marine supply chains and trade, but more importantly, it would destroy the livelihood of whole communities worldwide.

To address and mitigate the menacing consequences of climate change, international initiatives and treaties have been agreed upon by the global community to reduce the emission of GHGs into the atmosphere. After scientists first presented evidence of rising atmospheric CO_2 concentrations in the '60s and '70s, the first major global treaty was the Kyoto Protocol adopted on December 11, 1997 and entered into force on February 16, 2005. The main feature of this initiative is the commitment of 37 developed economies and the European Union (EU) to reduce and limit GHG emissions to individually defined binding targets over a time horizon (UNFCCC, 2021b). Another main international treaty is the Paris Agreement, adopted on December 12, 2015 and entered into force on November 4, 2016. The main goal of the agreement is to limit global warming to 2–1.5 degrees Celsius compared to pre-industrial levels (UNFCCC, 2021a). Notably, international shipping (and aviation) is not explicitly included in either treaty due to the global nature of its activities; hence, the formulation of treaties and initiatives was passed to the IMO. The IMO is a specialized agency of the UN and the global regulatory authority for the safety of shipping and the mitigation of atmospheric pollution by ships. Its main role is the development, implementation, and monitoring of policies for the maritime industry that are fair and effective (IMO, 2021). The first convention regulating air pollution and GHG emissions was Annex VI, which entered into force on May 19, 2005 to the International Convention for the Prevention of Pollution from Ships (MARPOL). In April 2018, the IMO reached an agreement with the initial IMO GHG strategy, which for the first time formally stated the vision to decarbonize the maritime industry and the level of ambition to achieve this vision (IMO, 2018).

The vision and ambitions of the IMO and other regulatory authorities, including the EU, to decarbonize the maritime industry are the cornerstones of the environmental policies and problem statement of the thesis. In its strategy, the IMO states the vision to remain committed to reducing GHG emissions from international shipping and to phase them out as soon as possible in this century (IMO, 2018). More precisely, the policy maker's targets indicating the level of ambition are stated as follows:

- to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008; and
- to peak GHG emissions from international shipping as soon possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008, while pursuing efforts toward phasing them out, as called for in the vision as a point on a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals.

Further, an important objective of the IMO, indicating the direction for action and measures, is to incentivize the adoption and development of clean shipping technologies to reduce the carbon footprint of the maritime industry. Similarly, the EU as part of the European Green Deal formulated the targets for shipping companies to reduce their average CO_2 emissions per transport work by at least 40% by 2030 for all their ships and to reduce transport GHG emissions in the EU by 90% until 2050, including maritime transport (EU, 2020). An important element of the vision and policy targets is that they focus on pathways to decarbonizing the maritime industry over time, which is also referred to as the *"green transition"* in this thesis. This aligns with the aforementioned intertemporal and dynamic nature of the sustainable development and climate change topics and highlights an important element of the thesis' problem statement. It is mandatory to investigate the green transition of the maritime industry through a dynamic and long-term lens, which is a common theme in the research papers to follow.

1.2 Environmental policies for the green transition

In general, the term environmental policy encompasses any measure by a regulatory authority regarding the effects of human activities on the environment and, in particular, measures designed to prevent the harmful impact of human activities on ecosystems (Van Bueren, 2019). In this thesis, of special relevance are environmental policies concerned with the harmful impact of air pollution through the emission of carbon dioxide into the atmosphere. There are multiple basic strategies a regulatory authority, which seeks to regulate directly, can utilize to design specific policy measures (see Baldwin et al. (2011) chapter 7 for an overview). In the maritime context, the most relevant strategies are command and control (C & C) regulations and economic incentive-based regulations, which will be referred to as market-based measures (MBMs).

The essence of C & C regulations is the exercise of influence by imposing mandatory standards backed by legal sanctions (Baldwin et al., 2011, p. 106). The standards can be design-based, imposing the usage of a specific technology, or performance-based standards, prescribing an acceptable level of pollution a regulated unit can emit. The determination of a unit's compliance usually entails some form of certification process to control whether the regulatory requirements are met. A virtue of this policy strategy is that the regulatory authority can directly impose standards through the force of law and can prohibit any activity not compliant with the set standards. Further, the simplicity of the strategy is appealing, as it entails a binary pass–fail criterion based on the standards. However, this strategy has the serious downside that it is in practice nearly impossible for the policy maker to set the appropriate performance standard. First, acquiring relevant data for standard setting is normally expensive and difficult for the regulatory authority, and even if possible, standard setting is a political process subject to external influence (Baldwin et al., 2011, p. 310). Second, setting uniform standards across industries or sectors leads to an inefficient regime, as some units will find it extremely hard to comply, while others have no incentive to exceed the standard despite being easily able to (Sunstein, 1990).

In contrast, MBMs are designed to harness market powers through prices to reach environmental policy targets. In the context of this thesis, two market-based regulatory strategies are of special interest: carbon taxes, operationalized through a levy on bunker fuels, and emission trading schemes (ETS), also referred to as cap-and-trade schemes. One key difference between these two strategies is the process of pricing harmful emissions. A carbon tax sets a price on carbon emissions, and polluters are a charged a fixed amount for every unit of emissions they output. Because taxing emitted carbon emissions directly is often impractical, carbon taxes are often implemented through a tax on every unit of bunker fuel a polluter purchases. On the other hand, an ETS fixes the amount of allowable carbon emissions in a defined period (i.e., a year) by issuing allowances. After the initial allocation of the allowances, they can be traded on a secondary market, where the price is determined through supply and demand. In theory, under perfect information, both strategies have the same effects and represent a cost-minimizing way of reaching a desired level of pollution under certain conditions (Baumol & Oates, 1988). However, in practice, the effectiveness of the two policies is dependent on specific design choices and the situational context in which they are implemented.

A rigorous comparison between the two market-based strategies is outside the scope of this thesis, and only some selected considerations are highlighted here. Two drawbacks of an ETS are the price uncertainty of allowances and the higher degree of administrative burden. Because the supply of allowances is fixed in an ETS, small demand changes can lead to huge price changes on the secondary market (EC, 2020). The price volatility makes revenues highly uncertain over time and, thus, can lead to a *"wait and see"* managerial approach with suboptimal emission reduction efforts (Ben-David et al., 2000). Further, targeting a large number of vessels and their emissions might be associated with high administrative costs to enforce the cap and transaction costs for making permits transferable between units (Lagouvardou et al., 2020; OECD, 2002; Stavins, 1995). On the other hand, two important drawbacks of a carbon tax are the emission reduction uncertainty and informational demands for regulatory authorities. By design, a carbon tax offers price certainty, but it is next to impossible for a policy maker to ex ante predict how much a given tax level will reduce the overall emissions. Hence, a carbon tax is not directly aligned to defined reduction goals as an emissions cap. In essence, setting the optimal tax to reach desired emission levels requires the policy maker to estimate the social costs of pollution, which often are unknowable in their entirety (Baumol, 1972). While it might be possible to adjust tax levels when observed reductions are deemed unacceptable, such trial and error is unfeasible in such contexts as the climate change problem, where the consequences can be catastrophic (Baldwin et al., 2011, p. 113).

The initial GHG strategy lists various candidate policy measures to foster the green transition of the maritime industry. These measures can be categorized into short-, mid-, and long-term measures dependent on the timeline for their adoption. At the moment, only measures in the short-term category are in place. In this category, of special interest are the measures seeking to improve and extend further the current energy efficiency framework, which comprises the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), which entered into force in 2013. The EEDI is a mandatory C & C regulation prescribing minimum energy efficiency standards for newly built vessels from a technical perspective. In contrast, the SEEMP focuses on measuring the operational energy efficiency on board vessels and aims at providing guidance on the best practices for fuel-efficient ship operations. In November 2020, two additional C & C measures were approved by the IMO's Marine Environment Protection Committee (MEPC): the Energy Efficiency Existing Ship Index (EEXI), which can be seen as the EEDI counterpart for existing vessels, and the Carbon Intensity Indicator (CII), building on the SEEMP to prescribe minimum operational performance standards. Mid-term measures most notably comprise the outlined MBMs, and discussions at the IMO about their adoption already started in 2010. At MEPC 60, 11 proposals were presented, which can be roughly categorized as MBMs based on a levy on bunker fuels, an ETS, or hybrids between them and the EEDI (see Psaraftis (2012) for a thorough discussion of the proposals). However, discussions about potential MBMs for the maritime industry were suspended in 2013, and, despite strong scientific and practical evidence for their effectiveness, the adoption of an MBM by the IMO is currently highly uncertain.

In contrast, the EU is taking policy action to ensure the marine sector contributes to the EU's climate change goals. As a first step, the EU Monitoring, Reporting, and Verification (MRV) system entered into force in 2018. The EU-MRV regulation requires all vessels above 5,000 gross tonnage (GT) calling a port in the European Economic Area (EEA) to monitor and report their voyage-related CO_2 emissions (EU, 2015). The main purpose of the regulation is not to lower emissions directly, but to provide the foundation to track marine emissions for the EU-ETS, the key policy measure in the EU. The EU-ETS has been in place since 2005, and it covers the manufacturing industry and power sector, as well as airlines operating in the EEA. In July 2021, the EU announced it would extend the EU-ETS to the maritime industry from 2023 and include it alongside the other sectors (EC, 2021). To put this into perspective, the EU is estimating that the inclusion of marine transport will govern roughly 90 million tons of CO_2, only approximately 8.5% of the total 1,056 million tons of marine CO_2 emissions in 2018 (Faber et al., 2020). Apart from the limited impact, previous studies have identified multiple shortcomings of the regional scope to tackle this global phenomenon like carbon leakage and distortions in competitiveness (Miola et al., 2011; Wang et al., 2015). However, the EU-ETS is currently the only market-based policy measure in sight for the industry, and it could potentially rekindle urgently needed discussions about the implementation of an MBM at the IMO level.

The scientific community generated multiple insights about the effectiveness of existing and potential policy measures for decarbonizing the maritime industry. In summary, previous studies have mostly questioned the effectiveness of the EEDI to reduce marine carbon emissions significantly. Two main reasons for this observation are the projected increase in marine transportation activities and the policy design. In a study by DNV GL, global maritime transport is forecasted to increase by 39% until 2050; thus, the authors conclude that current policy measures are insufficient to reach the IMO's GHG targets (DNV, 2018). Further, Smith et al. (2016) forecasted an increasing trajectory of maritime CO_2 emissions until 2050 and that the EEDI will only lead to a 3% emission reduction compared to a non-EEDI scenario. Another reason for these findings is the aforementioned difficulty for policy makers to ex ante define appropriate performance standards. Multiple studies have shown for different ship types that compliance with the minimum energy efficiency standard can be easily achieved (Ančić et al., 2018; Attah & Bucknall, 2015; Vladimir et al., 2018). This has led the IMO to tighten the standards further for certain ship types in hindsight (MEPC, 2020). However, such fixes do not address the root cause of the problem. Hence, revising existing policy measures and implementing additional MBMs are likely required for the green transition of the maritime industry to become a reality.

Previous research has investigated the effectiveness of an ETS to foster the green transition of the maritime industry. In these studies, a special focus lies on evaluating the role of the policy measure's design and scope to achieve desirable outcomes. To illustrate, an ETS can be designed as a global maritime ETS (METS) or as a regional ETS integrating the maritime sector alongside other sectors, as in the EU-ETS. In a case study involving ship operators, Kösler et al. (2015) concluded that a global METS considering the specific characteristics of the industry has the potential to reduce marine CO_2 emissions without high administrative costs for shipping companies. Further, according to Zhu et al. (2018), a METS can incentivize ship owners to adopt clean technologies and invest in renewing their fleet instead of retrofitting their existing fleet. A similar conclusion was reached by Gu et al. (2019), stating that a global METS can even in the short term lead to emission reductions and incentivize investments in clean technologies in the long run. It is notable that the aforementioned studies highlight the feasibility of a global and maritime ETS solution for global shipping. However, to foster technology adoption, it is crucial that the allowance price is not too low due to an oversupply of licenses, a fact observed in previous ETS schemes (Psaraftis & Lagouvardou, 2019). The design of a global METS is crucial for its success and must be tailored to the specific context of the maritime industry. It is currently not well understood how the system can incorporate the defined policy targets and how uncertainty in design choices impacts incentives under an METS.

1.3 Clean technology adoption for the green transition

Before outlining the role of clean technology adoption, it is worth defining the term technology in the context of this thesis. In general, technology can be broadly described as the practical application of scientific knowledge. In the thesis, the focus lies on applications in systems, like human-made technical devices and machinery in the maritime environment. These technologies enable maritime transportation services and are one of the cornerstones of international trade. However, these devices also have negative impacts on the natural environment by producing pollution as a byproduct and depleting natural resources. The term clean technologies then describes technologies that mitigate these negative impacts on the natural environment. While this definition of technology relates to an engineering perspective, the adoption of clean technologies is inherently linked to economic, environmental, and social considerations. Therefore, by investigating clean technology adoption, the thesis moves beyond a strictly technical perspective and investigates this driver for decarbonization in the specific context of the maritime industry.

A main factor of maritime carbon emissions is the combustion of fossil fuels in vessels to provide propulsion for transportation services. The most common engine type utilized in vessels as the prime mover is diesel due to its manifold advantages. One particular advantage is its relative insensitivity to the quality of fuel; thus, low-quality and inexpensive fuels, like heavy fuel oil or marine diesel oil, are the main fuels in the maritime industry. Due to their low quality, the combustion of these fuels leads to substantial air pollution with all the aforementioned negative side effects. Therefore, a vessel's total carbon emissions depends not only on the *amount* of fuel, but also on the *type* of fuel consumed on board. Figure (1.2) displays the relation between a vessel's total emissions and measures of energy efficiency in the maritime industry, which are broadly defined as total carbon emissions per unit of service (measured in transport work[1]). Therefore, reducing carbon emissions per unit of transport work is one of the top priorities in decarbonizing marine transport. Note that this is also often refereed to as *"carbon intensity"* in the maritime industry. However, for simplicity and to avoid confusion for the reader, I mostly refer to the expression in Figure (1.2) as a measure of energy efficiency throughout the thesis. There is a distinction between technical and operational energy efficiency measures; while technical energy efficiency relates to the design of a vessel and its technical specifications, operational energy efficiency indicates the observed efficiency during a ship's operations. Due to the definition of technology, the scope of this thesis is mostly concerned with technical energy efficiency and related topics.

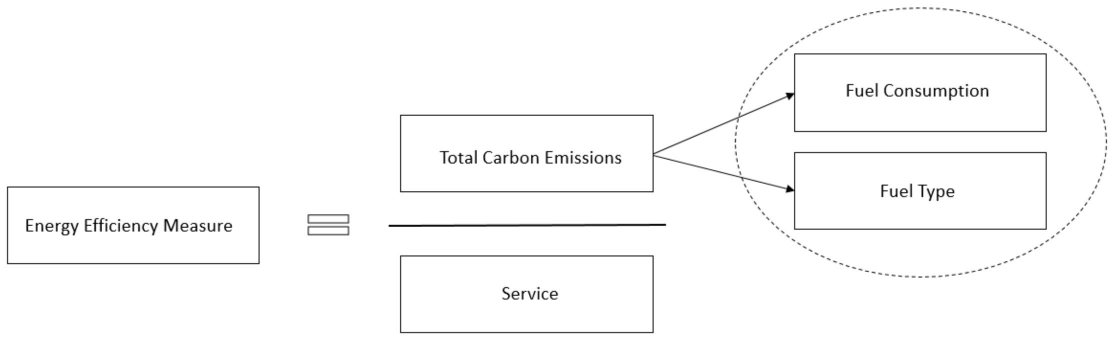

FIGURE 1.2: Relationship between clean technologies and measures of energy efficiency

There are two main levers to reduce the total carbon emissions of a vessel by adopting clean technologies. The first lever relates to technologies improving the fuel efficiency of the vessel from a design perspective. These solutions aim to reduce the required propulsive power at the desired speed to reduce the fuel consumption of a given fuel, in turn reducing carbon emissions. They include reducing hull resistance, improving engine efficiency, optimizing weight and capacity, and auxiliary propulsion devices using renewable energy like solar or wind (see Brynolf et al. (2016) for an overview). While most of these design measures are discussed for newly built vessels, it is

[1]Transport work is usually defined in the maritime context as the total amount of cargo times the distance sailed and is a quantitative measure of the amount of transportation service provided by a vessel.

mandatory to also implement solutions for existing vessels through retrofitting. Because modern vessels have a life span of up to 30 years, the existing fleet will impact the natural environment for a considerable time. The other lever relates to switching to a fuel with a lower environmental impact than traditional fuels, given the fuel consumption. The generic term alternative fuels describes this group of fuels. Alternative fuels include, but are not limited to, liquefied natural gas (LNG), biofuels (e.g., biodiesel and vegetable oils), alcohol-based fuels (e.g, methanol and ethanol), hydrogen, and ammonia. The amount of CO_2 emissions when burning a fuel depends on the carbon content of the fuel. Hence, switching to a fuel with a lower carbon content has a direct positive impact on a vessel's carbon emissions. The magnitude of the positive effect varies between alternative fuels. To illustrate, LNG can approximately reduce CO_2 emissions by 25% compared to traditional fuels, while providing the same propulsive power (Pavlenko et al., 2020). Hydrogen has the potential to be a zero-emission fuel, as water vapor is the only emission if used with fuel cells (Brynolf et al., 2016). There is also a significant difference in the maturity of different alternative fuel technologies. While LNG is already used in commercial applications, the widespread use of hydrogen in the maritime industry is still a distant vision.

The adoption of clean technologies related to vessel design is mainly driven by economic considerations. Fuel costs account for up to 60% of a vessel's operating costs; thus, reducing fuel consumption is of high importance from a business perspective (Royal Academy of Engineering, 2013). Solutions for reducing fuel consumption have a direct cost-reducing effect for shipping firms, which in turn also reduces carbon emissions. The costs for a shipping company associated with reducing emissions are called abatement costs. The related concept of a marginal abatement cost curve (MACC), which indicates the costs of abating an additional unit of emissions, has guided previous discussions about the adoption of fuel savings technologies in the maritime industry. In a nutshell, a MACC ranks technologies according to their associated abatement costs and depicts their emission reduction potential compared to the status quo. Previous studies have estimated a MACC for shipping to quantify the potential of different clean technologies and the associated costs. In these studies, a key finding is that there are design measures with a positive net-present value (i.e., negative marginal abatement costs), meaning that the fuel savings outweigh their costs and several more with only moderate costs (Buhaug et al., 2009; Eide et al., 2011). Recently, Faber et al. (2020) concluded that design measures have a CO_2 emission reduction potential of nearly 30% until 2050 (assuming there are no implementation barriers) at marginal costs ranging from negative to 18 USD/ton-CO_2. Therefore, at least in theory, improving energy efficiency through adopting fuel saving technologies has the potential to be a significant contributor to decarbonizing the industry and to be feasible from a business perspective.

Despite their key role in the green transition, there are several challenges in the adoption of alternative fuel technologies. Moving beyond fuel saving technologies, the widespread adoption of alternative fuels is needed to yield large reductions in emissions and to meet long-term policy targets (Anderson & Bows, 2012; Faber et al., 2020). One of the key aspects guiding the choice of fuel is economic costs. Here, one potential barrier is the higher fuel costs of most alternative fuels when compared to traditional fuels. Further, investment and installment costs of alternative fuel technologies vary significantly currently due to differences in the maturity of these technologies (Brynolf et al., 2016). The economic aspect of costs is inextricably linked to structural considerations. For any alternative fuel to be adopted on a large scale, the fuel production must be scaled to meet the demand of the industry and a wide-spread bunkering infrastructure must be developed. Further, some alternative fuels require non-traditional storage on board a vessel and special safety requirements due to their toxicity (DMA, 2012; Van Hoecke et al., 2021). From a social perspective, it is mandatory to assess the whole life-cycle of a fuel and its related impacts on the natural environment and society. To illustrate, while hydrogen has the potential to be a zero-carbon fuel, the production process of hydrogen crucially impacts its life-cycle carbon footprint. Further, alternative fuels based on feedstock (i.e., biofuels) pose the risk of increasing prices of agricultural commodities if production is expanded on a large scale, with unforeseeable consequences for fighting global hunger (Naylor et al., 2007). Because of this complex set of considerations and the risk among marine stakeholders of committing to the wrong fuel technology, it is currently uncertain what the marine fuel driving the green transition will be.

In summary, improving energy efficiency through clean technology adoption has a large emission reduction potential, but observed adoption rates are insufficient for a green transition in the industry. Especially, the low implementation of apparently cost-effective technology solutions seems puzzling and is often referred to as the energy efficiency gap. Previous research has investigated the energy efficiency gap in the maritime industry. These studies have identified market failures and insufficient incentives as potential drivers of this phenomenon. Studies have argued that the lack of information about real fuel savings after implementing these measures leads to low market premiums for energy efficient vessels, thus yielding little economic incentive to adopt clean technologies (Adland et al., 2017). Another reason is the split incentives problem in contractual agreements between parties in charter markets, where the ship owner determines the vessel's energy efficiency and the charterer incurs the costs of this decision (Agnolucci et al., 2014; Rehmatulla & Smith, 2020). In a survey of ship owners and operators, Rehmatulla et al. (2017) reported that only some selected measures are implemented on a sufficient scale and the measures with the highest implementation rates tend to be those with only small energy efficiency gains for vessels. They conclude that incentives provided by current regulation and market conditions are insufficient to foster the adequate adoption of clean technology. The thesis concentrates on the regulation pathway for stimulating clean technology adoption. The relationship between environmental policies and technology take-up is a common theme in the research papers and is elaborated in the next section stating the objectives and main research question of the thesis.

1.4 Objectives of the Ph.D. project

The green transition of the maritime industry is a complex societal challenge that must be addressed across scientific disciplines and with multiple levers. The complexity stems from the fact that global carbon emissions today have far-reaching consequences on the natural environment for a long period; thus, decarbonization is an inherently dynamic and global phenomenon. Currently, no single lever to foster the green transition appears sufficient on its own; thus, multiple approaches must likely be combined to reach the vision of decarbonized shipping. The two main research areas examined in the Ph.D. project are environmental policies and clean technology adoption, whose roles in the green transition process have been outlined in sections (1.2) and (1.3). Due to their high relevancy for current discussions and their interdisciplinary nature, a thorough investigation of these two key levers is warranted. Based on these reflections, the general structure of the Ph.D.

thesis is summarized in Figure (1.3).

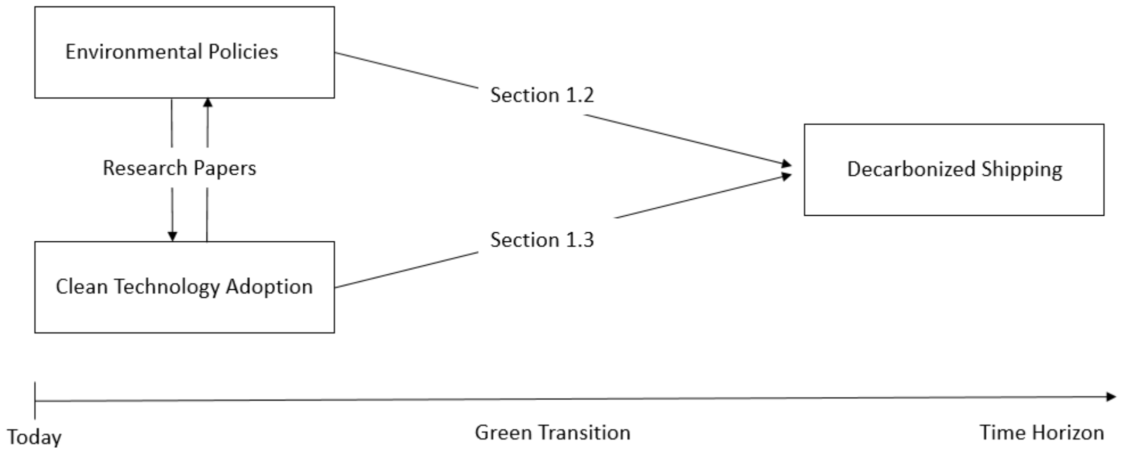

FIGURE 1.3: General structure of the Ph.D. project

The overarching objective of the Ph.D. thesis is to examine thoroughly the interplay between clean technology adoption and environmental policies to drive the green transition of the industry. Further, the thesis seeks to provide practical implications for stakeholders concerned with the transformation of marine transport. While both clean technology adoption and environmental policies are key levers on their own to decarbonize shipping, they are inextricably linked to each other, which makes their interplay a fruitful area of inquiry. The relationship between these two levers goes in both directions; a main cause for the adoption of clean technologies is regulatory pressure to comply with environmental policies. Similarly, environmental policies seek to foster the adoption of clean technologies to reach the policy targets. Therefore, the research papers of the Ph.D. project will investigate both pathways, in line with the thesis objective. The aim of the three papers is to explore specific aspects of the interplay between environmental policies and clean technology adoption in the context of the green transition of the maritime industry.

The overarching objective cannot be adequately addressed from a single stakeholder's viewpoint; thus, the research papers examine the interplay of clean technology adoption and environmental policies from a policy and managerial perspective. There are arguably many important stakeholders to drive the green transition of the maritime industry, and exploring all their perspectives would be impracticable. The thesis focuses on ship owners and policy makers as two key stakeholders due to their close relation to the two main research areas. To illustrate this point, ship owners are targeted and must comply with environmental policy measures in the maritime industry, including the EEDI, EEXI, and CII, as they are the owners of the vessels. Therefore, examining the economic incentives to adopt clean technologies under a market-based METS and investigating the efficacy of operational and technology levers to comply with the mandatory EEDI regulation from the ship owner's perspective are two topics investigated in the research papers. On the other hand, policy makers are the ones designing specific policy measures with the goal of fostering the continuous adoption of clean technologies and of reaching their set emission reduction targets. One research paper takes the policy maker's perspective by providing guidance on the current potential for energy efficiency improvements and presenting an alternative view to regulate energy efficiency. Before turning to an overview of the three research papers, the next section outlines the theoretical perspective, which has guided the research design and methodology.

1.4.1 Theoretical perspective

This section outlines the theoretical perspective of the Ph.D. thesis, which has guided the development of research designs and choice of methods. Instead of resorting to commonly used umbrella terms like *positivism* or *constructivism* to describe the philosophical stance adopted in the thesis, I will outline the general underlying ontology and epistemology separately for two reasons. First, the terminology in the philosophy of science literature is inconsistent on what assumptions these terms entail about the way of viewing the world, which might lead to confusion for the reader if their notion differs from mine. Second, I believe by laying out the philosophical basis of the thesis in this way, it is easier for the reader to assess the nature of my claims and findings. Because it is my aspiration that the thesis is also accessible to people who have not been in close contact with the philosophy of science, I will outline these topics in a rather general way, not highlighting all nuances and philosophical discussions about them.

The first element is the ontology, concerned with the nature of the reality about which humans can acquire knowledge. I adopt a realist stance in the thesis, meaning there is a single reality, and objects in the real world exist independently of human perception. However, I do not advocate a naive form of realism, claiming that our perceptions of the real world are unambiguously true and reality can be understood with certainty. This has important implications for the faith we can put in scientific knowledge and the claims made in the thesis. Because we may be unable to observe reality as it really is directly, the output of scientific research activities is not statements about universal truths, which are accurate and certain, but rather qualified assertions, which are tentative (Crotty, 1998).

After having positioned the ontology of the thesis, I describe the epistemology with regard to the nature of knowledge, including how it can be produced. The epistemological standpoint is that there is some sort of meaning within the considered objects, independent of the individual perception. Hence, there is a certain degree of distinction between scientific knowledge and subjective knowledge, such as opinions, feelings, and beliefs acquired in non-scientific ways. From this standpoint, the ideal image of scientific knowledge can be described as value-neutral and verifiable (Crotty, 1998). The general modus operandi in the thesis is a scientific abstraction involving formalization and quantification from the lived reality of our everyday experiences. This abstraction also entails a separation of the objects from the subject (i.e., the researcher) in the research process. However, this view does not degenerate into an overly simplistic epistemological notion of objectivism. I agree with Bird (1998) that there is no such thing as *the* scientific method, and that there are many knowledge-producing methods in science. The development of these methods is often itself a product of science, and science informs us that these methods are reliable means of knowledge production (Bird, 1998, p.175). As the reader will see, this thesis employs a variety of methods depending on the research questions of interest and the context at hand.

Further, I acknowledge that despite the ideals of a value-neutral science, the scientific outputs in this thesis are not (and cannot be) completely objective (Stanovich, 1999). The research process requires the researcher to make a series of informed choices and assumptions that contribute to knowledge creation. This involves the judgement and critical reflection of the researcher. I strive to make the research processes as transparent as possible to justify my choices and to enable a meaningful evaluation of their appropriateness. Further, the assessment of results used to justify knowledge claims often requires the idiosyncratic cognition of the researcher (Mantere & Ketokivi, 2013). This becomes apparent when the claims extend beyond empirical generalizations of the results. Here, I offer one possible interpretation based on reasoning and invite the reader to assess whether they find my resulting assertions plausible or even convincing.

Lastly, I want to discuss what kind of knowledge the thesis seeks to produce. The research questions in the thesis are in general of a descriptive and explanatory nature and address contemporary open questions related to the green transition of the maritime industry. Due to the specific context, the thesis puts a certain emphasis on pragmatic knowledge, which is relevant for stakeholders in the industry, and it seeks to support the efforts to foster the green transition of the industry. This leads to the question of how scientific research can be established as relevant and gain credibility in the view of practitioners. I agree with Van de Ven and Johnson (2006) that this is likely not a mere problem of translating and diffusing knowledge but rather a problem of knowledge production. Under this view, establishing relevance is not an ex post activity but must be embedded in the process of knowledge production (Ketokivi & Choi, 2014). This requires the research design to be contextually situated and the examined problem to be grounded in a concrete and real-world phenomenon.

1.5 Ph.D. project overview

In this section, an overview of the three research papers forming the core of the Ph.D. project is given and, their contribution to the main objective is briefly outlined. The full versions of the three papers can be found in chapters 2, 3, and 4, respectively. In the end, chapter 5 concludes the thesis by discussing the main findings, policy implications, and theoretical contributions of the Ph.D. project and pointing to potential avenues for further scientific research. Further, based on these insights, the conclusion highlights some key challenges for the green transition of the maritime industry, which must be addressed by stakeholders in the industry to realize the vision of decarbonized marine transport.

Table 1.1: Overview of research papers

Title	**Authors**	**Content**
Heterogeneous effects of technology and operational levers on environmental performance: Evidence from maritime regulation	Franz Buchmann, Leonardo Santiago, and Vasileios Kosmas	This empirical study examines the impact of technology & operational levers on vessels' energy efficiency and compliance with the EEDI regulation, with a focus on the heterogeneity of estimated effects.
The impact of an emission trading scheme on a ship owner's investment decisions	Franz Buchmann and Leonardo Santiago	This analytical study describes a ship owner's clean technology investments over time under a maritime ETS and investigates the impact of an environment with increased uncertainties on this investment decision.
Benchmarking energy efficiency of ship designs: Implications for maritime policies	Franz Buchmann	Empirical study for benchmarking the energy efficiency of ship designs to assess the scope for energy efficiency improvements and technological conditions in the different shipping sectors of the maritime industry.

Table (1.1) lists the three research papers, which each contribute to the overarching objective of the Ph.D. project. However, due to the article-based format of the thesis, the three research papers can also be read as standalone scientific articles outside the scope of this thesis. The following subsections 1.5.1, 1.5.2, and 1.5.3 seek to provide the reader a concise overview of the respective papers by outlining the research questions, methodologies, main results, and contributions. Further, based on Figure (1.3), the relation of the articles to the main objective is presented by highlighting the examined pathways and adopted perspectives.

1.5.1 Overview of first study

Relation to Ph.D. main objective: The first study focuses on ship owners having to comply with the mandatory EEDI regulation, which prescribes minimum performance standards for newly built vessels. For ship owners seeking to improve the environmental performance of their vessels, technology and operational drivers are key levers they can utilize to reach this goal. Therefore, the focal point of the first study is the complex relationship between technology and operational levers and environmental performance in the context of the EEDI regulation. Figure (1.4) illustrates the relation of the first study to the overarching objective of the Ph.D. thesis.

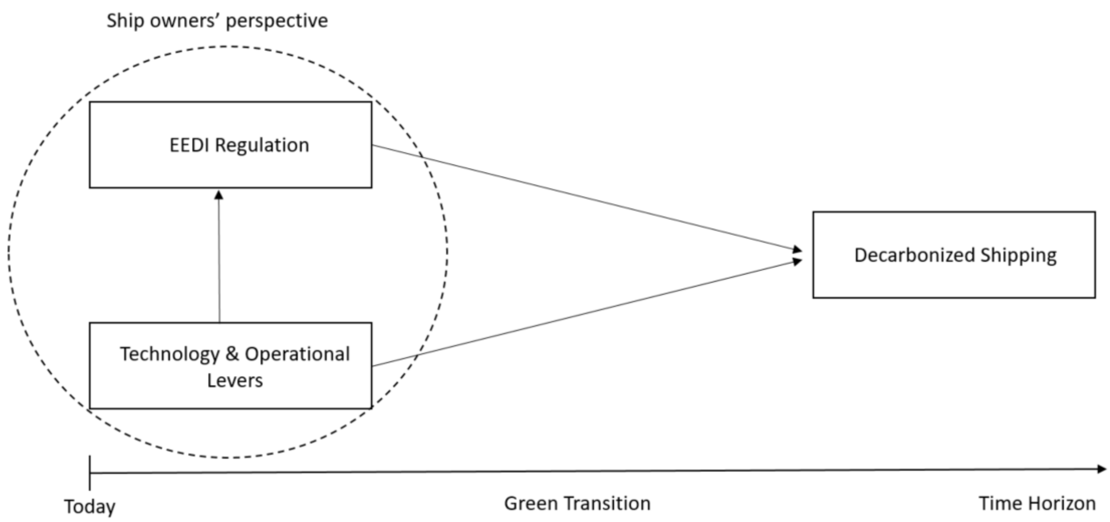

FIGURE 1.4: Relation of first study to the main objective

Purpose and research questions: From a bounded rationality perspective, ship owners seek *"good enough"* solutions in the context of the regulation and do not utilize all levers that could improve a vessel's environmental performance. Therefore, many different ship design solutions yield similar levels of environmental performance, and the levers can explain observed differences in performance. In line with the empirical setting, we examine two facets of vessels' environmental performance, namely, their technical energy efficiency and regulatory compliance. We seek to examine the impact of available technology and operational levers by asking:

RQ 1: "What is the impact of technology and operational levers on environmental performance?"

We utilize a design science perspective to establish a link between technology and operational levers and environmental performance for existing vessels. Further, based on previous work and empirical observations, we identify the adoption of alternative fuels, a vessel's lifetime, and emission prevention related to the main machinery technology as three key levers for ship owners. In our setting, the vessels with relatively poor environmental performance are of special interest for two reasons: first, they are the main targets of the minimum performance standards stipulated by the EEDI regulation and, second, they have a relatively higher impact on the carbon footprint of ship owners than vessels with good performance. In addition, what explains performance variations for vessels likely differs from what explains performance differences for poor vessels. Thus, we posit that important additional insights can be gained by examining the impact of technology and operational levers across the range of environmental performance. This conjecture is summarized in our second research questions:

RQ 2: "How does the impact of technology and operational levers vary across the range of environmental performance?"

Methodology: To answer our two research questions, we develop a set of hypotheses for the three aforementioned technology and operational levers and empirically test them with quantitative, statistical methods. For this purpose, we combine three secondary data sources to obtain a novel data set: the European Maritime Safety Agency's database incorporated in the EU-MRV regulation; the Clarkson World Fleet Register (CWFR); and the Thomson Reuters Eikon Shipping (TRES) database. The resulting data set contains detailed information about the environmental performance and ship-specific design features for 2,058 vessels across multiple shipping sectors. Because we are interested in examining the effects across the range of environmental performance, we utilize quantile regression (QR) methods to examine the relationship between technology and operational levers and environmental performance. It is well established that QR is particularly useful to analyze the potential heterogeneity of effects across the conditional distribution of the dependent variable, which complements methods focusing on a single point-wise measure, like linear regressions (Fitzenberger & Wilke, 2015).

Findings: Due to the outlined approach, the results present a granular appraisal of the impacts of technology and operational levers on environmental performance. A key result is that the estimated effects are indeed heterogeneous across the range of energy efficiency and regulatory compliance, which is not adequately captured by a single point-wise estimate. Our results provide preliminary empirical evidence that the adoption of alternative fuels is a strong lever to improve vessels' energy efficiency, as indicated by the EEDI rating, and to comply with the EEDI regulation. The results suggest that emission prevention related to the main engine features, is, at best, a moderate lever to improve the environmental performance of vessels, which is a surprising result. Lastly, the key covariate in our sample related to the managerial decision to adapt an existing vessel to prolong its operational use is a vessel's lifetime. We find that the later vessels are in their lifetime, the lower their environmental performance. In addition, the effect is most pronounced for vessels with poor performance, where improvements would be the most desirable. In summary, our results show that the relationship between technology and operational levers and environmental performance is complex.

Contribution: The derived empirical results have important implications for theory and practice. From a theoretical perspective, examining the drivers of performance and their performance implications has always been at the heart of operations management (Ketokivi, 2016). Further, explaining differences in performance at varying levels of performance is of high relevance in many settings (Bromiley & Rau, 2016). Our results show that the impacts of performance drivers can significantly vary across the range of observed performances. Therefore, we suggest that the understanding of and insights into drivers of performance can be advanced by considering the heterogeneity of their impacts. The research also connects previous analytical research focusing on clean technology adoption in the transportation sector with the highly relevant topic of alternative fuel adoption for the maritime industry. From a practical perspective, the results provide a granular analysis for decision makers in the maritime industry about the capabilities and limitations of the considered levers for improving environmental performance. To illustrate, main engine adjustments to reduce fuel consumption are often considered easy and effective measures to improve technical energy efficiency and comply with the EEDI regulation. However, our results overall highlight the limits of this technology lever, and we would advise ship owners to see measures like design speed reductions as complements to other levers, instead of mainly relying on them.

1.5.2 Overview of second study

Relation to Ph.D. main objective: The second study focuses on the ship owner's perspective subject to an ETS for the maritime industry over a time horizon. Environmental policies based on MBMs are seen as a key lever to foster the green transition of the maritime industry, as they provide economic incentives to adopt clean technologies among ship owners. In particular, regulations based on an ETS seem suited in the context of the green transition process due to their focus on the total quantity of carbon emissions. Therefore, the study strives to examine the impact of an ETS on a ship owner's decision to invest in clean technologies. The relation of the overarching objective of the Ph.D. thesis to the second study is summarized in Figure (1.5).

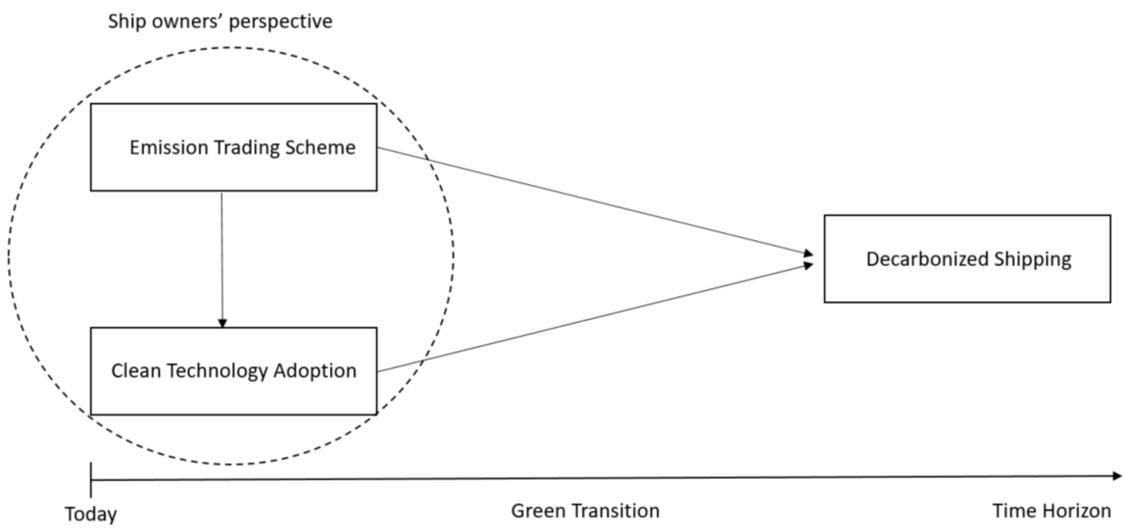

FIGURE 1.5: Relation of second study to the main objective

Purpose and research questions: Policy makers made ambitious commitments to the green transition of the maritime industry and mandated industry-wide emission reduction targets for maritime transport. Regulation based on an ETS appears one of the most promising instruments policy makers have at their disposal to decarbonize the industry over a time horizon and meet the targets. A key backing for this claim is based on economic reasoning; setting a cap on carbon emissions and pricing the negative social consequences raises the opportunity costs of emissions for polluters and, thus, provides them incentives to adopt clean technologies to reduce carbon emissions. In the context of an industry's transition process, the ship owner's investment decision is an inherently dynamic problem subject to various uncertainties, and it has implications for the decision problem. The real option theory suggests that investment decisions made in an uncertain environment might give rise to an option value of waiting to invest in costly technologies (Dixit & Pindyck, 1994). A common concern with a maritime ETS is that the carbon price uncertainty might lead to suboptimal levels of clean technology adoption by ship owners, as their investment decision and long-term investment planning are riskier (Psaraftis & Lagouvardou, 2019). This research thoroughly examines the ship owner's investments in clean technologies over the time horizon and the related value of actively managing the investment decision by asking:

RQ 1: "How is the ship owner's investment policy over time shaped under an ETS regulation ?"

Further, this research examines how uncertainties affect the costs of regulation and the value of flexibility and, in turn, the investment policy over time. Previous work concerned with the adoption of clean technologies under an ETS paid special attention to the impact of permit price or resource price uncertainties on the investment decision. We shift the focus to a different set of uncertainties that are of special importance in the context of an industry's green transition process. More precisely, we examine the impact of regulatory uncertainties, which are related to the policy design to reach industry-wide reduction targets, and pollution uncertainty, which is related to the demand of ship owners for emissions to provide transportation services. Therefore, we posit the following second research question:

RQ 2: "What impact does an environment with increased regulatory and demand uncertainties have on the ship owner's investment policy?"

Methodology: We develop a quantitative multi-period decision model in a stochastic environment and analyze it with mathematical optimization methods to describe the investment policy over the time horizon. Our departing point is the static case of a cost-minimizing ship owner subject to an ETS based on the efficient auction mechanism with an endogenous supply of licenses proposed by Montero (2008). To capture the dynamic and uncertain nature of the problem when facing such a mechanism, we develop a discrete and finite multi-period model for the investment decision. The stochastic dynamic programming method is utilized to solve our problem of decision-making under uncertainty. Based on this mathematical framework, we apply deductive reasoning to derive theorems describing the optimal investment policy over time and the impact of an environment with increased uncertainties.

Findings: Our analytical results suggest there is indeed value in actively managing the investment decision instead of utilizing a passive approach to cope with the regulation. The investment policy is characterized by an investment decision rule in every decision period. The rule states that it is optimal for the ship owner to wait with the investment if their pollution demand is below a certain threshold and to invest in clean technologies if it is above the threshold. The optimal size of the investment is increasing in their current demand for pollution. Therefore, the investment levels over time are of a decreasing shape to maximize cost reductions in the auctions over the time horizon. Further, the results suggest that an environment with increased uncertainties has a substantial impact on this policy. Higher regulatory and demand uncertainty increases both the expected costs and value of managerial flexibility for a ship owner leading to a higher incentive to invest in clean technologies.

Contribution: The derived analytical results yield important implications for theory and practice. The research enriches the theoretical understanding of a firm's investment decision problem under uncertainty when being subject to an environmental policy. In particular, we provide insights into a firm's investments in clean technologies over time and their associated value of managerial flexibility when facing an ETS designed to reach industry-wide emission reduction targets. Further, we contribute to the real option literature by showing how an environment with increased uncertainties pertinent to the green transition context impacts the costs of regulation and the value of managerial flexibility. The research also provides insights for policy makers into the design of a maritime ETS and the implications of design choices. Incentives to adopt clean technologies under a maritime ETS could be increased by incorporating the emission reduction targets into the policy design. This feasible property depends on the credible commitment of policy makers to the defined reduction targets through, for example, monetary ramifications if a ship owner's abatement efforts are insufficient. Another insight is that a maritime ETS can be a key instrument for the green transition of the industry even in an uncertain environment, as the uncertainty does not erode the value of actively managing the investment decision and incentives to invest in clean technologies.

1.5.3 Overview of third study

Relation to Ph.D. main objective: The third study focuses on the policy makers' perspective in seeking to reach environmental policy targets. A main focus of policy makers to foster the green transition in the maritime industry lies on technology to improve the energy efficiency of the global fleet. More precisely, policy makers have the objective of continuously incentivizing the adoption and development of clean technologies in ship designs through their policy measures. Therefore, the study places policy measures aimed at supporting this objective and their policy design at the center of the analysis. The relation of the overarching objective of the Ph.D. thesis to the third study is summarized in Figure (1.6).

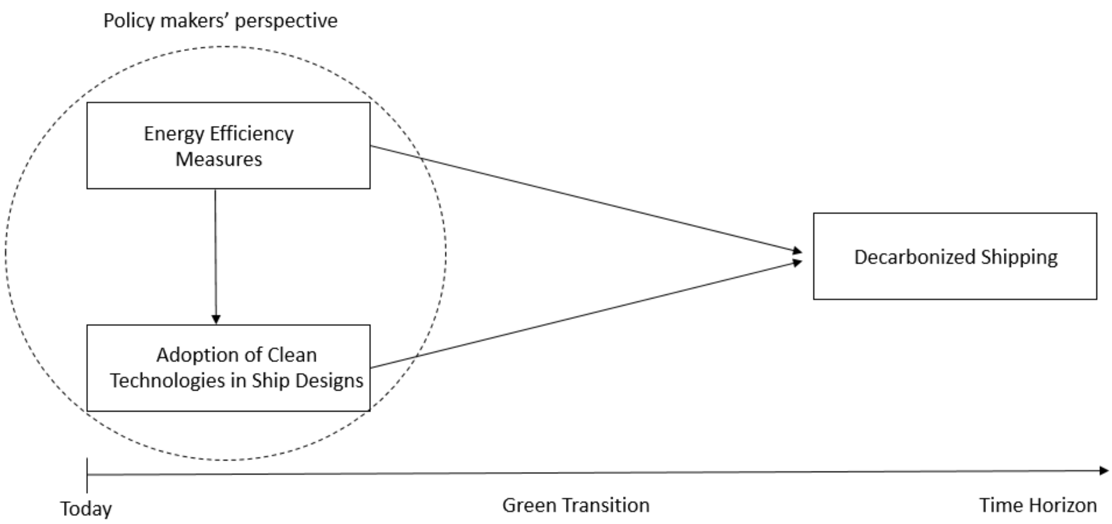

Figure 1.6: Relation of third study to the main objective

Purpose and research questions: Two key traits of mandatory policy measures focusing on the energy efficiency of ship designs are their focus on subsets of vessels and comparisons against minimum requirements. To illustrate, the EEDI regulation is designed to target mostly vessels built after 2013 and prescribes minimum performance standards these vessels must fulfill depending on the ship type and year. However, this perspective is not well suited for an analysis of the current potential for improvements in the energy efficiency of ship designs in the maritime industry. I argue that this potential is mostly determined by two factors, which likely vary across shipping sectors: the scope for improvements by adopting existing best-practice ship designs *within* sectors and the technological conditions *across* sectors limiting technology choice at the design stage and, thus, curbing the scope for improvements in a sector. The study seeks to examine the scope for efficiency improvements and the technological conditions for the different sectors by asking:

RQ 1: "What is the scope for efficiency improvements within the sectors of the maritime industry?"

RQ 2: "What are the technological conditions across the sectors of the maritime industry?"

Knowledge about these factors in the different sectors is crucial for policy makers to evaluate existing instruments and to develop additional instruments, as their effectiveness depends on the situational context in which they are implemented (Givoni, 2014; Justen, Fearnley, et al., 2014). To answer the research questions, the study derives estimates for the relative performance of vessels based on best-practice benchmarks and describes their distribution in the container, tanker, and dry bulk sectors, which account for roughly 90% of total maritime cargo transportation capacities (Faber et al., 2020). Based on these estimates, it is possible to quantify the two factors empirically and to describe the differences in situational contexts for the considered shipping sectors.

Methodology: The methodology utilizes a general framework for the energy efficiency of ship designs in the maritime industry and quantitative benchmarking methods for multiple inputs and outputs to derive empirical measures of relative performance. Departing from the rationale of existing energy efficiency indices, I develop a general theoretical framework for comparing the energy efficiency of ship designs to formulate empirical models. I collect a secondary data set with detailed information about the ship design characteristics for over 6,000 vessels from the CWFR and the TRES database. The data collection process is then validated with reported energy efficiency indices from the EU-MRV database to ensure the data set is a good representation of the actual vessel characteristics. To derive robust efficiency scores, the study employs a nonparametric metafrontier method based on data envelopment analysis in combination with bootstrapping techniques. This approach enables the assessment of the scope for efficiency improvements within sectors and to make industry-wide comparisons across sectors. Lastly, a sensitivity analysis confirms the robustness of derived results with respect to alternative empirical model specifications and data outliers.

Results: The results overall suggest that the two factors vary considerably across the examined sectors. To illustrate, the scope for improvements by adopting existing best practice ship designs within sectors ranges from 6.4% for the container shipping sector to 17.4% for the dry bulk sector. This variation in scope might be driven by differences in market structures and market dynamics in the considered shipping sectors, which impact the adoption of clean technologies in ship designs. Further, there appears considerable variation as well in the technological conditions across sectors. The results indicate that the chemical tanker sector has the most limiting technological conditions of the considered shipping sectors, which might make it more challenging for the sector to adopt existing industry best practices when compared to the other sectors. In summary, the results highlight that the sector-specific contexts are heterogeneous across the different shipping sectors.

Contribution: By shifting the focus from comparisons against minimum requirements to best practices and utilizing a general framework for the energy efficiency of ship designs, the study generates important insights and implications for policy. As suggested by O'Donnell et al. (2008), the analysis can act as a quantitative decision support tool for policy makers in the maritime industry to evaluate existing and to develop additional instruments. First, it is plausible that the presented perspective can improve the effectiveness of existing policy measures focusing on technology to enhance the energy efficiency of ship designs. Previous work has already questioned the effectiveness of the EEDI regulation in reaching the policy objective due to adverse side effects and the policy design (Ančić et al., 2018; Polakis et al., 2019; Vladimir et al., 2018). The presented approach addresses adverse side effects, such as design speed reductions, to comply with the regulation, and it introduces competitive market forces into the policy design. Second, based on the observed heterogeneity in sector-specific contexts, it appears that the considered shipping sectors can benefit from different additional policy measures. For instance, while additional initiatives fostering the adoption of existing best-practices can be still fruitful in the dry bulk sector, additional initiatives for the container shipping sector should support the development and introduction of innovative clean technologies in container ship designs.

References

Adland, R., Alger, H., Banyte, J., & Jia, H. (2017). Does fuel efficiency pay? Empirical evidence from the drybulk timecharter market revisited. *Transportation Research Part A: Policy and Practice*, *95*, 1–12.

Agnolucci, P., Smith, T., & Rehmatulla, N. (2014). Energy efficiency and time charter rates: Energy efficiency savings recovered by ship owners in the panamax market. *Transportation Research Part A: Policy and Practice*, *66*, 173–184.

Ančić, I., Theotokatos, G., & Vladimir, N. (2018). Towards improving energy efficiency regulations of bulk carriers. *Ocean Engineering*, *148*, 193–201.

Anderson, K., & Bows, A. (2012). Executing a Scharnow turn: Reconciling shipping emissions with international commitments on climate change. *Carbon Management*, *3*(6), 615–628.

Attah, E. E., & Bucknall, R. (2015). An analysis of the energy efficiency of LNG ships powering options using the EEDI. *Ocean Engineering*, *110*, 62–74.

Baldwin, R., Cave, M., & Lodge, M. (2011). *Understanding regulation: Theory, strategy, and practice*. Oxford University Press.

Baumol, W. J. (1972). On taxation and the control of externalities. *The American Economic Review*, *62*(3), 307–322.

Baumol, W. J., & Oates, W. E. (1988). *The theory of environmental policy*. Cambridge University Press.

Ben-David, S., Brookshire, D., Burness, S., McKee, M., & Schmidt, C. (2000). Attitudes toward risk and compliance in emission permit markets. *Land Economics*, *76*(4), 590–600.

Bird, A. (1998). *Philosophy of science* (1st ed.). Routledge.

Bromiley, P., & Rau, D. (2016). Operations management and the resource based view: Another view. *Journal of Operations Management*, *41*, 95–106.

Brynolf, S., Baldi, F., & Johnson, H. (2016). Energy efficiency and fuel changes to reduce environmental impacts. In K. Andersson, S. Brynolf, J. F. Lindgren, & M. Wilewska-Bien (Eds.), *Shipping and the environment: Improving environmental performance in marine transportation* (pp. 295–339). Springer.

Buhaug, Ø., Corbett, J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., ... Markowska, A. Z. (2009). *Second IMO GHG study 2009* (Tech. Rep.). International Maritime

Organization. Retrieved from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/SecondIMOGHGStudy2009.pdf

Cato, M. S. (2009). *Green economics: An introduction to theory, policy and practice.* Earthscan.

Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Solazzo, E., Monforti-Ferrario, F., ... Vignati, E. (2020). *Fossil CO_2 emissions of all world countries - 2020 report* (Tech. Rep.). European Commission. Retrieved from https://edgar.jrc.ec.europa.eu/booklet/Fossil_CO2_emissions_of_all_world_countries_booklet_2020report.pdf

Crotty, M. (1998). *The foundations of social research: Meaning and perspective in the research process.* Sage Publications.

Danilov-Danil'yan, V. I., Losev, K. S., & Reyf, I. E. (2009). Sustainable development in relation to the carrying capacity of the biosphere. In *Sustainable development and the limitation of growth: Future prospects for world civilization* (pp. 187–196). Springer.

DAWE. (2021). *Greenhouse effect.* Retrieved from https://www.environment.gov.au/climate-change/climate-science-data/climate-science/greenhouse-effect

DeLong, J. B. (1998). *Estimating world GDP, one million BC–present.* Working paper, University of California, Berkeley.

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty.* Princeton University Press.

DMA. (2012). *North European LNG infrastructure project: A feasibility study for an LNG filling station infrastructure and test of recommendations* (Tech. Rep.). Danish Maritime Authority. Retrieved from http://www.anave.es/images/seguridad/danish_maritime_authority-north_european_lng_infrastructure_project-mar_12.pdf

DNV. (2018). *Maritime forecast to 2050* (Tech. Rep.). DNV. Retrieved from https://eto.dnv.com/2018/maritime

EC. (2020). *Market stability measures* (Report). European Commission. Retrieved from https://ec.europa.eu/clima/sites/clima/files/ets/reform/docs/study_market_stability_measures_en.pdf

EC. (2021). *Commission proposal: Revision of the EU emissions trading system.* European Commission. Retrieved from https://eur-lex.europa.eu/resource.html?uri=cellar:618e6837-eec6-11eb-a71c-01aa75ed71a1.0001.02/DOC_1&format=PDF

Eide, M. S., Longva, T., Hoffmann, P., Endresen, Ø., & Dalsøren, S. B. (2011). Future cost scenarios for reduction of ship CO_2 emissions. *Maritime Policy & Management*, *38*(1), 11–37.

EU. (2015). *Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 april 2015 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport.* European Union. Retrieved from `https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015R0757&from=EN`

EU. (2020). *Decarbonising maritime transport: The EU perspective* (Report). European Union. Retrieved from `https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/659296/EPRS_BRI(2020)659296_EN.pdf`

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauerhof, E., & Yuan, H. (2020). *Fourth IMO greenhouse gas study 2020* (Tech. Rep.). International Maritime Organization. Retrieved from `https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf`

Fitzenberger, B., & Wilke, R. A. (2015). Quantile regression methods. In R. A. Scott & S. M. Kosslyn (Eds.), *Emerging trends in the social and behavioral sciences: An interdisciplinary, searchable, and linkable resource* (pp. 1–18). Wiley.

Gu, Y., Wallace, S. W., & Wang, X. (2019). Can an Emission Trading Scheme really reduce CO_2 emissions in the short term? Evidence from a maritime fleet composition and deployment model. *Transportation Research Part D: Transport and Environment*, *74*, 318–338.

IMO. (2018). *Adoption of the initial IMO strategy on reduction of GHG emissions from ships and existing IMO activity related to reducing GHG.* International Maritime Organization. Retrieved from `https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf`

IMO. (2021). *Introduction to IMO.* Retrieved from `https://www.imo.org/en/About/Pages/Default.aspx`

IPCC. (2014). *AR 5: Climate change 2014: Mitigation of climate change* (Tech. Rep.). Intergovernmental Panel on Climate Change. Retrieved from `https://www.ipcc.ch/report/ar5/wg3/`

Ketokivi, M. (2016). Point–counterpoint: Resource heterogeneity, performance, and competitive advantage. *Journal of Operations Management*, *41*(1), 75–76.

Ketokivi, M., & Choi, T. (2014). Renaissance of case research as a scientific method. *Journal of Operations Management*, *32*(5), 232–240.

Kösler, S., Achtnicht, M., & Köhler, J. (2015). Course set for a cap? A case study among ship operators on a maritime ETS. *Transport Policy*, *37*, 20-30.

Lagouvardou, S., Psaraftis, H. N., & Zis, T. (2020). A literature survey on market-based measures for the decarbonization of shipping. *Sustainability*, *12*(10), 3953.

Mantere, S., & Ketokivi, M. (2013). Reasoning in organization science. *Academy of Management Review*, *38*(1), 70–89.

MEPC. (2020). *Resolution MEPC.324(75).* International Maritime Organization. Retrieved from `https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.324%2875%29.pdf`

Miola, A., Marra, M., & Ciuffo, B. (2011). Designing a climate change policy for the international maritime transport sector: Market-based measures and technological options for global and regional policy actions. *Energy Policy*, *39*(9), 5490-5498.

Montero, J.-P. (2008). A simple auction mechanism for the optimal allocation of the commons. *American Economic Review*, *98*(1), 496–518.

Naylor, R. L., Liska, A. J., Burke, M. B., Falcon, W. P., Gaskell, J. C., Rozelle, S. D., & Cassman, K. G. (2007). The ripple effect: Biofuels, food security, and the environment. *Environment: Science and Policy for Sustainable Development*, *49*(9), 30–43.

OECD. (2002). *Implementing domestic tradeable permits: Recent developments and future challenges* (Report). Organisation for Economic Co-operation and Development. Retrieved from `https://www.oecd-ilibrary.org/content/publication/9789264191983-en`

Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). *The climate implications of using LNG as a marine fuel.* Working Paper, The International Council on Clean Transportation.

Psaraftis, H. N. (2012). Market-based measures for greenhouse gas emissions from ships: A review. *WMU Journal of Maritime Affairs*, *11*(2), 211–232.

Psaraftis, H. N., & Lagouvardou, S. (2019). Market based measures for the reduction of green house gas emissions from ships: A possible way forward. *Samfundsoekonomen*, *2019*(4), 60–70.

Rehmatulla, N., Calleya, J., & Smith, T. (2017). The implementation of technical energy efficiency and CO_2 emission reduction measures in shipping. *Ocean engineering*, *139*, 184–197.

Rehmatulla, N., & Smith, T. (2020). The impact of split incentives on energy efficiency technology investments in maritime transport. *Energy Policy*, *147*, 111721.

Royal Academy of Engineering. (2013). *Future ship powering options* (Tech. Rep.). Royal Academy of Engineering. Retrieved from `https://www.raeng.org.uk/publications/reports/future-ship-powering-options`

Salo, K., Zetterdahl, M., Johnson, H., Svensson, E., Magnusson, M., Gabrielii, C., & Brynolf, S. (2016). Emissions to the air. In K. Andersson, S. Brynolf, J. F. Lindgren, & M. Wilewska-Bien (Eds.), *Shipping and the environment: Improving environmental performance in marine transportation* (pp. 169–227). Springer.

Smith, T., Raucci, C., Hosseinloo, S. H., Rojon, I., Calleya, J., De La Fuente, S. S., ... Palmer, K. (2016). *CO_2 emissions from international shipping. Possible reduction targets and their associated pathways* (Tech. Rep.). UMAS. Retrieved from `https://www.u-mas.co.uk/wp-content/uploads/2020/11/Smith-et-al.-2016-Co2-emissions-in-shipping-targets-pathways.pdf`

Stanovich, K. E. (1999). *Who is rational? Studies of individual differences in reasoning.* Psychology Press.

Stavins, R. N. (1995). Transaction costs and tradeable permits. *Journal of Environmental Economics and Management*, *29*(2), 133–148.

Sunstein, C. R. (1990). Paradoxes of the regulatory state. *The University of Chicago Law Review*, *57*(2), 407–441.

UN. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development.* (`https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E`)

UNCTAD. (2019). *Review of maritime transport, 2019* (Report). United Nations Conference on Trade and Development. Retrieved from `https://unctad.org/webflyer/review-maritime-transport-2019`

UNFCCC. (2021a). *The Paris Agreement.* Retrieved from `https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement`

UNFCCC. (2021b). *What is the Kyoto Protocol.* Retrieved from `https://unfccc.int/kyoto` _protocol

Van Bueren, E. (2019). *Environmental policy.* Retrieved from https://www.britannica.com/topic/environmental-policy

Van de Ven, A. H., & Johnson, P. E. (2006). Knowledge for theory and practice. *Academy of Management Review*, *31*(4), 802–821.

Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S. W., & Lenaerts, S. (2021). Challenges in the use of hydrogen for maritime applications. *Energy & Environmental Science*, *14*(2), 815–843.

Vladimir, N., Ančić, I., & Šestan, A. (2018). Effect of ship size on EEDI requirements for large container ships. *Journal of Marine Science and Technology*, *23*(1), 42–51.

Wang, K., Fu, X., & Luo, M. (2015). Modeling the impacts of alternative emission trading schemes on international shipping. *Transportation Research Part A: Policy and Practice*, *77*, 35-49.

WCED. (1987). *Report of the World Commission on Environment and Development: Our common future* (Report). World Commission on Environment and Development. Retrieved from https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf

Zhu, M., Yuen, K. F., Ge, J. W., & Li, K. X. (2018). Impact of maritime emissions trading system on fleet deployment and mitigation of CO_2 emission. *Transportation Research Part D: Transport and Environment*, *62*, 474–488.

Chapter 2

Heterogeneous effects of technology and operational levers on environmental performance: Evidence from maritime regulation

Franz Buchmann, Leonardo Santiago, and Vasileios Kosmas

Abstract

Technology and operational drivers are key levers that decision makers can use to improve their environmental performance. From a bounded rationality perspective, multiple levers can yield similar performance outcomes, and their impacts might vary at different levels of performance. Thus, the relationship is complex, and additional insights can be gained through a fine-grained appraisal of their performance implications. Drawing from our theoretical perspective and previous work, we identify multiple levers linked to environmental performance in the context of a mandatory environmental policy in the maritime industry. By collecting a data set with over $2,000$ vessels and employing quantile regression techniques, we thoroughly examine the diverse effects such levers can have on vessels' energy efficiency and regulation compliance. One of our key results is that the impacts of technology and operational levers on environmental performance are heterogeneous across the range of performances. Therefore, we claim that OM research can advance the understanding of and insights into drivers of performance by considering the heterogeneity of their impacts. The empirical results provide guidance to maritime decision makers concerning the capabilities and limitations of key technology levers, such as the adoption of alternative fuels, to improve their environmental performance.

2.1 Introduction

The dire consequences of greenhouse gas (GHG) emission for our society are indisputable, calling for an improvement of the environmental performance across industries and firms. This phenomenon can be considered an area of inquiry of the interdisciplinary operations management (OM) literature, as it is well established that environmental performance is inextricably linked with sound operations management (Corbett & Klassen, 2006). In this regard, previous work already provides valuable insights on, inter alia, the interplay among clean technologies, regulatory policies, and environmental performance. Existing work covered topics ranging from the design of green policies and their impact on decision-making and emission reduction (Atasu et al., 2020) to the operational levers applied by firms to comply with a cap-and-trade policy (Kroes et al., 2012). Other studies touch upon the implications of policy measures for managerial decisions in terms of green investments (Klassen & Whybark, 1999a) and the adoption of energy efficient technologies (Plambeck & Taylor, 2013). In addition, the interplay of environmental policies with the adoption of new technologies and the adaption of existing technologies to reduce carbon emissions has also received special attention in the literature (see, e.g., Avci et al., 2015; Wang et al., 2013).

This research focuses on the interplay between technology and operational levers and environmental performance in the context of an industry-wide environmental policy. Examining the drivers of performance and their associated implications has a long tradition in the OM literature (Ketokivi, 2016). However, to the best of our knowledge, how such levers affect environmental performance under a global regulation that progressively becomes more stringent over time, has not yet been explored. One empirical context in which this subject of inquiry is particularly relevant is the maritime industry. The industry, which contributes around 3% of global GHG emissions (Global Maritime Forum, 2020), predominantly relies on the Energy Efficiency Design Index (EEDI) regulation to improve its environmental performance and to reach industry-wide emission reduction targets. To illustrate, the International Maritime Organization (IMO) — the chief regulatory agency of the maritime industry in terms of environmental performance — mandates a reduction in carbon intensity of at least 40% until 2030, while pursuing a 70% decline by 2050, compared to 2008 levels (IMO, 2018).

To support this ambition, the global and mandatory EEDI regulation prescribes minimum energy efficiency standards for all ships built after 2013 and has the objective to incentivize ship owners continuously to devote resources to measures improving a vessel's energy efficiency by constantly increasing the standards over time (IMO, 2021). Through the lens of bounded rationality, decision makers should seek "satisficing" solutions to cope with the regulation and do not utilize all measures that could improve the environmental performance of their units (i.e., ships). Therefore, many different solutions can yield similar levels of environmental performance, and technology and operational levers can explain performance variations in existing vessels. Within this context, the first research question that this study addresses is: "What is the impact of technology and operational levers on environmental performance?"

The overall approach followed by regulators, which is to impose minimum performance standards that target units (i.e., vessels in the case of the EEDI regulation) with the worst performance, seems rational. From the standpoint of ship owners and policy makers, the harmful impact of ships with poorer environmental performances is higher than that of ships with a better performance. Theoretical perspectives have already highlighted that explanations for performance variations among units likely vary across the range of performances (Bromiley & Rau, 2016). This conjecture is particular relevant in the maritime context, where special attention is paid to the units with poor environmental performance, given the evidence that firms often exceed the standards put in place by environmental policies (Kagan et al., 2003; Kleindorfer et al., 2005). Hence, this study claims that examining the impact of technology and operational levers across the range of environmental performances can yield important additional insights for theory and practice. Accordingly, the second research question addressed in this article is: "How does the impact of technology and operational levers vary across the range of environmental performance?"

The study utilizes a design science perspective to evaluate how well existing artifacts (i.e., vessels) reach a certain goal —- in this case, environmental performance, which is operationalized through a vessel's energy efficiency and compliance with the regulation. Following the underpinnings of design science, we argue that managerial decisions concerning technology and operational levers are linked to the environmental performance of ships, especially in terms of their design features.

Drawing from previous work and empirical evidence, the study identifies a key set of contextually relevant levers, namely, the adoption of alternative fuels, a vessel's lifetime, and emission prevention related to the main machinery technology. We develop a set of hypotheses and apply quantile regression techniques to test empirically the hypotheses on a novel data set of 2,000 ships collected from multiple, verifiable secondary sources.

The article has a threefold contribution. First, it complements the OM literature through the understanding of levers for improving environmental performance while focusing on an industry characterized by complexity in a regulatory framework to improve environmental performance over time. Second, the study has important implications for examinations of the drivers of performance. This research shows that the impact of performance drivers can significantly vary across the range of performances. Thus, we suggest that the theoretical insights derived from studying the drivers of performance can be enhanced by considering the heterogeneity of their effects. Finally, yet importantly, the study adds value to ship owners' decision-making process by providing detailed empirical evidence from the existing fleet about the impacts of the considered levers on energy efficiency and compliance with the mandatory EEDI regulation.

2.2 Empirical setting

Currently, the key environmental policy instrument to foster the green transition of the maritime industry is the EEDI, adopted in July 2011 by the IMO. In a nutshell, The EEDI regulation prescribes minimum performance standards to be fulfilled by all newly built vessels weighing over 400 tons gross tonnage after 1 January 2013. However, the EEDI regulation makes no prescriptions concerning which technologies should be implemented[1]; thus, decision makers have the flexibility to choose among design solutions to comply with the regulation (IMO, 2021). The basic goal of the EEDI is to provide an index stating the energy efficiency of the ship design. Energy efficiency in this context is defined as the ratio of costs to benefits for society due to the cargo transportation process. The costs are expressed as grams of CO_2 and benefits as a ship's capacity-mile, which

[1]One exception is certain requirements regarding the minimum propulsive power installed on the ship to ensure maneuverability under adverse weather conditions due to safety concerns (MEPC, 2013)

is determined by a vessel's cargo-carrying capacity and speed. Hence, the lower the EEDI, the higher the energy efficiency of the ship design. The basic idea behind the EEDI is summarized in Equation (2.1).

$$EEDI = \frac{\textit{Costs to Society}}{\textit{Benefits of Cargo Transportation}} = \frac{\textit{Grams of } CO_2}{\textit{Capacity} \times \textit{Speed (=Capacity-Mile)}}. \tag{2.1}$$

Based on this rationale, the actual formula for calculating the *attained EEDI* for a specific vessel includes various ship type-specific adjustment factors (e.g., capacity and propulsion power to avoid skewing the rating for individual ships). The minimum performance standard a ship must fulfill to comply with the regulation is expressed by the so-called *required EEDI*. The formula for calculating the required EEDI is,

$$\textit{Required EEDI} = (1 - \frac{\textit{Reduction factor}}{100}) \times \textit{Reference line value}. \tag{2.2}$$

In Equation (2.2), the two main components are the *reference line value* and the *reduction factor*. The reference line value is a baseline that captures the minimum performance requirement for a certain ship type, dependent on the vessel's capacity. In general, the larger (in terms of capacity) a vessel, the lower its reference line value. The reference lines for different ship types were derived through specific linear regression approaches elaborated by the IMO. The EEDI is a dynamic regulation with the objective of continuously stimulating the innovation and technical development of all components influencing a ship's energy efficiency from the design stage (IMO, 2021). This objective is reflected in the reduction factor, which is gradually lowered over time and, thus, lowers the required EEDI to comply with the regulation. The EEDI is organized into four phases, namely, Phase 0, Phase I, Phase II, and Phase III, corresponding to how the reduction factor is applied throughout the regulation period. The general framework for the dynamic adjustment over time is summarized in Figure (2.1)[2].

[2]It is worth highlighting, that there recently have been adjustments to this framework. More precisely, Phase III has been moved forward to 2022 and the Phase III reduction factor has been increased for some ship types. These changes do not affect our methodological approach and derived results due to the general formulation of our measures. Therefore, to avoid confusion and remain consistent, we refer to the initial framework throughout the paper.

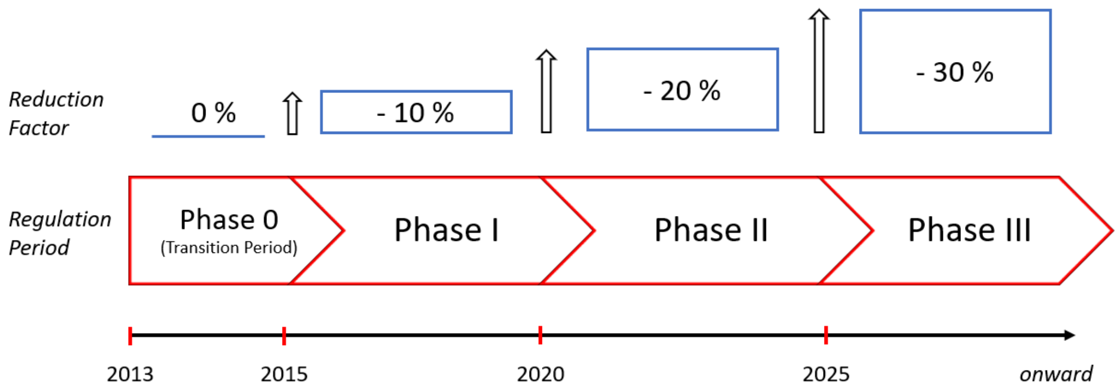

FIGURE 2.1: Empirical setting - Dynamics of the EEDI Regulation

In each phase, the formulas for calculating the attained EEDI and reference line value are equivalent. The only difference is that the reduction factor is increased over the four phases. Therefore, the later a ship is built, the more stringent the minimum performance standard expressed by the required EEDI. To illustrate, a vessel with a building contract in 2021 would be governed by Phase II of the regulation, and a 20% reduction from the reference line value would be required to comply with the EEDI regulation. The same logic applies to existing vessels that have undergone a major overhaul, as the administration regards them as newly constructed vessels (MEPC, 2011). We refer to this practice as a vessel being retrofitted. In addition, a vessel can only have one EEDI rating and must only be compliant with the phase in which the building contract was signed.

2.3 Theoretical background and related literature

We consider that environmental performance and managerial decisions are interconnected, and we focus on a dynamic and mandatory environmental policy in the maritime industry as our empirical context. Such emphasis can be seen as one of the areas of inquiry of the literature on sustainable operations management (SOM), an interdisciplinary academic field that has evolved quite substantially over the past three decades (Atasu et al., 2020; Kleindorfer et al., 2005; Linton et al., 2007). On the micro level, firms' decisions determine the system designs that they employ pertinent to an empirical context. These designs then in turn determine how efficiently resources are consumed and the amount of pollutants emitted. The key contention of SOM then lies in enabling decision makers to determine the technologies that operate their production and distribution systems more efficiently with respect to their environmental performance (Drake & Spinler, 2013). In addition, environmental issues also affect firms' performance, and, as suggested by Corbett and Klassen (2006), a superior environmental performance is usually a reflection of good management.

As a departing point, we consider a design science perspective concerned with the study of artifacts to examine the relationship between technology and operational drivers and environmental performance. Through this lens, an artifact can be broadly defined as a man-made (i.e., artificial) system designed to fulfill purposes or attain goals (Simon, 1996). We remark that artifacts usually serve multiple purposes or goals, and some effects might be unintended (Gregor, 2009). This becomes evident in the empirical context of the study. The unit of analysis is vessels, and one of their key purpose is to provide cargo transportation services for various goods. However, cargo transportation has the side effect of releasing carbon emissions; thus, environmental performance is another important goal. How well an artifact attains its goals depends on the relation among three terms: the specific goal, the characteristics of the artifact forming its inner environment and the outer environment, in which the artifact is operating. Hence, an artifact can be seen as an interface between the organization of its inner environmental components to achieve a particular goal in the outer environment (Simon, 1996). Based on this perspective, this research examines improving environmental performance as the key goal to be attained through the choice of specific ship design features.

The objective of this study is to evaluate existing vessels (i.e., designed by somebody else) that are used in the outer environment. Thus, we separate the process of designing or building a given artifact (i.e., the conception of the inner environment) from examining its goal-directness in the outer environment. The separability of the inner and outer environments is based on the theory of hierarchy in complex systems, outlined in Simon (1991), stating that all complex systems are to an extent hierarchically ordered and, thus, can be decomposed into their sub-systems, where the details of the subsystem's operations can be ignored. This distinction of the inner and outer environments allows for a separation of tasks (Gregor, 2009). The focus of this paper lies in the design features of existing vessels that are linked to the goal of improving environmental performance. This focus on goal attainment in the outer environment may allow the evaluation of artificial systems with minimal assumptions about the detailed mechanisms of the inner environment and related decision-making processes (Simon, 1996). A direct corollary of this observation is that the same level of goal attainment might be reached with different inner environments. Hence, many different ship design solutions can reach identical or similar levels of environmental performance.

In our assumptions about the decision-making process behind the design of existing vessels, we draw from the concept of bounded rationality and the related satisficing principle from behavioral theories of individuals (Simon, 1955, 1956) and firms (Cyert & March, 1963; Gavetti et al., 2012). We assume that decision-makers in general act rationally, but observed decisions might deviate from perfect economic rationality. Rationality is bounded by time, cognitive, or information constraints, and this is reflected in managerial decisions. This implies that managerial decisions are not seeking optimal outcomes in an economic sense but rather "good-enough" outcomes for the context of the problem, which is referred to as the satisficing principle. From this perspective, maritime decision-makers are not seeking "optimal" ship designs, which maximize environmental performance, but rather are willing to accept satisficing alternatives. Hence, we consider multiple levers linked to environmental performance and evaluate how they are related to the goal-attainment of existing vessels in practice.

The literature on environmental performance is large and has been investigated from different perspectives. Of interest are studies that investigate the interplay between environmental performance and management, mandatory environmental policies, and operational decisions. For instance, scholars have investigated the effect of adopting voluntary and certified environmental management systems (EMS) on firms' operations and environmental performance (Anton et al., 2004; Melnyk et al., 2003; Sroufe, 2003). More specifically, Mani and Muthulingam (2019) investigated whether firms improve their environmental performance by learning from regulatory facility inspections assessing whether a firm's operations comply with environmental policies. Murali et al. (2019) assessed the impact of voluntary ecolabels, signaling a firm's environmental performance, and mandatory environmental policy on green product development. Lastly, market reactions to environmental performance announcements have been investigated by Jacobs et al. (2010). We remark that previous work has most often focused on the firm level when evaluating environmental performance. In line with our theoretical perspective, this research is conducted at the level of the vessel, the key system for a firm's operations in our empirical context.

The impact of managerial decisions concerning technological and operational levers is essential for a firm to achieve a superior environmental performance and to cope with mandatory environmental policies. For instance, Klassen and Whybark (1999a, 1999b) explored the relationship between environmental technologies and performance, while Kroes et al. (2012) scrutinized the relationship among operational compliance levers, environmental performance, and firm performance under a cap-and-trade regulation. Moreover, decisions about new technology development and adoption, the adaption of existing systems, and business model innovations are at the heart of perennial solutions to environmental challenges, and the importance of innovation and design has already been highlighted in the literature (see, e.g., Atasu et al., 2020; Linton et al., 2007). For instance, special attention has been given to the operations management challenges faced when developing and adopting clean technologies (Avci et al., 2015; Lim et al., 2015; Plambeck, 2013) and to the role of business model innovation in fostering a green transition (Carayannis et al., 2015; Girotra & Netessine, 2013; Stubbs & Cocklin, 2008).

2.4 Hypotheses development

In the following, we theorize how technology and operational levers could impact the environmental performance of vessels. Based on the underpinnings of design science, Figure (2.2) illustrates the conceptual model guiding our hypotheses development. Managerial decisions concerning technology and operational levers determine ship design features that are linked to the environmental performance of the vessel from a design perspective. We ground our theorization about relevant levers in the empirical context by drawing from available evidence of what is done or what should be done from an industry perspective (Gregor, 2009; Ketokivi & Choi, 2014). As outlined, the range of potential solutions is large, and multiple ship designs can lead to similar levels of environmental performance. Therefore, we focus on selected main levers from an industry perspective, without claiming that this set of levers is unique or exhaustive.

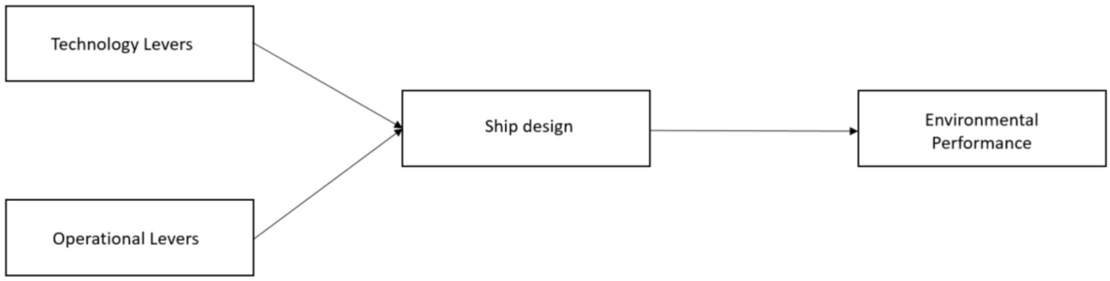

FIGURE 2.2: Conceptual model - Relationship between technology and operational levers and environmental performance

We operationalize environmental performance through a vessel's energy efficiency and compliance with the EEDI regulation. Hence, environmental performance is examined in two dimensions in our analysis. We remark that energy efficiency is not synonymous with regulation compliance. As outlined in section (2.2), the minimum performance standard to be fulfilled is dependent on time, capacity, and ship type; thus, additional scrutiny is required to evaluate the relationship with regulatory compliance. For this purpose, we derive a measure expressing a vessel's slack with respect to the energy efficiency regulation. The previous literature defined slack as being an excess pool of resources relative to the minimum amount required to produce a certain level of organizational output (Nohria & Gulati, 1996), and such a construct has been used in different empirical settings (see, e.g., Kovach et al., 2015; Leyva-de la Hiz et al., 2019; Wiengarten et al., 2019). A vessel's slack is defined as excess compliance with the energy efficiency regulation relative to the baseline performance standard, expressed by the ship-specific reference line value.

As previously stated, we claim that examining the impact of technology and operational levers *across* the entire range of environmental performances can augment the hypotheses development and situational grounding of our study. We support our claim by invoking a modified version of the perspective offered by the practise-based view concerned with the link of broadly available practices and performance (Bromiley & Rau, 2014, 2016). Vessels exhibit a wide variation in environmental performance, and because decision makers seek satisficing solutions, they do not utilize all levers that could improve a vessel's environmental performance. Consequently, technology and operational levers can explain the observed variations in environmental performance in our population.

In addition, what explains variations in environmental performance for vessels with poor performance probably differs from what explains variations in environmental performance for vessels with good performance. The empirical context further justifies examining the link between features of ship designs and environmental performance across the entire range. For example, vessels with low environmental performance are of special practical relevance: first, they are the main targets of the policy because the energy efficiency regulation prescribes minimum performance standards for comparable vessels. Second, these vessels also have a relatively higher impact on the carbon footprint of shipping firms compared to vessels with better environmental performance.

2.4.1 Environmental performance implications of technology and operational levers

We now thoroughly outline our set of hypotheses regarding the impact of technology and operational levers on environmental performance. Our set of hypotheses is clustered into three main pillars, each connected to one main technology or operational lever, namely, (i) environmental performance implications of alternative fuel adoption, (ii) environmental performance implications of a vessel's lifetime, and (iii) environmental performance implications of emission prevention. While all these levers determine the design features linked to the environmental performance of existing vessels in operational use, we refer to pillars (i) and (iii) as technology levers, as they relate to technologies. Further, we refer to a vessel's lifetime [i.e., pillar (ii)] as an operational lever, due to its relation to the managerial decision to adapt an existing vessel to prolong its operational use, which we elaborate on in section (2.4.1.2). For better readability, the hypotheses include assertions about "the range of energy efficiency (and slack)." However, to be technically precise, we only make statements about the *conditional* and not the *unconditional* energy efficiency (and slack) distribution of our sample.

2.4.1.1 Environmental performance implications of alternative fuel adoption

Prior research in the transportation sector suggests that the adoption of clean technologies can considerably reduce carbon footprints and, thus, improve the environmental performance (Avci et al., 2015; Wang et al., 2013). In addition, we draw from the Porter Hypothesis in our theorizing of the relationship between the adoption of clean technologies and environmental performance. Generally speaking, this theoretical argument highlights the positive effect a well-designed environmental policy can have on innovation efforts to comply with the regulation (Porter & Van der Linde, 1995). For our conjecture, of special interest is the "weak" version of the hypothesis, presuming a positive relationship between a strict but flexible environmental policy and the development and adoption of clean technologies (Jaffe & Palmer, 1997). However, note that the departing point in our study is different: our objective is to examine the effect that the decision to adopt clean technologies has on regulatory compliance. We therefore presume a positive relationship between clean technology adoption and environmental performance.

We focus on one particular clean technology, namely, alternative fuels. The adoption of alternative fuels is seen as one of the main technology levers to improve the environmental performance of ship design; consequently, they are a focal point of concern among ship owners and regulators in the maritime industry (DNV, 2019). Currently, many efforts in the maritime industry are devoted to the adoption of already available alternative fuels, such as biofuels or liquefied natural gas (LNG), and to the development of newer alternative fuels, including alcohol-based ones (e.g., methanol and ethanol), other cryogenic gases (e.g. hydrogen), and non-cryogenic gases (e.g., ammonia). Furthermore, the decision to adopt alternative fuels should have a direct lowering effect on a vessel's energy efficiency rating because these fuels get assigned a lower carbon factor when computing the attained EEDI. Based on these reflections, we presume a positive impact of the adoption of alternative fuels on environmental performance, which is formally stated in hypothesis 1.

Hypothesis 1(a) (H1(a)). *The adoption of alternative fuels has a positive impact on vessels' energy efficiency across the range of energy efficiency.*

Hypothesis 1(b) (H1(b)). *The adoption of alternative fuels has a positive impact on vessels' slack across the range of slack.*

2.4.1.2 Environmental performance implications of a vessel's lifetime

We suggest that the link between a vessel's lifetime and its environmental performance is of high interest. A plausible presumption about this relationship is that vessels later in their lifetime have less efficient ship design features with respect to environmental performance than vessels earlier in their lifetime. Given a certain point in time, a "younger" vessel had access to more recent technology systems and advanced ship designs in the design process than an "older" vessel and, thus, should have a better environmental performance (see, e.g., Angell & Klassen, 1999; Zhu & Sarkis, 2004). As vessels are capital-intensive investments with an average lifetime span of 28 years, the current fleet will operate and impact the environment for a long time (Clarksons, 2019). Therefore, a vessel's lifetime raises an intriguing decision for ship owners seeking to improve the environmental performance of the assets and overall fleet they are operating, while complying with regulatory requirements. Decision makers with this goal can decide to adapt an existing vessel later in its lifetime (i.e., retrofitting) to improve its performance and, thus, prolong its operational use or can replace it with a new vessel with better performance.

Note that the data set yields empirical support for the prevalence of the managerial decision concerning this operational lever in practice. While mostly targeting newly-built vessels, the EEDI regulation is also a requirement for existing vessels undergoing a major overhaul. Because we measure lifetime with a vessel's age, age together with the EEDI rating can be used as a proxy for vessels that have been retrofitted. In other words, if a ship was built before 2013 and has an EEDI rating, it is in most cases due to being retrofitted during the regulation horizon. In our data set, roughly 10% of vessels meet this criterion. From a practical perspective, the operational decision to adapt existing vessels to improve environmental performance is vital to reduce carbon emissions in the maritime industry (Green Ship, 2020). In addition, due to the higher projected costs of alternative fuels, the importance of energy efficiency increases from a financial standpoint over time (Green Ship, 2020). To summarize, we theorize that a vessel's lifetime has a negative effect on environmental performance.

Hypothesis 2(a) (H2(a)). *The later vessels are in their lifetime, the lower their level of energy efficiency across the range of energy efficiency.*

Hypothesis 2(b) (H2(b)). *The later vessels are in their lifetime, the lower their level of slack across the range of slack.*

We are especially interested in such a relationship concerning vessels with poor environmental performance due to their high relevance to the green transitioning process in the maritime industry. Drawing from our empirical context and theoretical lens allows us to theorize further about the relationship between a vessel's lifetime and its environmental performance. As described in section (2.2), the EEDI regulation increases the minimum performance standard over time, meaning vessels later in their lifetime had to comply with less stringent reduction targets. Based on behavioral theory, decision makers seek satisficing solutions for the minimum performance standard to they are subject. Consequently, decision makers could seek *less* satisficing solutions for older vessels, as these are subject to lower reduction target levels. In summary, it seems plausible that the effect outlined in H2(a) and H2(b) is increasing over the range of energy efficiency and slack, respectively (i.e., more pronounced for vessels with relatively poor environmental performance). This presumption is summarized in hypothesis 2(c).

Hypothesis 2(c) (H2(c)). *The effect described in H2(a) and H2(b) is increasing across the range of energy efficiency and slack, respectively.*

2.4.1.3 Environmental performance implications of emission prevention

In the literature, emission prevention technologies to avoid pollution have been linked to improved environmental performance for a long time (Klassen & Whybark, 1999b). In this spirit, previous empirical studies have posited a positive relationship between technologies for pollution prevention and environmental performance (Fu et al., 2019; Kroes et al., 2012). For our purpose, we refer to emission prevention as adapting the ship design to avoid carbon emissions. In the maritime industry, the main source of carbon emissions is the combustion of fuels to provide propulsion for transportation services. Thus, reducing the energy requirements of a vessel should have a direct positive effect on environmental performance. The main energy requirement of most vessels is its main machinery technology providing propulsion, and we focus on this technology lever for emission prevention in our analysis.

The relationship between a vessel's machinery technology and its environmental performance is of high practical relevance. Three main ship design features directly related to the main engine technology are speed, propulsive power, and specific fuel oil consumption. Based on insights from maritime engineering, it is generally accepted that adjusting these features are effective ways to improve energy efficiency (Molland et al., 2017). To give the reader some specific examples, because the required power varies approximately as speed cubed, reducing a vessel's speed should lead to a reduced fuel consumption and, in turn, higher energy efficiency. Further, reducing a vessel's speed is seen as an effective and easy measure to comply with the minimum performance standards of the EEDI regulation (Ančić et al., 2018; Lindstad & Bø, 2018). Similarly, reducing the propulsive power, while keeping the ship's speed and dimensions fixed, increases the propulsive efficiency of the vessel and, thus, should improve its energy efficiency. Therefore, based on practical and theoretical insights, we hypothesize that emission prevention with respect to the machinery technology has a positive effect on a vessel's environmental performance.

Hypothesis 3(a) (H3(a)). *Lower levels of emission prevention with respect to the machinery technology, have a negative impact on vessels' energy efficiency across the range of energy efficiency.*

Hypothesis 3(b) (H3(b)). *Lower levels of emission prevention with respect to the machinery technology, have a negative impact on vessels' slack across the range of slack.*

Figure (2.3) graphically illustrates our hypotheses. Based on the conceptual model in Figure (2.2) and empirical evidence, we theorize about the relationship between key technology and operational levers and environmental performance, which is operationalized through a vessel's energy efficiency and regulatory slack. With respect to technology levers, we focus on the adoption of alternative fuels and emission prevention related to machinery technology. We hypothesize that the adoption of alternative fuels has a positive impact on energy efficiency levels (H1(a)) and regulatory slacks (H1(b)). Furthermore, we posit that the relationship between emission prevention measures and energy efficiency (H3(a)) and slack (H3(b)) is positive. The key operational lever of the analysis is a vessel's lifetime. We propose that vessels' lifetime is negatively associated with their energy efficiency (H2(a)) and slack (H2(b)). Further, drawing from our empirical context and theoretical lens, we posit that this effect is increasing across the range of energy efficiency and slack (H2(c)).

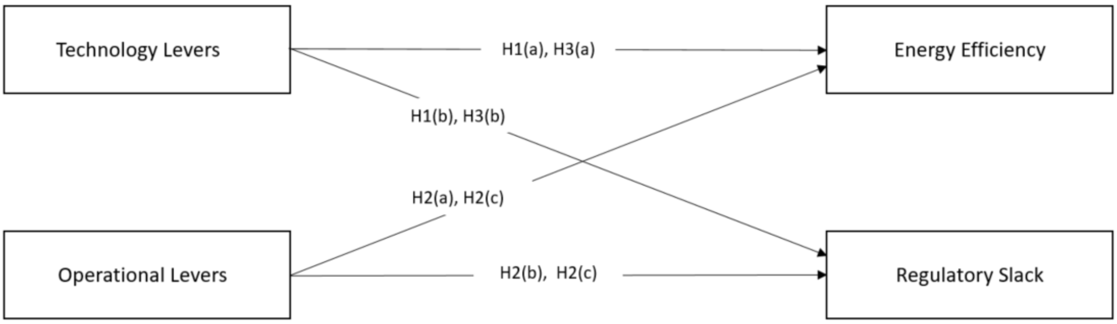

FIGURE 2.3: Research model

2.5 Method

2.5.1 Data and measures

The data for the empirical analysis was obtained from three sources: the European Maritime Safety Agency's database, incorporated in the EU Monitoring, Reporting, and Verification (MRV) regulation (EU, 2015); the Clarkson World Fleet Register (CWFR); and the Thomson Reuters Eikon Shipping (TRES) database. The EU-MRV aims to monitor CO_2 emissions and energy efficiency from shipping activities within the EU by making ship owners and operators report their emission data annually on a per-vessel basis. These data are then certified by an accredited verifier and made publicly available annually for the preceding reporting period. The mandatory first reporting period was from January 1, 2018 to December 31, 2018, and the public data were released in July 2019. Hence, our data are limited to the vessels calling any EU port in that period. The EU-MRV data contain some basic features of the ships (e.g., the ship type) and different measures of energy efficiency of the governed vessels.

In this paper, we are interested in the energy efficiency quantified by the EEDI rating. In 2018, $2,106$ distinct vessels with EEDI ratings between 1 and 100 were reported in the EU-MRV. We decided to exclude the 17 passenger ships and six ships with electric propulsion from the analysis, as the EEDI benchmark for passenger ships is determined using a different measure for capacity (namely gross tonnage), and the main engine's power for electric ships is defined differently (namely, total electric propulsion). We matched the remaining vessels by their IMO number with the CWFR and TRES databases. Both databases contain detailed information about ship-specific design features for the global fleet. Therefore, we were able to match all but two vessels of interest in the EU-MRV with the data from CWFR and TRES. The quality of the resulting data set is overall very good, except for 206 and 263 missing values for the service speed and main engine's fuel efficiency variables, respectively.

To address the issue of missing values for the main engine's fuel efficiency, if available, either computerized engine application system (CEAS) tools or technical specifications provided by the engine manufacturers have been used to obtain the missing fuel efficiency data. We were able to find the required data for most of the main engines and were left with only 19 missing values after this exercise. To derive an approximation of the missing speed values, a different imputation strategy was utilized. The intuition of the approach is as follows: a vessel's service speed, defined as the average speed under normal load and weather conditions, should be well approximated by the actual recorded average speed of the respective vessel. The recorded average speed is publicly available through the automatic identification system (AIS) data service, which tracks the current speed and position of the world fleet. Hence, as a first step, we collected the average recorded speed by AIS data for all ships in our sample. Then, the service speed was regressed on the collected average speed and ship type to allow for ship type-specific intercepts for the full sample in a multivariate regression. The derived regression coefficients were then used to predict the missing service speed variables of our data set. After these additional steps, the final data set consists of $2,058$ complete observations.

By collecting and generating this novel data set, we are, to our knowledge, the first to study empirically the impact of technology and operational drivers on environmental performance in the

Table 2.1: Summary statistics

Variable	Mean / Share	St. Dev.	Description
EEDI	7.02	5.69	EEDI value (in g CO_2/ capacity-mile)
EERS	0.81	0.30	Slack with EEDI regulation
Age	5.39	3.93	Age of ship (in years)
Speed	16.38	3.58	Average speed under normal load and weather (in knots)
Chemical tanker	0.16		1 if ship type is chemical tanker
Container ship	0.16		1 if ship type is container ship
Gas carrier	0.04		1 if ship type is gas carrier
General cargo	0.05		1 if ship type is general cargo ship
Oil tanker	0.21		1 if ship type is oil tanker
Other	0.05		1 if ship type is other ship type
VLS fuel	0.83		1 if ME fuel type is IFO-VLS or IFO-ULS
Alternative fuel	0.01		1 if dual fuel ME for alternative fuels
Main efficiency	169.80	3.33	ME-specific fuel consumption (in g/kWh)
Main power	15.24	14.96	ME derived total mechanical propulsion (in thousand kW)
Capacity	74.96	58.01	Capacity of ship (in thousand deadweight tonnes)
Draught	12.86	2.81	Draught of ship's hull (in m)
LOA	220.23	62.29	Length overall of ship (in m)
Beam	35.26	9.55	Width overall of ship (in m)

maritime context. Prior to the EU-MRV data publication, studies examining the EEDI relied mainly on calculated estimates of the rating, as the EEDI for specific ships was not publicly available on a large scale. One notable exemption is the report by T&E (2017) due to their access to the IMO EEDI database. However, they do not include detailed ship-specific features in their empirical analysis. We now describe the specific variables of our econometric analysis in more detail. The variables of interest are summarized in Table (2.1). Note that all the numerical variables are centered around their respective mean in the forthcoming empirical analysis. Hence, the intercept in our quantile regressions (QRs) has a direct interpretation as the estimated conditional quantile function of a bulk carrier with average dimensions and of average age, capacity, and speed; having a main engine of average power and fuel consumption; and using heavy fuel oil.

2.5.1.1 Dependent variables

The dependent variable for testing the hypotheses H1(a), H2(a), H2(c), and H3(a) is the attained EEDI rating (*EEDI*) expressing a vessel's energy efficiency. As stated previously, we are particularly concerned with the high quantiles that capture vessels with low energy efficiency. For example, to give the reader a specific reference point, the 90% quantile of the unconditional EEDI distribution is around a value of 15.25 grams of CO_2 per capacity-mile. Note that due to the strong positive skew of the unconditional EEDI distribution, we decided to use the logarithm of the dependent variable in the econometric QR model.

To test our hypotheses H1(b), H2(b), H2(c), and H3(b), we formulate a dependent variable indicating a vessel's slack with the energy efficiency regulation (*EERS*). Such a measure can be directly derived from Equation (2.2) by replacing a vessel's required EEDI with the attained EEDI and rearranging terms,

$$\begin{aligned} Attained\ EEDI &= (1 - \frac{Reduction\ factor}{100}) \times Reference\ line\ value \\ EERS &:= (1 - \frac{Reduction\ factor}{100}) = \frac{Attained\ EEDI}{Reference\ line\ value}. \end{aligned}$$

The procedure is as follows: we first derive the reference line value for each ship in our data set according to ship type-specific formulas (ClassNK, 2015). Then, we divide the attained (absolute) EEDI value by the individual reference line value to attain the *EERS* variable. Intuitively, a value of 0.65 indicates that a vessel's attained EEDI is 65% of its reference line value and, thus, has a slack of 35% with respect to the energy efficiency regulation. Note that due to formulating the *EERS* based on Equation (2.2), it is directly akin to the reduction factors of the EEDI regulation. For instance, a *EERS* value of 0.65 also indicates that the ship is compliant with the Phase III reduction target of 30% because its slack is 35%. Another feasible feature of the measure is that it allows us to make more general statements about a vessel's likelihood of compliance with the energy efficiency regulation. A lower *EERS* implies a higher slack and increases a ship's likelihood of compliance with *any* set of uniform reduction factors in the EEDI regulation. Hence, the results of our analysis are not sensitive to adjustments or changes in the reduction factors. Similar to before, the logarithm of the dependent variable is used in our econometric models.

2.5.1.2 Independent variables

The explanatory variables in our empirical analysis are concerned with the ship design features related to the technology and operational levers potentially impacting technical environmental performance. The measure for a vessel's lifetime is the variable *Age* indicating the age of the ship, which is derived from the year the ship was built. The speed of the vessel (*Speed*) is measured by the vessel's service speed in knots and is defined as the average speed of the ship under normal load and weather conditions. Note that due to data quality, we use the service speed instead of the design speed, which is the speed at which a ship was designed to operate. These two variables, however, appear to nearly coincide in our data set, which makes this a worthwhile trade-off[3].

The ship's main engine features are measured by the following variables: the main engine's derived total mechanical propulsion (*Main power*) in thousand kW, the main engine-specific fuel consumption in g/kWh (*Main efficiency*), and the main engine's fuel type. Note that *Main power* indicates the sum of power generated by the main engine(s) and transferred mechanically to the main propulsor(s), and it thus describes the actual power arriving at the propulsors instead of a nominal power output by the main engine (expressed by the maximum continuous rating), which makes our analysis more relevant to practice. The main engine's fuel type is divided into three categories: very (ultra) low sulfur fuel (*VLS fuel*) and the option of using alternative fuels (e.g., LNG, methanol, or ethanol) (*Alternative fuel*). The omitted category is heavy fuel oil (*IFO-380*) as the main fuel type, and the fuel type categorical variables are interpreted relative to this category.

2.5.1.3 Control variables

We control for the ship's dimensions in the empirical analysis. The ship's dimensions are expressed by the variables length overall (*LOA*), *Beam*, and *Draught*, which are all measured in meters. While not being directly part of the EEDI formula, the relation of these dimensional variables determines the so-called block coefficient, which is the ratio of a ship's underwater volume to the

[3]To illustrate, the pairwise correlation coefficient for original service and design speed in our data set is 0.94, and a simple linear regression (without intercept) suggests a regression coefficient of 0.99.

volume of a rectangular block defined by these three variables. A higher block coefficient leads to a higher hull resistance, and in turn, more power is required for propulsion and lower fuel efficiency. Therefore, controlling for these ship design features in the empirical analysis is imperative.

The cargo-carrying capacity of a ship is reflected by the variable *Capacity*, which is measured in thousand deadweight tonnes (DWT). DWT states the vessel's maximum weight-carrying capacity, excluding its own weight, and is in practice indicated by the certified load line marking amidships. Capacity is an important part of the EEDI formula, as it reflects, together with a ship's speed, the benefit part of the equation. Further, we control for the type of vessel due to the structural differences in ship design. The ship type is reflected by a categorical variable divided into seven categories: chemical tanker, container ship, gas carrier, general cargo ship, oil tanker, and other ship type, and the omitted categorical level is bulk carrier. We have chosen to follow the classification in the EU-MRV data set to determine the ship type.

2.5.2 Empirical model

A standard method in empirical studies is the ordinary least squares (OLS) method. This approach yields an approximation of the conditional mean function $E(y|x)$, which describes how the mean of the dependent variable changes with the set of covariates. However, as previously discussed, in our empirical context, particularly the right-tail behavior of the distributions is of greater interest than the location measure of the mean. One could also consider the empirical method of a logit or probit regression by defining a threshold value for the EEDI value and could use an indicator as the dependent variable. However, this only sheds light on the effects of covariates on a specific EEDI outcome (attaining the required threshold value or not), which is not uniform across ship type or age and, thus, is of limited interest. In our setting, the method of QR yielding a description of the whole conditional distribution is an alternative method to gain further insights. Contrary to OLS and probit/logit methods, QR allows one to investigate what influence various covariates have on different quantiles of the conditional distribution; thus, it gives a more complete picture. We now turn to a brief description of the QR approach, which was first proposed by Koenker and

Bassett (1978). For a quantile $\tau \in (0, 1)$, the conditional quantile function can be formulated as,

$$q_{y|x}(\tau) \coloneqq x\beta_\tau. \tag{2.3}$$

Similar to OLS, the conditional quantile function is assumed linear in the parameters β_τ. An important distinction of OLS is that the marginal effects depicted by β_τ are allowed to vary in τ. In fact, only in the case of $y = x\beta_\tau + u_\tau$, with homoscedastic error term u_τ, will the slopes of parameters β_τ be the same across τ. This also leads to the fact that effects can change signs across quantiles, which might suggest no effect of a covariate if investigated with the conditional mean model. For example, under these circumstances, one might conclude that a covariate has no effect on the dependent variable, which might not be true (Fitzenberger & Wilke, 2015). The empirically observed quantile τ of a random variable's y distribution $q_y(\tau)$ can be expressed as the solution to the following minimization problem,

$$q_y(\tau) \coloneqq \arg\min_q \Big[\tau \sum_{i:y_i>q} |y_i - q| + (1-\tau) \sum_{i:y_i<q} |y_i - q|\Big]. \tag{2.4}$$

This expression is the so-called check function and can be interpreted as the (asymmetrically) weighted absolute difference from the location parameter q. In a linear QR, the location parameter is stated as a function of the covariates x_i, and the conditional quantile of the response variable $q_{y|x_i}(\tau)$ is a linear function of $x_i\beta_\tau$. Thus, the check function in Equation (2.4) can also be stated as,

$$\beta_\tau \coloneqq \arg\min_\beta \Big[\tau \sum_{i:y_i>x_i\beta} |y_i - x_i\beta| + (1-\tau) \sum_{i:y_i<x_i\beta} |y_i - x_i\beta|\Big]. \tag{2.5}$$

Note that due to the piece-wise linear form of Equation (2.5), special techniques to provide asymptotic refinements of the standard errors are required (Horowitz, 2001). Two feasible features of the QR estimator, when compared to the OLS estimator, are that it is more robust to outliers in the dependent variable due to its focus on the median and that it makes no assumption regarding the distribution of the error term (Koenker, 2005). The interpretation of the linear QR parameters β_τ is analogous to the OLS case: they describe the change in the conditional quantile of the dependent variable when the respective covariate changes by one unit.

The basic model formulation for testing H1(a), H2(a), H2(c), and H3(a) can be written as:

$$\begin{aligned} log(EEDI_i) =& \beta_0 + \beta_1 Age_i + \beta_2 Speed_i + \beta_3 VLS\ fuel_i + \beta_4 Alternative\ fuel_i \\ &+ \beta_5 Main\ efficiency_i + \beta_6 Main\ power_i + \boldsymbol{\beta}_{controls}\mathbf{Z}_i + \epsilon_i \end{aligned}$$

Similarly, our basic empirical model for testing H1(b), H2(b), H2(c), and H3(b) is:

$$\begin{aligned} log(EERS_i) =& \beta_0 + \beta_1 Age_i + \beta_2 Speed_i + \beta_3 VLS\ fuel_i + \beta_4 Alternative\ fuel_i \\ &+ \beta_5 Main\ efficiency_i + \beta_6 Main\ power_i + \boldsymbol{\beta}_{controls}\mathbf{Z}_i + \epsilon_i \end{aligned}$$

Before turning to the empirical results, we address two important points. First, we formally test our initial presumption that the relationship between technology and operational levers and environmental performance is not adequately captured by a single point-wise estimate. Second, we briefly outline the strategy for a heteroscedasticity-robust inference in the empirical models.

2.5.2.1 Test for location shift hypothesis

We test our presumption that the effects of technology and operational levers on environmental performance are heterogeneous across the range of environmental performance. In formal terms, we test the so-called location shift hypothesis, stating that the estimated slopes are equal across a specified set of quantiles $\tau \in \{0.1, 0.25, 0.5, 0.75, 0.9\}$ of the conditional distribution. If the hypothesis is rejected, it is an indication of the presence of heteroscedasticity in the data. To test this hypothesis, a variant of the Wald-test proposed in Koenker and Bassett (1982) is conducted with the energy efficiency measure (i.e., EEDI rating) as the dependent variable. To obtain a robust inference, the kernel method for the sandwich estimator proposed by Powell (1991) is performed with the kernel function stated in Powell (1991) and the bandwidth described in Koenker (2005) as parameter choices. The following tests are conducted.

Joint test of equality of slopes for all slope parameters across quantiles:

This first test checks for any statistically significant differences in the estimated coefficients β_τ across two of the specified quantile levels. For this purpose, the joint test is performed for each pairwise combination of the five quantiles of interest and for the full set of quantiles. The results are reported in the appendix in Table (2.5). In all pairwise tests, the null hypothesis of the joint equality of slopes is rejected at the 1% significance level, indicating that the slopes of the conditional quantile functions differ significantly across quantiles.

Test of equality of slopes for individual slope parameters across quantiles:

This test examines whether, given a certain covariate, the estimated coefficient significantly changes across the specified set of quantiles. For example, the null hypothesis for the variable *Age* is $\beta^{AGE}_{\tau=0.1} = \beta^{AGE}_{\tau=0.25} = \beta^{AGE}_{\tau=0.50} = \beta^{AGE}_{\tau=0.75} = \beta^{AGE}_{\tau=0.90}$. The results of the test are depicted in Table (2.2).

TABLE 2.2: Test of equality of distinct slopes

Covariate	F-statistic	p-value
Age	16.999	.000
Speed	3.072	.015
VLS fuel	3.07	.016
Alternative fuel	3.78	.004
Main efficiency	0.87	.481
Main power	7.389	.000
Capacity	2.873	.022
Draught	6.703	.000
LOA	2.623	.033
Beam	0.878	.476

Note: Test of equality of slopes for individual slope parameters across quantiles according to the Wald-test with omitted ship type controls. Heteroscedasticity-robust standard errors are derived using the kernel method of the sandwich estimator. The null hypothesis in the Wald-test is the equality of distinct slopes across quantiles.

Except for the main engine's fuel efficiency and beam variable, the effects of the individual covariates change significantly along the conditional energy efficiency distribution. To conclude, both the joint and distinct Wald test overall reject the location shift hypothesis. This is an important finding, as it has two implications for our further analysis. First, there is an indication of the presence of heteroscedasticity, as the conditional variation in energy efficiency changes with the covariates. This must be addressed in the empirical analysis to ensure a heteroscedasticity-robust inference. Second, the presence of changing effects confirms our initial presumption that technology and operational levers have heterogeneous impacts across the range of environmental performance. Therefore, we find evidence that explaining variations in performance across different levels of performance might yield important additional insights into our empirical context.

2.5.2.2 Estimation of asymptotic standard errors

To address the presence of heteroscedasticity in our data, we consider resampling techniques, such as the bootstrap, to approximate the asymptotic distributions of the estimators without having to make assumptions about them. The standard approach for QR is to use a full-sample (x, y)-pair bootstrap that is replicated B times to obtain a heteroscedasticy-robust inference (Koenker, 2005). In this approach, samples of the (x_i, y_i) pairs are drawn from the empirically observed joint distribution of the sample (with replacement), and then a QR is estimated at the specified different quantiles, yielding estimates of the covariance matrix. It is worth noting that the accuracy of the approximation depends on the choice of B; hence, a sufficiently high B must be chosen. There is no clear guidance in the literature about the precise value of B, and recommendations range from 200 to $1,000$ replications depending on the application (see Cameron & Trivedi, 2005, p.361, for a more thorough discussion of the literature on this topic). In line with this literature, we consider for each quantile estimator 700 bootstrap replications in our analysis, and the obtained standard errors are reported in Table (2.3)[4]. Note that we did not consider approaches relying on asymptotic theory, due to their reliance on assumptions to estimate the (unknown) density of the error term.

[4]Note that as a robustness check, we have conducted the alternative QR gradient condition bootstrap method proposed by Parzen et al. (1994). The differences in estimated standard errors are marginal.

2.6 Results

This section deals with outlining and interpreting our empirical results regarding the relationship between technology and operational levers and environmental performance, which is operationalized through energy efficiency and regulatory slack. Further, due to examining the conditional distribution of energy efficiency and slack, the estimates should be considered as local effects given a set of vessels with certain characteristics. Our results cannot be generalized as effects that would affect the unconditional distribution of interest. We will now turn to the examination of the hypotheses concerned with the relationship between key technology and operational levers and energy efficiency.

2.6.1 Results for technology and operational levers and energy efficiency

The results of our QR model concerned with hypotheses H1(a), H2(a), H2(c), and H3(a) are depicted in Table (2.3) at a specified set of quantiles $\tau \in \{0.1, 0.25, 0.5, 0.75, 0.9\}$, as are, for comparison, the linear regression estimates. Standard errors are reported in parentheses and are computed according to the bootstrap procedure described in subsection (2.5.2.2) for the QRs and heteroscedasticity-robust in the OLS regression. When looking at the results depicted in Table (2.3), overall, all the reference OLS estimates are significant at the 1% level, except for *VLS fuel*. Similarly, a large fraction of the QR point estimates are significant across the different quantiles and have the expected sign.

First, we investigate the relationship between alternative fuels and energy efficiency (H1(a)). Overall, the adoption of alternative fuels has the expected negative sign, and the effect is of high magnitude. We are unable to identify a significant relationship for all specified quantiles. To illustrate, we are unable to confirm H1(a) for the 90% populated by the key vessels of interest with lower energy efficiency levels. The negative effect is the most pronounced at the quantiles around the median of the conditional EEDI distribution, and is highly similar to the OLS results. Based on the OLS results, on average, the EEDI ratings of vessels' having adopted alternative fuels is around 50% lower than for vessels not having adopted them, all else being equal. There is an indication that alternative fuels have considerable potential for improvements in energy efficiency. However,

Table 2.3: Quantile and OLS regression results for energy efficiency

	Quantile regression					*OLS*
	10%	25%	50%	75%	90%	
(Intercept)	1.382***	1.418***	1.465***	1.533***	1.642***	1.526***
	(0.018)	(0.015)	(0.011)	(0.01)	(0.025)	(0.018)
Age	−0.002	0.006***	0.0138***	0.019***	0.043***	0.017***
	(0.003)	(0.002)	(0.002)	(0.007)	(0.002)	(0.007)
Speed	0.028***	0.026***	0.011**	0.007***	0.006	0.032***
	(0.009)	(0.008)	(0.005)	(0.003)	(0.004)	(0.007)
VLS fuel	−0.017**	0.008	0.001	−0.01	−0.025	−0.01
	(0.008)	(0.01)	(0.006)	(0.008)	(0.021)	(0.013)
Alternative fuel	−0.176	−0.273	−0.404***	−0.425***	−0.121	−0.41***
	(0.148)	(0.195)	(0.152)	(0.125)	(0.253)	(0.078)
Main efficiency	0.009***	0.011***	0.013***	0.013***	0.007	0.01***
	(0.003)	(0.002)	(0.002)	(0.002)	(0.005)	(0.003)
Main power	0.008***	0.009***	0.011***	0.013***	0.011***	0.01***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)
Capacity	0.002***	0.003***	0.004***	0.004***	0.004***	0.003***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
Draught	−0.048***	−0.061***	−0.071***	−0.079***	−0.087***	−0.065***
	(0.008)	(0.004)	(0.004)	(0.004)	(0.007)	(0.007)
LOA	−0.005***	−0.004***	−0.004***	−0.004***	−0.004***	−0.004***
	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
Beam	−0.016***	−0.02***	−0.023***	−0.022***	−0.023***	−0.019***
	(0.004)	(0.002)	(0.002)	(0.001)	(0.004)	(0.002)
Ship Type	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*

Note: Significance levels are indicated by * = $p < 0.1$; ** = $p < 0.05$; *** = $p < 0.01$. The dependent variable is the logged EEDI rating. Bootstrapped standard errors in parentheses (for QR), using 700 repetitions. OLS standard errors are heteroscedasticity-robust. All regressions control for the aforementioned ship type categories according to the EU-MRV classification.

the results only partially support hypothesis H1(a), which stipulates a significant energy efficiency improvement across the range of energy efficiency.

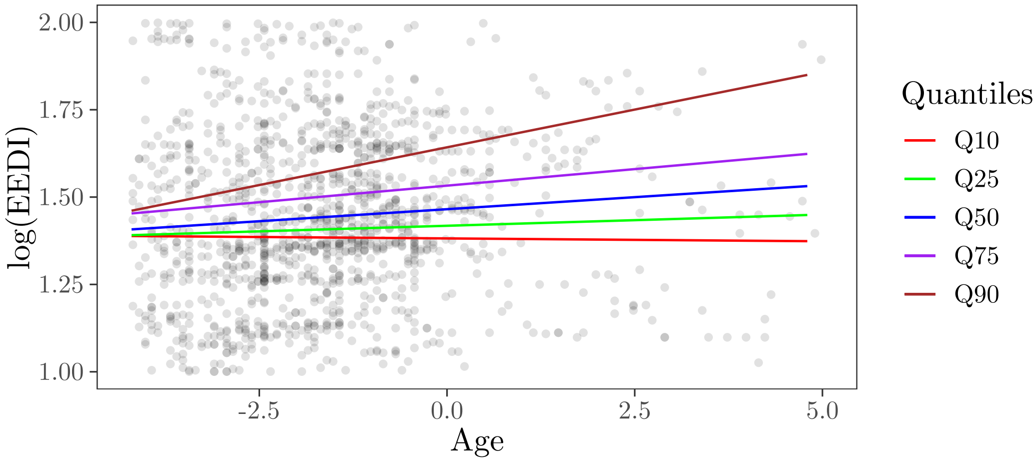

FIGURE 2.4: Conditional quantile function in age

Next, we turn to evaluate H2(a) by investigating the relationship between vessels' lifetime and energy efficiency in Table (2.3). It can be seen that the *Age* coefficient is significant across the conditional EEDI distribution, except for the 10% quantile, and it has the hypothesized positive sign. Hence, vessels' lifetime overall has a negative effect on energy efficiency, supporting hypothesis 2(a). Further, the effect of a ship's age on the EEDI rating appears to increase monotonically when moving from low to high quantiles. This is illustrated by the conditional quantile functions in age (with all other covariates fixed) depicted in Figure (2.4). The slope of the conditional quantile functions increases when moving from low to high quantiles, supporting one part of hypothesis 2(c). Further, the point-wise OLS estimator overestimates the positive effect at low quantiles and underestimates it at high quantiles. At the 90% quantile of the conditional distribution, the EEDI ratings for vessels being one year older (than average) are 4.3% higher than for vessels of average age, all else being equal. To conclude, higher age is associated with lower energy efficiency throughout the conditional energy efficiency distribution. The only exception occurs at the 10% quantile, indicating vessels with higher energy efficiency levels. Further, the positive effect is the most pronounced for vessels with lower levels of energy efficiency. To summarize, the results overall support our hypotheses H2(a) and H2(c).

Lastly, we examine hypothesis H3(a) by investigating the relationship between emission prevention with respect to vessels' machinery technology and energy efficiency. Overall, the point-wise estimates of the three covariates have the expected positive sign. Increasing ships' speed, propulsive power, or fuel oil consumption is associated with lower energy efficiency. However, when looking at the speed variable, the effect decreases when moving from low to high quantiles, where it becomes insignificant, and it is in general only moderate. At the 10% quantile, a typical vessel with a 1 knot lower speed has a 2.8% lower EEDI rating, all else being equal. Similar to the speed estimate, we were surprisingly unable to identify a significant relationship between the main engine's fuel efficiency and the EEDI rating at the 90% quantile, which allows us to at least question the efficacy of this technology levers for vessels at the top of the conditional distribution. Further, as indicated by the Wald-test in Table (2.2), *Main efficiency* seems only to exhibit a pure location shift on the conditional EEDI distribution. The point estimates for propulsive power are significant throughout the conditional EEDI distribution, and more pronounced at high quantiles compared to low quantiles. To summarize the results, despite finding overall support for H3(a), we were unable to confirm it for vessels with relatively poor energy efficiency.

2.6.2 Results for technology and operational levers and regulatory slack

We now turn to examine the relationship between technology and operational levers and vessels' regulatory compliance. To address hypotheses H1(b), H2(b), H2(c), and H3(b), we use a vessel's slack with the energy efficiency regulation (*EERS*) as a dependent variable. The methodological approach follows that outlined in section (2.6.1). Similar to before, the empirical results are reported in Table (2.4) for the specified set of quantiles $\tau \in \{0.1, 0.25, 0.5, 0.75, 0.9\}$ alongside the OLS results for comparison. Overall, the signs and significance of the independent variables are similar to the results in section (2.6.1), which validates the consistency of our results.

We start by examining hypothesis H1(b) by exploring the relationship between the adoption of alternative fuels and slack with the energy efficiency regulation. The *Alternative fuel* variable has the expected negative sign, and the results suggest a significant relationship at the 5% significance level for all specified quantiles, except for the first decile (quantile $\tau = 0.1$), where it is significant

Table 2.4: Quantile and OLS regression results for regulatory slack

	Quantile regression					*OLS*
	10 %	25 %	50 %	75 %	90 %	
(Intercept)	−0.294***	−0.243***	−0.193***	−0.125***	−0.002	−0.148***
	(0.021)	(0.013)	(0.008)	(0.012)	(0.03)	(0.018)
Age	0.005**	0.013***	0.018***	0.026***	0.05***	0.022***
	(0.002)	(0.002)	(0.001)	(0.003)	(0.007)	(0.003)
Speed	0.007	0.007	0.01**	0.01***	0.009*	0.021***
	(0.01)	(0.005)	(0.004)	(0.002)	(0.005)	(0.006)
VLS fuel	0.014	0.008	0.003	−0.004	−0.029	−0.026
	(0.011)	(0.008)	(0.006)	(0.01)	(0.026)	(0.014)
Alternative fuel	−0.529*	−0.458***	−0.453***	−0.39***	−0.102	−0.388***
	(0.316)	(0.147)	(0.078)	(0.125)	(0.241)	(0.077)
Main efficiency	0.006*	0.01***	0.014***	0.012***	0.007*	0.008***
	(0.003)	(0.002)	(0.002)	(0.002)	(0.004)	(0.003)
Main power	0.000	0.003***	0.002***	0.004***	0.003*	0.003**
	(0.002)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)
Capacity	0.001*	0.002***	0.002***	0.002***	0.002***	0.001**
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Draught	0.016***	0.018***	0.014***	0.018***	0.016**	0.021***
	(0.006)	(0.003)	(0.003)	(0.005)	(0.007)	(0.006)
LOA	−0.002***	−0.002***	−0.002***	−0.003***	−0.003***	−0.002***
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Beam	−0.001	−0.01***	−0.008***	−0.007***	−0.007**	−0.007***
	(0.004)	(0.002)	(0.001)	(0.002)	(0.004)	(0.002)
Ship Type	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*

Note: Significance levels are indicated by * = $p < 0.1$; ** = $p < 0.05$; *** = $p < 0.01$. The dependent variable is the logged EERS measure. Bootstrapped standard errors in parentheses (for QR), using 700 repetitions. OLS standard errors are heteroscedasticity-robust. All regressions control for the aforementioned ship type categories according to the EU-MRV classification.

at the 10% level, and the ninth decile (quantile $\tau = 0.9$). The potential slack increases are high in magnitude and indicate the potential of adopting alternative fuels to comply with the minimum performance requirements. Based on the OLS results, on average, the $EERS$ value of vessels' having adopted alternative fuels is expected to be around 46% lower than that of vessels not having adopted them, all else being equal. Overall, the results mostly confirm hypothesis H1(b). However, the efficacy of adopting alternative fuels as a lever to comply with the energy efficiency regulation for vessels with lower slacks remains inconclusive.

Next, the relationship between vessels' lifetime and regulatory slack proposed in hypothesis H2(b) is investigated. Throughout the conditional EERS distribution, *Age* has the expected positive sign and is significant. Hence, all else being equal, a higher vessel age is associated with a higher EERS value and, thus, a lower slack across the range of slack, which supports H2(b). Similar to before, the effect increases monotonically throughout quantiles and is most pronounced for vessels at the top of the conditional distribution. To illustrate, the EERS values among vessels being one year older (than average) are expected to be only 0.5% higher than EERS values for vessels of average age at the first decile (quantile $\tau = 0.1$), but 5% higher at the ninth decile (quantile $\tau = 0.9$). The OLS estimate overestimates the effect at low quantiles and underestimates it at high quantiles. To summarize, the results overall confirm hypothesis H2(b) positing a negative relationship between vessels' lifetime and regulatory slack, as well as confirm the second part of hypothesis H2(c).

Lastly, the results for hypothesis H3(b) stating a positive relationship between emission prevention related to the machinery technology and regulatory slack are highlighted. Overall, the point-wise estimates for the three relevant covariates, that is speed, propulsive power, and fuel oil consumption, have the expected positive sign across the conditional distribution. However, the significance of the estimates only partially supports hypothesis H3(b). For example, *Speed* only appears to have a significant effect at the median and 75% quantile of the conditional distribution. Similar to the results for hypothesis H3(a), we are unable to identify a significant relationship at the 5% significance level for the three measures at the top of the distribution, populated by vessels with lower slacks. In addition, we are unable to identify significant effects at the 5% level for these measures at the first decile and the overall magnitude of estimated effects is again only moderate.

We conclude that the results only yield partial support for the hypothesized positive relationship between emission prevention and regulatory slack, as it does not explain performance variations at the tails of the conditional distribution.

2.7 Discussion

Departing from a bounded rationality perspective, where decision makers seek satisficing solutions for the context of the problem, we examined the link between broadly available technology and operational levers and environmental performance for existing vessels, which are used in the external environment. The research aimed to answer two broad research questions. First: *What is the impact of technology and operational levers on environmental performance?* Based on previous work and empirical evidence, we identified key levers affecting the environmental performance of vessels in the context of a mandatory environmental policy in the maritime industry. In this section, we will thoroughly assess our results with respect to each of these technology and operational levers and discuss their theoretical and practical implications. The second question was: *How does the impact of technology and operational levers vary across the range of environmental performance?* Drawing from our theoretical lens and the empirical context, we posit that examining the link between technology and operational levers and environmental performance across the range of environmental performance can yield important additional insights. The overall results suggest that the relationship is indeed heterogeneous, and effects vary across the range of environmental performance. Thus, the impacts of technology and operational levers on environmental performance appear complex and require a granular appraisal.

This heterogeneity of effects has important implications for research theorizing about the link between technology and operational drivers and the performance of the object of inquiry. Examining the drivers of performance and their performance implications has a long tradition in operations management (see, e.g., Skinner, 1969). Further, it is well established in the OM literature that the heterogeneity of units gives rise to differences in their performance, which has been the subject of many empirical examinations (Ketokivi, 2016). Our results indicate that the *impacts* of performance drivers are also exhibiting significant heterogeneity across the range of performance variation in our sample. Therefore, our results empirically show that the same performance drivers may not explain differences in performance among all units. In the OM context, explaining differences in performance among varying levels of performance is of high relevance in many settings (Bromiley & Rau, 2016). To illustrate, in our setting, the units with levels of relatively poor environmental performance are of particular interest from a policy and managerial perspective. In the spirit of the practice-based view, we argue that theoretical insights can be enhanced by considering that the impacts of technology and operational drivers on performance might be heterogeneous across performance levels.

We now turn to the discussion of the specific technology and operational levers impacting environmental performance. We find preliminary evidence that the adoption of alternative fuels is a strong lever to improve environmental performance. Overall, our results partially support hypothesis H1(a) and mostly support H1(b), which posit that the adoption of alternative fuels has a positive impact on vessels' energy efficiency and regulatory slack. In addition, the magnitude of estimated effects is high, thus emphasizing the potential of alternative fuels for decision makers seeking to improve the environmental performance of their fleet. By examining the pathway between the adoption of alternative fuels and environmental performance, our study contributes to previous research concerned with the challenges of clean technologies. More precisely, we provide empirical evidence and granular estimates complementing previous analytical models suggesting that the adoption of clean transportation technologies reduces carbon footprints (see, e.g., Avci et al., 2015; Wang et al., 2013). Our results cautiously suggest that if ship owners want to improve energy efficiency significantly and comply with future, more stringent regulations, they should strongly consider adopting alternative fuels in their ship designs.

The "only" partial support for these hypotheses might be driven by the low prevalence of vessels having already adopted alternative fuels in our sample. This seems surprising given the important role of the adoption of alternative fuels for the green transition of the industry (DNV, 2019). We suggest that the bounded rationality of decision makers might explain this puzzling fact. Many different ship design solutions can reach similar levels of environmental performance, and we assume that decision makers seek "good-enough" solutions to, e.g., comply with current performance standards. Thus, if the adoption of alternative fuels was not required to reach satisficing outcomes, their low adoption rates seem plausible considering their associated challenges. Previous work has already identified important challenges for clean technology adoption, such as price uncertainty (Wang et al., 2013; Plambeck, 2013) and availability (Avci et al., 2015; Lim et al., 2015), which are also present in our empirical context. Fuel costs represent a large share of a vessel's operational costs and are a dominant factor in many business cases for technology investment. Yet, most alternative fuels are projected to be more expensive than traditional ones, and their future prices are highly uncertain (DNV, 2019). Moreover, even if most alternative fuels theoretically have the potential to fulfil maritime energy demands, a rapid increase in demand would require substantial investments in the production and distribution capacities of these fuels (DNV, 2019). Thus, the bounded rationality of decision makers might hinder the widespread adoption of alternative fuels, and policy makers should seek to address actively these challenges to support their adoption.

A vessel's lifetime is the key considered operational lever related to the managerial decision to adapt an existing vessel to prolong its operational use. The lifetime of a vessel has a negative effect on its environmental performance. Our results confirm hypotheses 2(a) and 2(b), hypothesizing that the later a vessel is in its lifetime, the lower its level of energy efficiency and regulatory slack. In addition, the effect is increasing across the range of energy efficiency and slack, which confirms hypotheses 2(c). In other words, the later a vessel is in its lifetime, the lower its environmental performance, and the negative effect is most pronounced for vessels with poor environmental performance. These results have important implications for decision makers seeking to improve the environmental performance of the assets they are operating. Due to the long lifetime span of vessels, retrofitting would be feasible for poor-performing vessels to reduce their relatively high environmental impact (Green Ship, 2020). However, many retrofitting projects are already under pressure due to their high upfront investment costs, especially for vessels with a shorter remaining life (i.e., later in their lifetime) (Bullock et al., 2020). In our context, the results indicate that adapting older vessels is less compelling, as they have significantly lower levels of energy efficiency and regulatory slack, which is highly marked for vessels with poor performance. Improving the environmental performance of an existing vessel to comparable performance standards of a new vessel most likely entails significant additional efforts. Therefore, climate-conscious ship owners might tend to favor ordering a new vessel instead of adapting an existing vessel to reach satisficing outcomes under the mandatory environmental policy, which is problematic considering the severe socio-environmental issues associated with recycling retired vessels (Hsuan & Parisi, 2020).

Emission prevention related to a vessel's machinery technology appears, at best, a moderate lever to improve environmental performance. Our results overall mostly support hypothesis 3(a) and partially support 3(b), but we are unable to confirm both for vessels with relatively poor environmental performance. In other words, the technology lever does not explain performance variations for vessels with poor performance, where improvements would be most desirable. In addition, the magnitude of statistically significant effects is moderate from a practical viewpoint. The efficiency of vessels' main engine technology has been substantially improved over the past four decades (Anantharaman et al., 2015); thus, the scope for emission prevention improvements is limited in practice. Emission prevention measures are often seen as easy and effective methods to improve energy efficiency and comply with the EEDI regulation (Ančić et al., 2018; Lindstad & Bø, 2018; Molland et al., 2017). While being relatively easy to implement, the empirical results in general question their effectiveness, which is an unexpected result. This ties in with previous observations stating that, for most vessel classes, the measure of reducing a vessel's design speed was not frequently adopted as an immediate response to the environmental policy, despite its theoretical attractiveness (OECD, 2017). Our results overall highlight the potential limits of the emission prevention lever. Hence, we would suggest ship owners not consider emission prevention related to the machinery technology as a main driver to improve vessels' environmental performance, especially not for vessels with relatively poor performance. Due to the moderate impacts, we suggest that this lever could rather complement other technology and operational levers.

2.8 Conclusion

This research provides a thorough assessment of the relationship between technology and operational levers and environmental performance. We argue that a fine-grained estimate of technology and operational levers and their impact on environmental performance can help decision makers better drive the green transitioning process and yield additional theoretical insights. Using the context of a mandatory environmental policy in the maritime industry, we examine two facets of environmental performance, namely, vessels' energy efficiency and regulatory compliance. Previous research and our theoretical lens allow us to specify precise hypotheses about this relationship across the range of environmental performance. Our study identifies that this relationship is complex and that the impacts of technology and operational levers on environmental performance can vary drastically at different levels of performance. Therefore, the empirical insights from our analysis provide decision makers with a deeper understanding of the levers' capabilities (and limitations) to improve energy efficiency and comply with the energy efficiency regulation. The heterogeneous effects also highlight the importance of exploring drivers of performance and their performance implications in a more granular fashion. However, our sample is from a single sector in a narrowly defined context, which naturally sets contextual boundaries for our theoretical argument (Holmström et al., 2009). Future research should build on our results to explore the heterogeneous impacts of performance drivers in other contexts to foster the general theoretical understanding of this phenomenon.

We recognize that our findings are focused on energy efficiency from a design perspective, and they might differ in the case of observed energy efficiency during day-to-day operations. The dynamic nature of network decisions to accommodate operational contingencies might not be adequately captured by aggregating operational energy efficiency across a certain interval (i.e., yearly), and it poses a challenge for data availability and measurability to derive meaningful results. Another limitation is that our study focuses on one pathway of ship owners' decisions to reduce their carbon footprint. Namely, we investigate levers to improve vessels' energy efficiency and regulatory compliance. Hence, we do not consider all facets of the costs and benefits associated with these managerial decisions. For example, we highlighted that high up-front economic costs relative to economic benefits might stress short-term profitability and hinder the adaption of existing vessels and adoption of technologies. Hence, the derived results are unsuitable to make general predictions about how ship owners will make design choices to reach satisficing solutions and cope with environmental policy measures.

Lastly, this research is an early attempt to connect previous analytical research concerned with clean technology adoption in transportation with the — from an industry perspective — highly relevant topic of alternative fuel adoption by providing granular empirical evidence. Due to the low prevalence of vessels' having already adopted alternative fuels, our results concerning this technology lever are rather exploratory and not conclusive. More evidence is needed to quantify more precisely the positive impacts the adoption of alternative fuels can have on environmental performance. In addition, our study does not distinguish between the different adopted alternative fuels in the sample. However, the candidate alternative fuels differ structurally from each other; thus, a detailed analysis of the impacts of different fuels on environmental performance is feasible in the future. We hope that our study can further stimulate empirical research in this direction.

Appendix

Table 2.5: Joint test of equality of all slope parameters

Combination	F-statistic	p-value
Q10 & Q25	70.793	.000
Q10 & Q50	68.251	.000
Q10 & Q75	133.236	.000
Q10 & Q90	60.492	.000
Q25 & Q50	19.565	.000
Q25 & Q75	29.029	.000
Q25 & Q90	49.025	.000
Q50 & Q75	5.468	.000
Q50 & Q90	32.439	.000
Q75 & Q90	32.377	.000
All	87.413	.000

References

Anantharaman, M., Garaniya, V., Khan, F., & Lewarn, B. (2015). Marine engines and their impact on the economy, technical efficiency and environment. *Marine Engineering*, *50*(3), 360–367.

Ančić, I., Theotokatos, G., & Vladimir, N. (2018). Towards improving energy efficiency regulations of bulk carriers. *Ocean Engineering*, *148*, 193–201.

Angell, L. C., & Klassen, R. D. (1999). Integrating environmental issues into the mainstream: An agenda for research in operations management. *Journal of Operations Management*, *17*(5), 575–598.

Anton, W. R. Q., Deltas, G., & Khanna, M. (2004). Incentives for environmental self-regulation and implications for environmental performance. *Journal of Environmental Economics and Management*, *48*(1), 632–654.

Atasu, A., Corbett, C. J., Huang, X., & Toktay, L. B. (2020). Sustainable operations management through the perspective of manufacturing & service operations management. *Manufacturing & Service Operations Management*, *22*(1), 146–157.

Avci, B., Girotra, K., & Netessine, S. (2015). Electric vehicles with a battery switching station: Adoption and environmental impact. *Management Science*, *61*(4), 772–794.

Bromiley, P., & Rau, D. (2014). Towards a practice-based view of strategy. *Strategic Management Journal*, *35*(8), 1249–1256.

Bromiley, P., & Rau, D. (2016). Operations management and the resource based view: Another view. *Journal of Operations Management*, *41*, 95–106.

Bullock, S., Mason, J., Broderick, J., & Larkin, A. (2020). Shipping and the Paris climate agreement: A focus on committed emissions. *BMC Energy*, *2*(1), 1–16.

Cameron, A. C., & Trivedi, P. K. (2005). *Microeconometrics: Methods and applications.* Cambridge University Press.

Carayannis, E. G., Sindakis, S., & Walter, C. (2015). Business model innovation as lever of organizational sustainability. *The Journal of Technology Transfer*, *40*(1), 85–104.

Clarksons. (2019). *World shipyard monitor.*

ClassNK. (2015). *Survey and certification for EEDI and SEEMP required by the amendments to Annex VI of MARPOL 73/78* (Tech. Rep.). Nippon Kaiji Kyōkai. Retrieved from `https://`

www.classnk.or.jp/hp/pdf/tech_info/tech_img/T1048e.pdf

Corbett, C. J., & Klassen, R. D. (2006). Extending the horizons: Environmental excellence as key to improving operations. *Manufacturing & Service Operations Management*, *8*(1), 5–22.

Cyert, R. M., & March, J. G. (1963). *A behavioral theory of the firm.* Englewood Cliffs, NJ.

DNV. (2019). *Assessment of selected alternative fuels and technologies* (Tech. Rep.). DNV. Retrieved from https://www.dnv.com/maritime/publications/alternative-fuel-assessment-download.html

Drake, D. F., & Spinler, S. (2013). OM forum — Sustainable operations management: An enduring stream or a passing fancy? *Manufacturing & Service Operations Management*, *15*(4), 689–700.

EU. (2015). *Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport.* European Union. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015R0757&from=EN

Fitzenberger, B., & Wilke, R. A. (2015). Quantile regression methods. In R. A. Scott & S. M. Kosslyn (Eds.), *Emerging trends in the social and behavioral sciences: An interdisciplinary, searchable, and linkable resource* (pp. 1–18). Wiley.

Fu, W., Kalkanci, B., & Subramanian, R. (2019). Are hazardous substance rankings effective? An empirical investigation of information dissemination about the relative hazards of chemicals and emissions reductions. *Manufacturing & Service Operations Management*, *21*(3), 602–619.

Gavetti, G., Greve, H. R., Levinthal, D. A., & Ocasio, W. (2012). The behavioral theory of the firm: Assessment and prospects. *Academy of Management Annals*, *6*(1), 1–40.

Girotra, K., & Netessine, S. (2013). OM forum—Business model innovation for sustainability. *Manufacturing & Service Operations Management*, *15*(4), 537–544.

Global Maritime Forum. (2020). *Getting to zero coalition.* Retrieved from https://www.globalmaritimeforum.org/getting-to-zero-coalition/

Green Ship. (2020). *The retrofit project* (Report). Green Ship of the Future. Retrieved from https://greenship.org/wp-content/uploads/2020/05/GSF-Retrofit-Project.pdf

Gregor, S. (2009). Building theory in the sciences of the artificial. In *Proceedings of the 4th* *international conference on design science research in information systems and technology* (pp. 1–10).

Holmström, J., Ketokivi, M., & Hameri, A.-P. (2009). Bridging practice and theory: A design science approach. *Decision Sciences*, *40*(1), 65–87.

Horowitz, J. L. (2001). The bootstrap. In J. J. Heckman & E. Leamer (Eds.), *Handbook of econometrics* (Vol. 5, pp. 3159–3228). Elsevier.

Hsuan, J., & Parisi, C. (2020). Mapping the supply chain of ship recycling. *Marine Policy*, *118*.

IMO. (2018). *Adoption of the initial IMO strategy on reduction of GHG emissions.* International Maritime Organization. Retrieved from `https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf`

IMO. (2021). *Energy efficiency measures.* Retrieved from `https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx`

Jacobs, B. W., Singhal, V. R., & Subramanian, R. (2010). An empirical investigation of environmental performance and the market value of the firm. *Journal of Operations Management*, *28*(5), 430–441.

Jaffe, A. B., & Palmer, K. (1997). Environmental regulation and innovation: A panel data study. *Review of Economics and Statistics*, *79*(4), 610–619.

Kagan, R. A., Gunningham, N., & Thornton, D. (2003). Explaining corporate environmental performance: How does regulation matter? *Law & Society Review*, *37*(1), 51–90.

Ketokivi, M. (2016). Point–counterpoint: Resource heterogeneity, performance, and competitive advantage. *Journal of Operations Management*, *41*(1), 75–76.

Ketokivi, M., & Choi, T. (2014). Renaissance of case research as a scientific method. *Journal of Operations Management*, *32*(5), 232–240.

Klassen, R. D., & Whybark, D. C. (1999a). Environmental management in operations: The selection of environmental technologies. *Decision Sciences*, *30*(3), 601–631.

Klassen, R. D., & Whybark, D. C. (1999b). The impact of environmental technologies on manufacturing performance. *Academy of Management Journal*, *42*(6), 599–615.

Kleindorfer, P. R., Singhal, K., & Van Wassenhove, L. N. (2005). Sustainable operations management. *Production and Operations Management*, *14*(4), 482–492.

Koenker, R. (2005). *Quantile regression.* Cambridge University Press.

Koenker, R., & Bassett, G. W. (1978). Regression quantiles. *Econometrica*, *41*(1), 33–50.

Koenker, R., & Bassett, G. W. (1982). Robust tests for heteroscedasticity based on regression quantiles. *Econometrica*, *50*(1), 43–61.

Kovach, J. J., Hora, M., Manikas, A., & Patel, P. C. (2015). Firm performance in dynamic environments: The role of operational slack and operational scope. *Journal of Operations Management*, *37*(1), 1–12.

Kroes, J., Subramanian, R., & Subramanyam, R. (2012). Operational compliance levers, environmental performance, and firm performance under cap and trade regulation. *Manufacturing & Service Operations Management*, *14*(2), 186–201.

Leyva-de la Hiz, D. I., Ferron-Vilchez, V., & Aragon-Correa, J. A. (2019). Do firms' slack resources influence the relationship between focused environmental innovations and financial performance? More is not always better. *Journal of Business Ethics*, *159*(4), 1215–1227.

Lim, M. K., Mak, H.-Y., & Rong, Y. (2015). Toward mass adoption of electric vehicles: Impact of the range and resale anxieties. *Manufacturing & Service Operations Management*, *17*(1), 101–119.

Lindstad, E., & Bø, T. I. (2018). Potential power setups, fuels and hull designs capable of satisfying future EEDI requirements. *Transportation Research Part D: Transport and Environment*, *63*, 276–290.

Linton, J. D., Klassen, R., & Jayaraman, V. (2007). Sustainable supply chains: An introduction. *Journal of Operations Management*, *25*(6), 1075–1082.

Mani, V., & Muthulingam, S. (2019). Does learning from inspections affect environmental performance? Evidence from unconventional well development in pennsylvania. *Manufacturing & Service Operations Management*, *21*(1), 177–197.

Melnyk, S. A., Sroufe, R. P., & Calantone, R. (2003). Assessing the impact of environmental management systems on corporate and environmental performance. *Journal of Operations Management*, *21*(3), 329–351.

MEPC. (2011). *Amendments to the annex of the protocol of 1997 to amend the international convention for the prevention of pollution from ships.* International Maritime Organization. Retrieved from `https://imointernetcdn.azureedge.net/localresources/en/OurWork/Environment/Documents/TechnicalandOperationalMeasures/ResolutionMEPC.203(62)`

.pdf

MEPC. (2013). *Interim guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions.* International Maritime Organization. Retrieved from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/MEPC.1-CIRC.850-REV2.pdf

Molland, A. F., Turnock, S. R., & Hudson, D. A. (2017). *Ship resistance and propulsion.* Cambridge University Press.

Murali, K., Lim, M. K., & Petruzzi, N. C. (2019). The effects of ecolabels and environmental regulation on green product development. *Manufacturing & Service Operations Management*, *21*(3), 519–535.

Nohria, N., & Gulati, R. (1996). Is slack good or bad for innovation? *Academy of Management Journal*, *39*(5), 1245–1264.

OECD. (2017). *Analysis of selected measures promoting the construction and operation of greener ships* (Report). Organisation for Economic Co-operation and Development. Retrieved from https://www.oecd.org/industry/ind/analysis-of-measures-promoting-greener-ships.pdf

Parzen, M., Wei, L., & Ying, Z. (1994). A resampling method based on pivotal estimating functions. *Biometrika*, *81*(2), 341–350.

Plambeck, E. L. (2013). OM forum— Operations management challenges for some "cleantech" firms. *Manufacturing & Service Operations Management*, *15*(4), 527–536.

Plambeck, E. L., & Taylor, T. A. (2013). On the value of input efficiency, capacity efficiency, and the flexibility to rebalance them. *Manufacturing & Service Operations Management*, *15*(4), 630–639.

Porter, M. E., & Van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives*, *9*(4), 97–118.

Powell, J. L. (1991). Estimation of monotonic regression models under quantile restrictions. *Nonparametric and semiparametric methods in Econometrics*, 357–384.

Simon, H. A. (1955). A behavioral model of rational choice. *The Quarterly Journal of Economics*, *69*(1), 99–118.

Simon, H. A. (1956). Rational choice and the structure of the environment. *Psychological Review*, *63*(2), 129.

Simon, H. A. (1991). The architecture of complexity. In *Facets of systems science* (Vol. 7, pp. 457–476). Springer.

Simon, H. A. (1996). *The sciences of the artificial* (3rd ed.). MIT Press.

Skinner, W. (1969). Manufacturing-missing link in corporate strategy. *Harvard Business Review*, *50*(3), 136–145.

Sroufe, R. (2003). Effects of environmental management systems on environmental management practices and operations. *Production and Operations Management*, *12*(3), 416–431.

Stubbs, W., & Cocklin, C. (2008). Conceptualizing a "sustainability business model". *Organization & Environment*, *21*(2), 103–127.

T&E. (2017). *Statistical analysis of the energy efficiency performance (EEDI) of new ships* (Tech. Rep.). Transport and Environment. Retrieved from `https://www.transportenvironment.org/discover/statistical-analysis-energy-efficiency-performance-eedi-new-ships/`

Wang, W., Ferguson, M. E., Hu, S., & Souza, G. C. (2013). Dynamic capacity investment with two competing technologies. *Manufacturing & Service Operations Management*, *15*(4), 616–629.

Wiengarten, F., Fan, D., Pagell, M., & Lo, C. K. (2019). Deviations from aspirational target levels and environmental and safety performance: Implications for operations managers acting irresponsibly. *Journal of Operations Management*, *65*(6), 490–516.

Zhu, Q., & Sarkis, J. (2004). Relationships between operational practices and performance among early adopters of green supply chain management practices in Chinese manufacturing enterprises. *Journal of Operations Management*, *22*(3), 265–289.

Chapter 3

The impact of an emission trading scheme on a ship owner's investment decisions

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Abstract

Regulatory authorities are eager to foster the green transition of maritime transport and have set ambitious emission reduction targets for the maritime industry. A possible policy instrument to reduce emissions by encouraging the adoption of clean technologies is regulation based on an ETS, which puts a global cap on carbon emissions and distributes emission licenses. This paper focuses on how a ship owner's investment policy is shaped under an ETS regulation, and the impact of an environment with increased uncertainties on this policy. We investigate the effects of a maritime ETS designed to reach industry-wide emission targets on a ship owner's investment decisions, which are subject to uncertainty concerning pollution and regulatory risks. The results indicate that the magnitude of the investment increases in the ship owner's pollution level, and that the optimal investment policy must consider the trade-off between the costs of installing technological measures and expected future cost reductions through higher carbon efficiency. More importantly, we show that increased uncertainty in the demand for pollution and regulatory risks has a substantial impact on a ship owner's costs of regulation and the value of managerial flexibility. We close by discussing the implications for regulatory authorities aspiring to incentivize the adoption of clean technologies to decarbonize the maritime industry.

3.1 Introduction

Reducing carbon emissions across industries to combat the climate crisis is a top priority for the international community and led to important global treaties, such as the Paris Climate Change Agreement of 2015. The main climate change goal stipulated in the Paris Agreement is to limit global warming to 1.5–2.0 degrees Celsius. However, the fifth evaluation report of the Intergovernmental Panel Climate Change (IPCC, 2014) concludes that to reach the 2 degrees Celsius goal, global greenhouse gas (GHG) emissions must be reduced by 40–70% until 2050[1] and be near or below zero until 2100. The maritime industry is an example of an industry at the center of the global climate crisis debate. Despite being a key enabler of international trade and economic growth, the maritime industry contributes approximately 2.8% of annual global GHG emissions. Even more concerning, maritime CO_2 emissions are expected to rise between 50% to 250% if no actions are taken (Smith et al., 2014). This stands in sharp contrast to the climate change goal of the Paris Agreement, and the maritime industry is in urgent need of a green transition towards decarbonized international shipping.

To address this issue, policy makers have formulated ambitious commitments to the green transition process of the maritime industry to support global climate change goals. In 2018, the International Maritime Organization (IMO), the chief regulatory authority for the industry, stated its vision to reduce the GHG emissions of international shipping and to phase them out as soon as possible in its initial IMO GHG strategy. The level of ambition in the strategy is exemplified by the set emission reduction targets for the industry, mandating a reduction of the total annual GHG by at least 50% by 2050 compared to 2008 (IMO, 2018). Hence, policy makers aspire to reduce GHG emissions and, in particular, carbon emissions from international shipping over time with the vision of decarbonized shipping. A key lever to meet these ambitious commitments is investments in technologies, which mitigate the negative impacts of maritime transport on the climate, by the industry. We refer to these technologies as clean technologies throughout the paper. Due to their importance for the green transition of maritime transport, the IMO seeks to incentivize their adoption through their policy instruments (IMO, 2018).

[1] The baseline year for the calculation is 2010.

Market-based measures (MBMs), such as an emission trading scheme (ETS), appear a promising regulatory instrument to incentivize clean technology adoption and reach mandated emission reduction targets. In contrast to other policy measures, measures based on MBMs provide market incentives by pricing carbon emissions to incentivize the adoption of clean technologies for firms and, in turn, to reduce their carbon emissions (see section [3.2] for a discussion of the policy measures in the maritime industry). A regulation based on an ETS seems suited to the context of an industry's transition process due to its focus on the quantity of carbon emissions and, thus, its direct relation to the industry-wide emission reduction targets. We remark that in this context, examining the impact of an industry-wide ETS on firms' investment decisions concerning clean technologies requires an intertemporal and long-term perspective. This has implications for the investment decisions of firms operating in an uncertain environment, as there might be value in deferring investments until uncertainty resolves (Dixit & Pindyck, 1994). To illustrate, a common concern with a maritime ETS is that the inherent carbon price uncertainty makes the decision to invest in clean technologies and associated payoffs less certain (Kachi et al., 2019; Psaraftis et al., 2021). This might significantly curb incentives to invest in clean technologies for ship owners and lead to a passive managerial approach to cope with the policy.

However, the long-term implications of an ETS designed to reach industry-wide reduction targets for the investment decisions of firms subject to an uncertain environment are not yet well understood. The previous literature has examined how an ETS (and/or a carbon taxation scheme) influences the technology choice of regulated firms (see, e.g., Drake et al., 2016; Krass et al., 2013; Krysiak, 2008). Here, the focus often lies on the specific choice between different technologies under the respective regulation schemes. However, an equally important issue to understand is how the investment policy and path over the whole regulation horizon would be shaped under an ETS. Another string of literature is concerned more explicitly with green technology investments under uncertainty over a time horizon, and the corresponding value of flexibility arising from the uncertain environment (see, e.g., Bøckman et al., 2008; Boomsma et al., 2012; Wang et al., 2013). In these models, resource price (e.g. electricity price) and permit price uncertainties are the most commonly investigated sources of uncertainty. However, how other sources of uncertainty, especially around the regulator's design choices related to the industry-wide reduction targets when implementing the ETS, affect the value of flexibility, and the incentive to invest in technology is not yet clear.

This study aims to address these two gaps in the literature by modeling the effects of an ETS designed to decarbonize the industry on ship owners' investments in clean technologies over a finite time horizon. This paper focuses on how the investment policy over time would be shaped under an ETS regulation and the impact of an environment with increased uncertainties on this policy. We shift the focus from common permit price and resource price uncertainties to a different set of uncertainties, which are of major importance in the context of a green transition in an industry. Our study aims to further deepen the knowledge of the value of managerial flexibility under an ETS when a ship owner faces various regulatory and demand uncertainties. Furthermore, a notable feature of our model is that the auction price for licenses is derived endogenously through an efficient auction mechanism in every review stage, and this deviates from the common theoretical assumption of exogenous permit prices.

The contribution of this study is twofold. First, we derive the ship owner's optimal investment policy under an ETS regulation, with a focus on the ship owner's value to manage actively the investment decision over the regulation horizon. We characterize the policy and describe the investments in clean technologies over time in an industry-wide ETS. The second contribution is to show how the costs of regulation and the value of managerial flexibility are affected by an increase in different sources of uncertainty. In particular, we consider two main sources of uncertainty: demand uncertainty influencing a ship owner's demand for pollution and regulatory uncertainties about the target emission level for the ship owner and associated penalties for missing this target. We show that a higher uncertainty influences the optimal investment policy, as it increases both the expected costs of regulation and the value of managerial flexibility. Hence, the incentive to invest in clean technologies is also increasing, and investment levels are higher under the new optimal investment policy.

The remainder of the paper is structured as follows. Section 2 provides a brief introduction to the existing and considered regulations aimed at reducing carbon emissions in the maritime industry.

Section 3 gives an overview of the related literature. In section 4, the auction mechanism efficiently allocating the licenses and its appealing features are described. Section 5 presents the dynamic cost minimization problem of a ship owner facing carbon regulation in a stochastic environment and derives the optimal investment policy and the value of managerial flexibility. Afterwards, section 6 deals with investigating the effects of increased variability in the pollution demand and regulatory uncertainties on the investment decision. Section 7 concludes this research by discussing its main results and implications for policy makers designing an ETS mechanism.

3.2 Regulation in the maritime industry

Current regulatory measures to reach the vision and ambition stipulated in the IMO GHG Strategy focus on the energy efficiency of vessels. These measures relate to the technical energy of the ship design and the operational energy efficiency of ship operations. To illustrate, consider the case of the Energy Efficiency Design Index (EEDI) regulation, the main policy measure focusing on the technical energy efficiency in the industry. The EEDI regulation is a mandatory measure prescribing minimum performance standards for newly built vessels, and it seeks to incentivize continuously the development and adoption of clean technologies by tightening the minimum performance standards over time. The Ship Energy Efficient Management Plan (SEEMP) is a monitoring tool for a vessel's operational energy efficiency, and it aims to provide guidance and best practices for fuel-efficient ship operations to shipping companies (MEPC, 2009). Current efforts at the IMO revolve around strengthening these two frameworks for energy efficiency, and for this purpose, two additional measures will enter force in 2023 (MEPC, 2021). On the technical side, the Energy Efficiency Design Index for Existing ships regulation is intended to be the EEDI counterpart for existing vessels. On the operational side, the Carbon Intensity Index is intended as a mandatory rating scheme building on the SEEMP, which prescribes a minimum rating for ships' annual operational efficiency and tightens the rating thresholds over time.

The aforementioned measures utilize the regulatory strategy of top-down policies based on mandatory performance standards, which are defined and enforced by the regulative authority. We remark that measures based on this rationale will most likely not reach the industry-wide reduction targets. One reason is that they could distort incentives for low-cost, short-term alternatives adopted by ship owners, who would not have to face the immediate social costs of their pollution (Psaraftis, 2018). MBMs are an alternative strategy marine policy makers can utilize, as they provide market incentives to reach the aforementioned vision and level of ambition. MBMs apply the "polluter's pay" principle by making shipping companies internalize the social costs of their carbon emissions through carbon pricing. The pricing of emissions would raise the opportunity costs of carbon emissions for shipping companies and, thus, provide economic incentives to adopt clean technologies to reduce carbon emissions. Hence, MBMs appear one of the most promising approaches policy makers have at their disposal to meet the industry-wide reduction targets outlined in the IMO GHG Strategy.

In the IMO GHG strategy, MBMs are considered potential measures implemented in the future, and multiple proposals have been discussed since 2010 at the IMO (for a recent overview, see Lagouvardou et al., 2020). This research focuses on regulation based on an ETS for the maritime industry. In an ETS, there is ex ante a cap on emissions, and emission licenses are distributed through a mechanism to regulated firms (e.g., grandfathering licenses or auctions). Furthermore, licenses can be traded on a secondary market, allowing actors to buy permits for the market price or sell excess licenses. Recently, the European Commission formalized their intention to include the shipping sector into the European Union Emission Trading Scheme (EU-ETS) from 2023 over a transition period of three years (EC, 2021).

While an important signal to the maritime industry, the suitability of a regional approach to regulate carbon emissions in a global industry appears questionable. Besides only covering a fraction of the industry's global carbon emission, the regional scope bears the risk of regulated firms shifting their activities to a region in which carbon emission charges are absent or lower, a phenomenon known as "carbon-leakage" (Huang et al., 2021). Previous research has already suggested that a global ETS for the maritime industry is more feasible than regional solutions (Gu et al., 2019). Further, if the maritime industry is included alongside other sectors in an ETS regulation, the overall cap on carbon emissions has no direct relation to the industry-wide emission reduction goals (T&E, 2020). Hence, policy makers cannot directly assess how well the ETS supports the green transition of the maritime industry. Therefore, the setup of this research and derived policy implications focus on a global ETS for the maritime industry designed to reach the level of ambition stipulated in the IMO GHG Strategy.

3.3 Related literature

This paper is mainly connected to two streams in the literature: real option theory and sustainable technology choice in environmental economics and sustainable operations management (SOM). Real option theory is concerned with valuing the flexibility inherent in many operations decisions (for a recent review, see, e.g., Trigeorgis & Tsekrekos, 2018). Through this lens, investment timing problems when facing uncertainty lead to an option value of waiting to invest (irreversibly) in technology. Hence, a central result of these studies is to identify a threshold value separating the region to invest from the region to wait to invest.

Kort et al. (2010) report that payoff uncertainty makes a lump-sum investment more attractive compared to a flexible, stepwise investment strategy. However, they assume that the single-step investment is cheaper due to economies of scale, which is in contrast to our assumption of convex increasing installment costs per review stage. Another study examined the investment timing and optimal capacity of small hydropower plants when facing inter alia electricity price uncertainty (Bøckman et al., 2008). They identify a unique electricity price limit below which it is optimal to defer investments and above which to invest according to the function of optimal size. In a study investigating a municipality's choice to invest in a flexible waste management program, Di Corato and Montinari (2014) report that the value of operational flexibility may outweigh the investment costs when facing recycling price uncertainty. There are also some noteworthy studies attempting to link real option theory to MBMs. For instance, Lukas and Welling (2014) model green investments in a sequential bargaining game under an ETS. Their main results are that a firm conducting investments independent of their supply chain will conduct an economically efficient investment as soon as the permit price exceeds the threshold value. However, the investment level will not be efficient from a ecological viewpoint. Furthermore, the outcome will become less economically and ecologically efficient with every additional chain of the supply chain involved in the investment decision. Boomsma et al. (2012), in turn, report that a renewable energy certificates support scheme incentivizes larger investments compared to feed-in tariffs when an investment has been undertaken.

The second stream of literature this study is linked to is the sustainable technology choice literature exploring the adoption of clean technologies. While there is no clear delineation between technology choice research in SOM and environmental economics, the scope is usually different. SOM focuses more on a firm's objectives and decision process (Drake & Spinler, 2013), while environmental economics tries to understand the interactions of technology choice and environmental policy over a time horizon (Popp et al., 2010). In addition, these two different scopes lead to differences in the underlying assumptions of the respective models. Our proposed model has features related to both streams of literature. The departing point of an efficient auction mechanism to price carbon emissions, providing economic incentives to adopt clean technologies, relates to one of the central concepts of environmental economics. Further, our focus on a set of uncertainties pertinent to an ETS regulation in the specific empirical setting is related to the research focus of SOM.

In these studies, the main source of uncertainty concerns the permit price in the trading scheme, and often the supply of licenses (and the permit price) is assumed exogenous to the models. For a broader literature review of the sustainable technology choice literature in SOM, please refer to Plambeck (2012), and in environmental economics, please refer to Popp et al. (2010). Krass et al. (2013) examine the economic impact of environmental taxation on a firm's technology choice and the firm's response to different levels of taxation. A related study by Drake et al. (2016) reports that the firm's expected profit is greater under an ETS compared to a fixed emission taxation level due to permit price uncertainty. Another result is derived by Chen and Tseng (2011) in their study examining a coal plant owner's decision to invest in clean technologies when facing regulation based on an ETS and environmental taxation. In this paper, higher levels of permit price uncertainty are likely to trigger earlier investments to hedge against carbon risk, and an ETS triggers investments at a lower level of carbon prices compared to fixed tax levels. In a study investigating the effect of permit price uncertainty caused by abatement cost uncertainties on technology investments under an ETS and environmental taxation, Zhao (2003) reports a different result. According to him, abatement cost uncertainties reduce the incentive to invest in both schemes. However, the adverse effect is greater under carbon taxation than under an ETS.

3.4 An auction mechanism for efficient license allocation

Externalities, such as emissions, arise when firms operate. To reduce emission levels, we consider that a regulator puts forward an ETS that allocates licenses for firms (ship owners) to operate and incentivizes the emission level to be reduced. Ship owners' demand to operate can be seen as a demand for pollution, and there is a price to operate (and pollute). Thus, by coping with such an ETS, ship owners face a cost to reduce emission levels and investing in clean technologies is one way to do so. To investigate how the investment in clean technology is shaped under an ETS regulation, we first introduce an auction mechanism to capture the allocation of licenses at every decision stage. Our formulation uses, as a departing point, the auction mechanism proposed by Montero (2008). It is characterized by a uniform price format and has two distinct features, namely, endogenous supply of licenses and payback policy. A consequence of such features is that the resulting auction guarantees the regulator's objective to be the same as the one faced by ship owners. We first establish some notation and discuss the static case for a single ship owner that operates in such a market. We then, in the next section, move to the dynamic case, in which investments are made to reduce the total cost to operate throughout the regulation horizon.

3.4.1 Notation and properties

Consider a ship owner who is subjected to a single period auction for carbon licenses at review stage t and who does not have the option to invest in clean technologies. The ship owner is assumed to have an inverse demand function for pollution of the form $P_t(x)$ with $P_t'(x) < 0$, and x is the ship owner's pollution level monitored by the regulator. Further, consider $P_t(\cdot)$ to be only known by the ship owner. In line with recent approaches to quantify the damages resulting from a marginal increase in carbon emissions (Greenstone et al., 2013; Nordhaus, 2017; Pizer et al., 2014), we model the damages to society as a function of the pollution level using a social cost curve $D(x)$ with $D(0) = 0$, $D'(x) > 0$ and $D''(x) \geq 0$. The convex shape of the social cost function reflects the fact that pollution damage is compounding, and high levels are exponentially less feasible to society. Furthermore, $D'(x)$ can be interpreted as the regulator's supply of licenses for pollution. We model the abatement costs of the ship owner by $C_t(x) = \int_x^{x_t} P_t(z)dz$. This function represents the cost of reducing emissions by the ship owner in the presence of regulation from a baseline value x_t to a lower level x, where x_t is the ship owner's pollution demand at stage t in the absence of regulation. Note that $P_t(x) \equiv -C_t'(x)$ and $P_t(x) = 0$ for all $x \geq x_t$. There is a minor difference in our notation from Montero (2008), who uses x^0 for the demand of pollution in the absence of regulation. The regulator's objective is to minimize the sum of abatement costs and social damages from emissions,

$$min \quad C_t(x) + D(x). \tag{3.1}$$

The social optimal or first-best level of pollution in review stage t satisfies,

$$P_t(x^*) = D'(x^*). \tag{3.2}$$

Because the regulator cannot directly impose this first-best solution, as $P_t(\cdot)$ is endogenous to the ship owner, the use of a payback policy is proposed to make the ship owner reveal their private information to the regulator (for more details, see Montero, 2008).

3.4.2 The static auction mechanism

Once the ship owner is informed of the auction rules, they are asked to bid a non-increasing inverse demand schedule $\hat{P}_t(x)$. Using this information, the regulator clears the auction by determining the price per license p_t and the number of licenses l_t as,

$$p_t = \hat{P}_t(l_t) = D'(l_t). \tag{3.3}$$

Thus, the ship owner receives l_t licenses at price p_t. Montero (2008) proposes a payback policy $\gamma(l_t)$ for the ship owner to submit their true inverse demand $P_t(x) \equiv -C_t'(x)$ to the regulator and, consequently, implement the first-best outcome. Therefore, the ship owner gets back a fraction $\gamma(l_t)$ of their payments —- i.e., the payback by the regulator is $\gamma(l_t)p_tl_t$. Thus, considering the payback policy $\gamma(l)$, $0 \leq \gamma(l_t) \leq 1$, the ship owner must find the inverse demand schedule $\hat{P}_t(l_t)$ that solves the following problem

$$min \quad C_t(l_t) + \big(1 - \gamma(l_t)\big)\, p_t\, l_t \quad ; subject\ to \quad p_t = \hat{P}_t(l_t) = D'(l_t). \tag{3.4}$$

As shown by Montero (2008), the regulator's problem turns out to be setting $\gamma(l)$ as

$$\gamma(l_t) = 1 - \frac{D(l_t)}{D'(l_t) l_t}. \tag{3.5}$$

Considering $D'(l_t)$ a non-decreasing function of l_t, Montero (2008) characterizes the final price paid by the ship owner for each license as $\big(1 - \gamma(l_t)\big)\, p_t \leq D'(l_t)$. Plugging (3.5) back into the ship owner's cost minimization problem (3.4), one can see that such an auction mechanism induces the firm to minimize its cost according to the regulator's objective (3.1) by minimizing the sum of abatement costs and pollution damages, i.e., $C_t(l_t) + D(l_t)$. In other words, the auction mechanism makes the firm bear the full cost of its pollution damages and achieves the first-best pollution level.

3.5 Dynamic investment in clean technologies

When assessing an investment in clean technologies, ship owners faces the trade-off between the cost associated with acquiring and installing the technology and the benefits associated with expected cost savings given that the firm is subjected to the ETS. Understanding the potential consequences is of interest, as technology investments are crucial from the perspective of both the regulator and ship owner. The regulator wants to incentivize technological change through regulation, as it is one main lever to reduce industry emissions and reach emission reduction targets. Furthermore, technological investments are important for the ship owners, as they are the main measure that can reduce their demand for pollution and reduce their costs to operate under such a regulatory environment.

The static mechanism, described in the previous section, yields no insight into how such a regulation influences the ship owner's investment in technology measures over time. As such, we introduce a model that captures the choice faced by ship owners who need to comply with an ETS designed to reach industry-wide emission reduction targets over a fixed time horizon. During this time horizon, the ship owner must comply with the expected emission level and has the recurring option to invest in clean technologies. Both regulators and ship owners face uncertainties with respect to the ship owner's demand for pollution and the regulatory framework. Hence, investing to reduce emissions can be seen as a dynamic problem, fraught with uncertainty, in which ship owners must consider the latest information and exploit the best option to cope with regulation. Such a situation, where decisions are made in multiple review stages in an uncertain environment, can be captured by the dynamic programming approach. Next, we introduce our model to investigate the ship owner's decision over time under demand and regulatory uncertainties.

3.5.1 A ship owner's investment decision

Assume that due to the operations of its fleet, a ship owner requires a certain level of pollution (carbon emissions) to fulfill the demand for transportation services. In our model, this need for pollution is reflected by the ship owner's demand for pollution in the absence of regulation $x_t, x_t \in X \geq 0$. By restricting x_t, we assume that demand cannot take negative values. Consider now that the ship owner is affected by an ETS regulation that aims towards a target emission level c at the end of the regulation horizon T and has the option to invest in clean technologies in every review stage t, $t = 0, 1, .., T-1$. How well this objective is reached depends on the ship owner's terminal demand for pollution $x_T \in X$. The ship owner has two possible choices in every review stage t, which impacts their demand for pollution in the next stage $t+1$: invest in clean technologies or defer the investment. The evolution of demand for pollution over time is captured by the system equation

$$x_{t+1} = f_t(x_t, i_t, \omega_t) = \begin{cases} x_t - s i_t + \omega_t & i > 0 \\ \\ x_t + \omega_t & i = 0, \end{cases} \tag{3.6}$$

where $i_t \in I_{x_t} = [0, x_t/s]$ states the investment level in technological measures ($i > 0$) in decision period t, and it is chosen from the set of admissible controls in state x_t. Furthermore, s is the increase in carbon efficiency per unit of technology, $s > 0$, and $\omega_t \in \Omega$ is the uncertain change in the ship owner's pollution demand in stage t. If the ship owner decides to wait and not invest in technological measures, reducing the demand for pollution, its demand at the next stage is expected to be the same as in the current stage, plus some uncertainty. On the other hand, if they decide to invest, it decreases their demand for pollution by increasing carbon efficiency si_t, plus some uncertainty.

The uncertainty of the ship owner's pollution demand is captured by a random variable ω_t, which represents the resolution of internal and external uncertainty at every review stage. Similar to Santiago and Vakili (2005), we consider that ω_t captures the "pure" uncertainty in the sense that there is no expected known "drift" in the resolution of uncertainty at each decision stage. Specifically, we consider ω_t a random variable with mean zero ($E[\omega_t] = 0$) and finite variance σ_ω, which are assumed independent per stage. For instance, ω_t could reflect macroeconomic developments affecting the whole shipping industry or idiosyncratic strategic and operational decisions by the ship owner affecting their pollution demand. Demand uncertainty causes the demand for pollution to drift between stages, and an increase in uncertainty can be expressed by an increase in the variance σ_ω.

Investing in clean technologies to increase carbon efficiency comes at a price. When choosing $i_t > 0$, the ship owner must consider the total net costs v of the measure[2] and installment costs $F(i_t)$. To adjust a ship owner's fleet to the new emission technology, we assume the installment cost at every review stage t to be convex, $F'(i_t) > 0$, $F''(i_t) > 0$ and $F(0) = 0$. For instance, the convex installment costs could reflect the fact that rapid and major investments in clean technologies are costly for the ship owner through downtimes of the fleet and operational adjustments. Furthermore, independent of the choice of investment, in line with Montero (2008), the ship owner incurs the costs of regulation $C_t(l_t, x_t) + D(l_t)$ due to submitting their (true) demand schedule $P_t(\cdot)$ and the regulator clearing the auction according to (3.3).

However, given the inherent uncertainty of pollution demand x_t, we consider the ship owner's demand for pollution, over the upcoming review stage, to be a function of the number of permits,

[2] In line with Psaraftis (2016), chapter 8, one can consider the total expected costs of a measure as the net difference in annualized costs attributed to the measure, including fuel costs.

its actual demand, and the investment in clean technology. Furthermore, at stage t, when assessing whether investments in clean technologies should be made, we consider the ship owner's demand for pollution vis-à-vis their expected cost reduction at the next stage (i.e., $x_t - s * i_t$), the social damage caused by pollution $D(l_t)$, and the abatement costs a firm incurs to reduce emissions $C_t(l_t, x_t)$. We consider $C_t(l_t, x_t)$ is characterized by $\frac{\delta(C_t(l_t,x_t)}{\delta x_t} > 0$ and $\frac{\delta^2(C_t(l_t,x_t)}{\delta x_t^2} > 0$ at every review stage t. Note that the convex increasing assumption of $C_t(l_t, x_t)$ captures that the higher the x_t, the higher the cost to operate with l_t licenses, and, intuitively, states that large emission reductions lead to exponential abatement costs for the ship owner. Hence, the total cost incurred by the ship owner $G_t(x_t, i_t)$ in every stage t is defined as

$$G_t(x_t, i_t) = \begin{cases} D(l_t) + C_t(l_t, x_t) + vi_t + F(i_t), & \text{if investing} \\ \\ D(l_t) + C_t(l_t, x_t), & \text{if waiting.} \end{cases} \tag{3.7}$$

Once the regulation target horizon T is reached, the regulator imposes a penalty on the ship owner in case its demand x_T exceeds the defined target emission level c. We consider the penalty to be convex increasing in the x_T. In addition, we assume the target emission level c, $c \in Z \geq 0$, to be a random variable with finite mean $E[c] = \mu_c$ and finite variance σ_c, which captures the uncertainty of the regulatory requirement. The penalty is defined as

$$G_T(x_T) = \begin{cases} 0, & \text{if } x_T \leq c \\ \\ (x_T - c)^\delta, & \text{if } x_T > c, \end{cases} \tag{3.8}$$

where δ captures the uncertainty concerning the regulatory intensity. We consider it a random variable, $\delta \in \Delta = (1, M]$ with finite mean $E[\delta] = \mu_\delta$ and finite variance σ_δ. Furthermore, we consider c and δ independent. The convex shape of the penalty function reflects the desire of the regulator to punish large deviations from target emission levels (emission reduction goals) and to incentivize investments in clean technologies through the regulation mechanism [3].

[3]To ensure the convex properties of the penalty function, we assume that $(x_T - c) > 1$ throughout our analysis. This assumption considers that (very) small deviations from the target emission level will not be tracked and thus will not be sanctioned.

3.5.2 Regulation costs and optimal investment policy

The ship owner seeks to minimize the costs over the regulation horizon by choosing an investment policy $\pi = \{\mu_0, \mu_1, ..., \mu_{T-1}\}$, where μ_t is an investment decision rule at stage t and is a function of the pollution demand, and $\mu_t(x_t) = i_t$ such that $\mu_t(x_t) \in I_{x_t}$ for all $x_t \in X$. Thus, the expected costs for a ship owner with an initial demand for pollution x_0 under policy π are as follows

$$J_\pi(x_0) = E\left\{ G_T(x_T) + \sum_{t=0}^{T-1} G_t\big(\, x_t,\, \mu(x_t),\, \omega_t\,\big) \right\}. \tag{3.9}$$

The expectation is taken over the random variables ω_t, δ, and c. Furthermore, the decision to invest or wait in every decision stage t depends on whether the investment costs incurred by the ship owner at t are offset by expected cost savings in future review stages $\{t+1, ..., T-1\}$ and a lower penalty at the terminal stage T. This trade-off between present costs and future benefits is captured by the dynamic programming equation

$$J_t(x_t) = \min_{i_t} \left\{ D(l_t) + C_t(l_t, x_t) + v i_t + F(i_t) + \frac{1}{1+r} E\left[\, J_{t+1}(x_{t+1}) \,\right] \right\}, \tag{3.10}$$

where, at the terminal stage T, $J_T(x_T) = G_T(x_T)$ holds and $J_t(x_t)$ is the so-called cost-to-go function of the regulation. We turn our focus to the behavior of an optimal policy $\pi^* = \{\mu_0^*, \mu_1^*, ..., \mu_{T-1}^*\}$, from the set of admissible policies Π. The optimal policy is one that minimizes the total expected costs $J_\pi(x_0)$, defined as,

$$J^*(x_0) = \min_{\pi \in \Pi} J_\pi(x_0). \tag{3.11}$$

First, it is of interest to know whether the monotone nondecreasing nature of $J_T(x_T)$ is inherited by all $J_t(x_t)$. If such a property holds, ship owners would be able to manage better investments and cash flows over the regulation horizon. We show that the cost-to-go functions are monotone nondecreasing in x_t. Using this fact, we then show that the optimal policy π^* is also nondecreasing in x_t. Based on this, the optimal decision rule μ_t^* at every stage t in every state x_t is specified. The insights into the optimal policy π^* and optimal investment decision rules μ_t^* are summarized in Theorem 1.

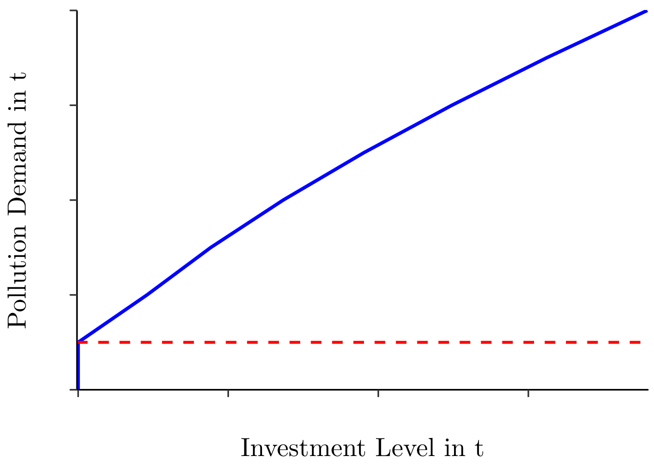

FIGURE 3.1: Illustration of optimal investment decision rule in stage t

Theorem 1: *At review stage t, the optimal policy π^* is monotone nondecreasing in x_t. Furthermore, the optimal decision rule μ_t^* in review stage t is characterized by a control limit b_t, such that it is optimal to choose option "waiting" if $x_t \leq b_t$ and to choose option "investing" if $x_t > b_t$. Moreover, in the region of $x_t > b_t$, the optimal investment i_t^* is increasing in x_t.*

The shape of the decision rule is depicted in Figure (3.1), where the red dashed line indicates the threshold value b_t separating the regions of "waiting" and "investment." Further, the investment path over the finite time horizon is characterized by a downward sloping curve, as illustrated in Figure (3.2), which is based on the fact that the earlier a unit of investment is deployed, the higher the expected cost reductions will be over the regulation horizon. Hence, investment levels are decreasing over time such that the regulation cost savings are maximized. Before assessing the impact of increased uncertainty on this policy, we focus on the value of managerial flexibility, which captures the benefit for the ship owner to react proactively to an ETS and invest in clean technologies throughout the regulation horizon.

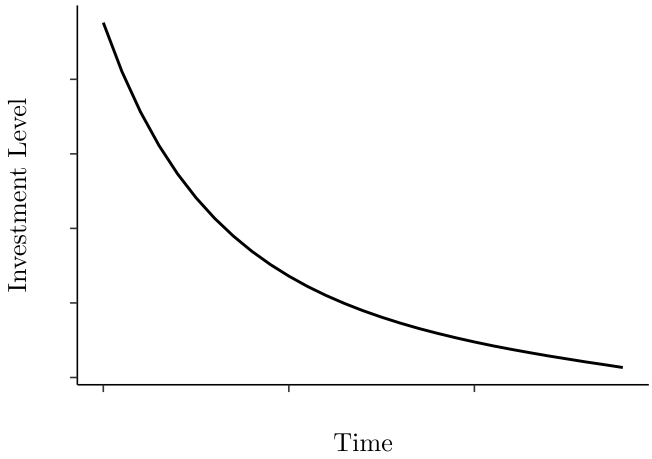

Figure 3.2: Illustration of investment path over time horizon

3.5.3 Value of managerial flexibility

Even though in the long run, one of the main regulatory objectives is to reduce carbon emissions through investments in clean technologies, it is unclear whether a ship owner would harvest any benefit from investing in them. One alternative for the ship owner is to "just wait" and face the consequences once the regulatory requirement is implemented and the penalty is applied to those who do not comply. In other words, from a ship owner's perspective, it might be worthwhile to face the ETS regulation passively and choose the option "waiting" throughout the regulation horizon. For instance, due to the uncertain environment, it might be risky for the ship owner to commit to costly technology investments and potentially over-invest. Thus, a superior management strategy for the ship owner could be simply to adopt a passive approach and resort to short-term, logistics-based measures. Moreover, if ship owners became passive to a certain policy measure, it would imply that the regulation scheme does not directly stimulate investments in clean technologies and, hence, it is of limited value for the green transition process of the industry.

We capture the ship owner's benefit by assessing the value of managerial flexibility, which we consider the difference between the passive value of a project (i.e., no investment over the regulation horizon) and the active value of the project. We denote the costs of a ship owner committing to passive management at stage t by $PV_t(x_t)$, as the ship owner bears the passive value of the regulation costs given the pollution demand, x_t, under this scenario. Active management, in turn, defines the possibility for the ship owner to choose flexibly the investment level at every review stage. For instance, the ship owner's benefit at stage 0, in terms of cost savings, for investing in clean technologies is captured by the value of managerial flexibility, denoted as $PV_0(x_0) - J_0(x_0)$.

It can be shown that, when "investing" and "waiting" are the two options available for management, the terminal state and costs of the ship owner will be lower compared to management sticking to the option "waiting" (passive management) across the regulation horizon (see Proposition 5.3 in the appendix). The lower terminal state implies an option value of managerial flexibility. Hence, there is value in the form of reduced costs for the ship owner to manage actively the investment in clean technologies over the regulation horizon. This is further illustrated by the fact that the investment decision in every review stage depends on the currently available information and expectations about the future. Therefore, the decision is independent of past investments and only considers the trade-off between costs today and expected cost reductions, as illustrated by Proposition 5.3. In short, ship owners should make use of the value of managerial flexibility to minimize their regulation costs instead of ex ante committing to a passive strategy due to the inherent uncertainty that characterizes the decision problem.

3.6 Impact of an environment with increased uncertainties

We now shift our focus to the impact of increased variability/uncertainty on the cost of regulation and the value of managerial flexibility. Assessing the impact of an environment with increased uncertainty is important in our setting, as we consider a dynamic investment decision problem over a long time horizon. We will focus on some main sources of uncertainty in the context of an ETS designed to reach emission reduction targets in an industry. In particular, we examine the impact of uncertainty concerning pollution demand, regulatory requirement, and regulatory penalty intensity. It is of interest to understand how these different risk sources influence the decision problem concerning investments in clean technologies. Such an analysis can also yield important policy implications by shedding light on how the ship owner's incentive to invest under the industry-wide ETS is affected by certain policy design choices and by changes in the uncertainty of the environment.

3.6.1 Increased uncertainty in regulatory intensity

In this subsection, we examine the impact of increased uncertainty in regulatory intensity and its impact on the value of investing in clean technologies. Even though policy makers have formalized their ambitious commitments to the green transition process, it is unclear what the appropriate consequences should be if the emission reduction targets are not met. From an economics perspective, the policy maker is deemed to incorporate certain consequences, such as a monetary penalty in a maritime ETS mechanism at the end of the regulation horizon to make its commitment to the defined reduction targets credible to ship owners. As this section shows, incorporating a convex penalty function in the policy design and the uncertainty around its intensity have far-reaching consequences for ship owners.

Recall that the regulatory penalty intensity is expressed by the random variable $\delta \in \Delta = (1, M]$ with $E[\delta] = \mu_\delta$ and finite variance σ_δ, where σ_δ can be interpreted as a measure of the uncertainty concerning regulatory intensity. To capture an increase in the uncertainty, we consider our base model and examine two scenarios for the regulatory intensity. In particular, we reflect an increase in regulatory intensity uncertainty by adding an independent, zero-mean disturbance to the random variable δ, i.e. a mean-preserving spread (for a formal definition of a mean-preserving spread please refer to the appendix). Note that this implies $E[\bar{\delta}] = E[\delta]$ and $\bar{\sigma}_\delta \geq \sigma_\delta$. In other words, this allows us to capture the scenario where the uncertainty concerning the regulatory intensity is increased while preserving the ship owner's expectations with regard to the penalty intensity.

Theorem 2: *If uncertainty in the regulatory intensity increases, then (i) the costs of regulation $J_0(x_0)$ and (ii) the value of managerial flexibility increase. Hence, the incentive to invest in clean technologies increases.*

Theorem 2 highlights the effect of increased uncertainty in regulatory intensity. The "added noise"

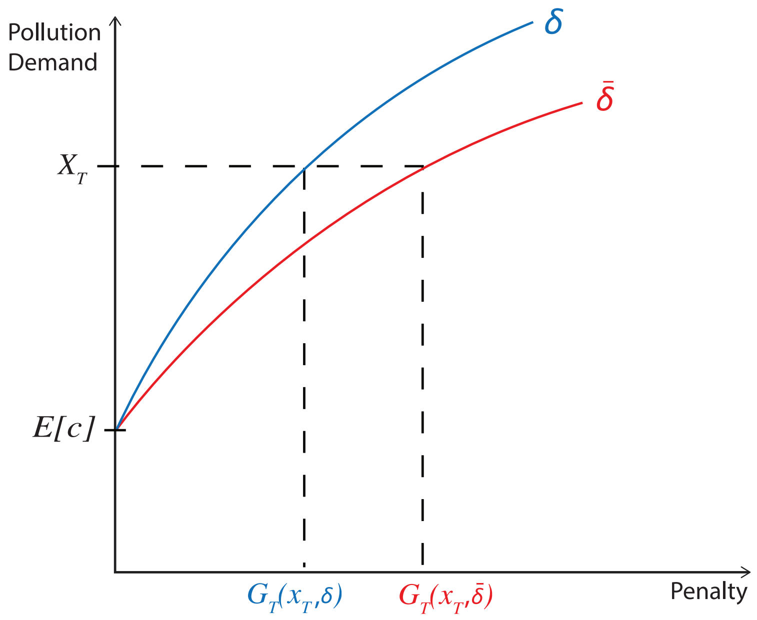

FIGURE 3.3: Graphical representation of an increase in regulatory intensity

in the higher uncertainty scenario increases the variability of δ, if compared to the lower uncertainty scenario. Scrutinizing the convex shape of the penalty function, this higher variability leads to an increase in the expected penalty at the end of the regulation horizon T. Since this increase converts to higher expected costs at stage $t = 0$ and a higher value of managerial flexibility, the incentive to invest in clean technologies increases.

Figure (3.3) provides intuition about the impact of increased regulatory intensity on the terminal penalty as a function of pollution demand. In the graph, the red curve indicates the high intensity case and the blue curve the low intensity one. Similar to this illustrative example, increasing the uncertainty in regulatory intensity leads to, informally speaking, an increase in the "convexity" of the expected terminal penalty function and, thus, a higher expected penalty. It is worth noting that the magnitude of the effect stated in Theorem 2 depends on the initial pollution demand x_0. Moreover, the expected costs and value of managerial flexibility are monotone nondecreasing in x_0. Hence, the investment incentive due to uncertainty around the regulatory intensity is also monotone nondecreasing in x_0. For instance, if a ship owner's initial pollution demand, x_0, is close to the expected regulatory requirement $E[c]$, their incentive to invest in clean technologies will be smaller when compared to a ship owner with a higher pollution demand.

In summary, higher uncertainty concerning regulatory intensity increases a ship owner's expected costs and the value of managerial flexibility. Therefore, such a signal leads to higher investment levels under the optimal investment policy. Furthermore, the magnitude of such an incentive is monotone nondecreasing in the initial pollution demand of the ship owner. Hence, uncertainty around the regulatory intensity has a higher impact on ship owners who are further from the expected emission target level.

3.6.2 Increased uncertainty in regulatory requirement

We now turn the attention to the regulatory requirement. Assume the regulator defines a certain target for emissions c to reach emission reduction goals at the terminal stage. We examine the impact of the increased uncertainty of such a measure on a ship owner's costs of regulation and value of managerial flexibility. This is an important source of regulatory risk for ship owners. First, emission reduction targets to support global climate change goals are naturally uncertain, as they are informed by the latest projections from climate change research and the progress made globally to combat climate change over the time horizon. Second, emission reduction targets are defined for the whole maritime industry (see, e.g., IMO GHG strategy postulated by the IMO), and a ship owner's investments in clean technologies are based on their specific reduction in carbon emissions. How the regulator utilizes the private information about the ship owner's demand for pollution obtained in the auction to mandate specific reduction targets is a priori uncertain for the ship owner.

In our model, a measure of regulatory requirement uncertainty is the finite variance σ_c of the emission target c. To assess the impact of increased uncertainty, we examine two uncertainty scenarios for the regulatory requirement. To ensure a meaningful comparison, we assume that the random variables concerning the regulatory requirement in the two scenarios have the same mean but different variability due to one random variable being a mean-preserving spread of the other. In other words, we consider two scenarios characterized by $E[\bar{c}] = E[c]$, and $\bar{\sigma}_c \geq \sigma_c$. This formulation allows us to model the scenario where the ship owners has less information about the precise regulatory requirement at the terminal stage. The next theorem describes the impact of increased uncertainty in the regulatory requirement on the costs of regulation and value of managerial flexibility.

Theorem 3: *If uncertainty in the regulatory requirement increases, then (i) the costs of regulation* $J_0(x_0)$ *and (ii) the value of managerial flexibility increase. Hence, the incentive to invest in clean technologies increases.*

The results of Theorem 3 might seem counterintuitive at first sight, as one could expect that the higher the uncertainty of the regulatory requirement, the more attractive it would be to defer investments in clean technologies. The reason for this (myopic) intuition is that a higher uncertainty of regulatory requirements would make the effect of an (irreversible) investment in clean technologies to cope with emission targets less known, which consequently could both reduce the value captured by the ship owner and the benefit for investing (i.e., the value of flexibility). It turns out this is not the case. In fact, an increase in the uncertainty of the regulatory requirement increases both the regulation costs incurred by the ship owner and the value of managerial flexibility, thus yielding increased investment levels under the higher uncertainty scenario. The additional incentive to invest can be interpreted as a hedge against extreme scenarios. In the face of uncertainty around the target emission values, the proposed regulation mechanism preserves its incentive for ship owners to invest and does not create an incentive to defer (irreversible) investments in clean technologies.

Figure (3.4) illustrates the impact of increased regulatory requirement uncertainty on the expected terminal penalty as a function of the regulatory requirement given x_T. In this figure, the black solid line indicates the terminal penalty function, the red dashed line the high uncertainty case, and the blue dashed line the low uncertainty case. The increase in the uncertainty on regulatory requirement increases the risk concerning the target emission level at the end of the regulation horizon T. Hence, due to convexity, the expected terminal penalty is higher for every level of terminal pollution demand $x_T \in X$. Because these higher expected terminal costs transition through the intermediate review stages, the regulatory costs and the value of managerial flexibility for the ship owner are also higher in the initial stage $t = 0$. Therefore, the incentive to invest increases

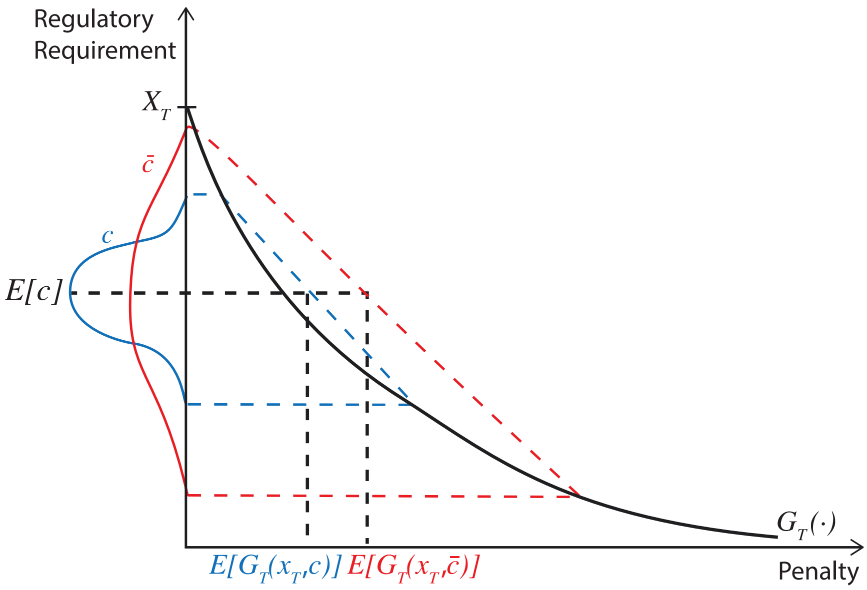

FIGURE 3.4: Graphical representation of an increase in regulatory requirement uncertainty

with uncertainty.

3.6.3 Increased uncertainty in pollution demand

This subsection deals with investigating the effect on investment decisions if the ship owner is operating in an environment where the future carbon emission demand becomes more uncertain. This is relevant, as estimates about future idiosyncratic demand are usually derived by projections or forecasting models that inherently contain a forecasting error, and such an error increases with the length of the forecasting horizon. In addition, international shipping is an integral part of global supply chains, as it transports over 80% of the volume of international trade in goods (UNCTAD, 2021). A main determinant of the demand for shipping services and, in turn, the industry's demand for emissions is the state of the global economy. To illustrate, disruptive events (like the COVID-19 pandemic) increase uncertainties on global markets and, in turn, increase the demand uncertainty for international shipping. Hence, future demand for emissions is inherently uncertain and largely out of the regulator's hands, as it is idiosyncratic to the ship owner or affected by market conditions in international shipping.

Therefore, a required feature of a mechanism would be to preserve the incentive to invest in clean technologies in an environment characterized by an increased uncertainty of pollution demand. Our results, captured by Theorem 4, indicate that the mechanism could incentivize even further investments in clean technologies under such a scenario. As discussed, $\omega_t \in \Omega$ captures the change in pollution demand. To investigate the impact of increased uncertainty on pollution demand, we consider our base model and focus on two uncertainty scenarios for pollution demand. Similar to before, we model the increase in uncertainty by spreading out the probability density function in one scenario, while keeping the expectation unchanged, with a mean-preserving spread. Theorem 4 summarizes the impact of increased pollution demand uncertainty on the costs of regulation and value of managerial flexibility.

Theorem 4: *If uncertainty in the pollution demand increases, then (i) the costs of regulation $J_0(x_0)$ and (ii) the value of managerial flexibility increase. Hence, the incentive to invest in clean technologies increases.*

Figure (3.5) describes the impact of increased pollution demand uncertainty by illustrating the effect on the expected terminal penalty. The black solid line depicts the terminal penalty function, the blue dashed line the low demand uncertainty case, and the red dashed line the high demand uncertainty case. Intuitively, the increase in pollution demand uncertainty shifts more probability weight to the tails of the random variable's ω_t distribution without changing the mean. Due to the convex shape of the terminal penalty function, this leads to an overall increase in the expected terminal penalty at the end of the regulation horizon T. Similarly, the increased uncertainty in pollution demand leads to higher expected costs at the intermediate stages, thus yielding higher costs of regulation $J_0(x_0)$ and a higher value of managerial flexibility. Hence, the overall incentive to invest in clean technologies increases.

3.7 Final discussion

In this paper, we examined the long-term effects of carbon regulation based on an ETS on the incentive to invest in clean technologies in the maritime industry. Using a multistage decision

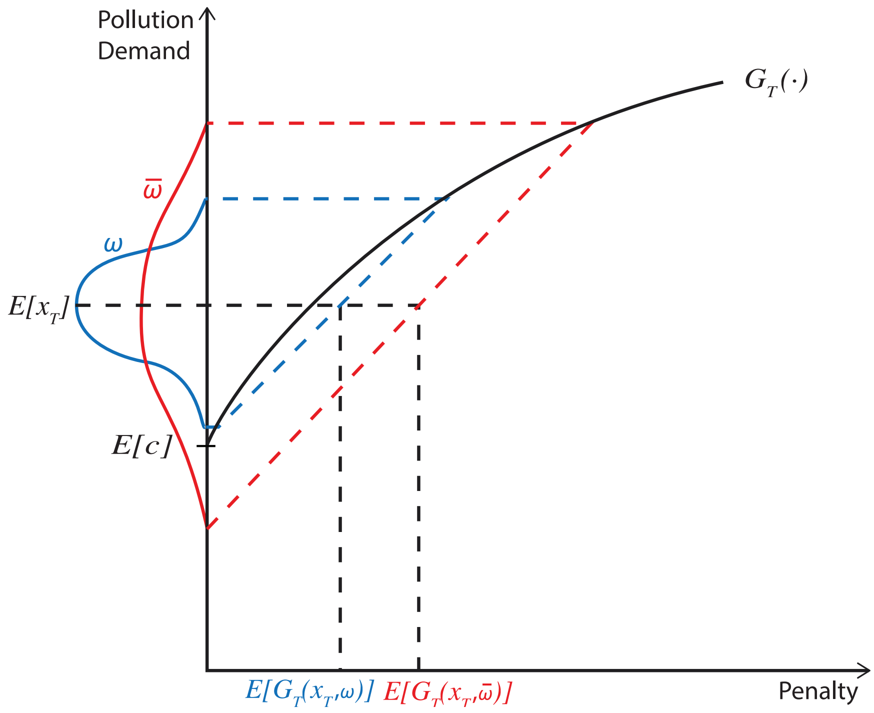

FIGURE 3.5: Graphical representation of an increase in pollution demand uncertainty

model, where ship owners choose their optimal investment levels to cope with the regulation in every review stage, we provide a comprehensive presentation of these effects in a stochastic environment. We derived a description of a ship owner's optimal investment policy and the related value of actively managing the investment decision over the regulation horizon. Further, we assessed the impact of an environment with increased uncertainties on the costs of regulation and value of managerial flexibility. Next, we evaluate our analytical results and highlight their implications for theory and practice. Lastly, we discuss the limitations of this research and provide avenues for future research to foster further the understanding of a firm's decision of whether to invest in clean technologies under green policies.

The analytical results show that there is indeed value for the ship owner in actively managing the investment decision under an METS regulation scheme, as opposed to passively deferring investments in clean technologies. The derived investment policy for the ship owner is characterized by an investment decision rule in every review stage. According to the decision rule, it is optimal for the ship owner to wait for the investment if their pollution demand is below a certain threshold value, and above this threshold, the optimal size of the investment increases in the current pollution demand. This leads to investments decreasing over time to maximize the cost reductions in the intermediate auctions over the regulation horizon. One appealing characteristic of the analysis is that the optimal level of licenses (and price per license) is determined endogenously in every review stage; thus, the derived results do not hinge on assumptions about the auction price or license allocation over time being exogenous to the model.

Because ship owners act in an environment of various demand and regulatory uncertainties, it is also important to understand how increased uncertainty in these variables may affect the incentive to invest in clean technologies. We focus on three distinct sources of uncertainty: intensity of the regulatory penalty, the regulatory requirement, and a ship owner's pollution demand. First, an increase in the uncertainty surrounding the regulatory penalty intensity increases the regulation costs, the value of managerial flexibility, and investment levels under the optimal investment policy. Further, the magnitude of this effect is nondecreasing in the initial pollution demand of the ship owner. Interestingly, increased regulatory requirement uncertainty also increases regulation costs, the value of managerial flexibility, and investment levels under the optimal investment policy, despite the fact that the contribution of irreversible technology investments to comply with target emission levels is less certain. Lastly, increased pollution demand uncertainty increases the value of managerial flexibility to invest and investment levels under the optimal investment policy.

This study enriches the theoretical understanding of a firm's investment decision problem under uncertainty in the context of green policies. We complement previous work in the sustainable technology choice literature by thoroughly examining the dynamic decision to invest in clean technologies over time when facing a green policy based on an ETS. In particular, we characterize the optimal investment policy over time and the related value of actively managing the investment decision. The setting of this research is an environmental policy based on an ETS and designed for the green transition of a global industry, which is a key contemporary area of inquiry for the academic community in the face of climate change. The study contributes to the real option literature by shedding light on how the investment timing problem is affected by a set of uncertainties pertinent to such a setting. More precisely, the analytical results show how an environment with increased regulatory and demand uncertainties impacts a firm's costs of regulation and the value of managerial flexibility. Therefore, this research provides a thorough understanding of the long-term impact of an industry-wide ETS designed to reach emission reduction targets concerning the investment decision of firms subject to a stochastic environment.

In addition, the study provides insights for policy makers in the maritime industry seeking to foster the green transition of the industry with their regulatory measures. A global maritime ETS appears a suitable measure to reach industry-wide emission reduction targets over a time horizon by providing long-term incentives to adopt clean technologies. A key insight is that incorporating the emission reduction targets into the policy design can enhance the effectiveness of the maritime ETS by increasing the ship owner's investment levels in clean technologies. However, this insight hinges crucially on the ex ante credible commitment of the policy maker to the reduction targets. One example of such a commitment is well-designed monetary ramifications when the ship owner does not met defined reduction targets. If the ship owner does not expect that there will be any consequences of insufficient abatement efforts, the investment incentive would reduce to the additive auction cost reductions across review stages and, hence, would be lower.

Another key insight is that a maritime ETS designed to reach industry-wide emission reduction targets can be robust to an environment with increased uncertainties and does not necessarily lead to regulated ship owners deferring investments until uncertainty resolves. To illustrate, one could argue that emission reduction targets are inherently fraught with uncertainty and, thus, cannot be set ex ante with certainty by the policy maker. However, this research suggests that even if there is uncertainty in the required emission reductions, a global maritime ETS can retain its incentivizing properties. Further, another key source of risk in maritime transport is increased uncertainty in the future demand for carbon emissions due to, for example, external events that cannot be controlled by the regulatory authority. As shown, an increase in this uncertainty could actually increase the value of managerial flexibility for the ship owner and lead to higher levels of clean technology investments to cope with the regulation. Further, by design, the proposed mechanism would yield higher incentives to invest if a higher demand for emissions is expected in the shipping industry, which is another key property of the green transition of the maritime industry.

In terms of extensions of our framework, a feasible option for future research would be to include the commonly researched uncertainty in resource prices. To illustrate, fuel costs can account for up to 60% of a vessel's operating costs (Royal Academy of Engineering, 2013). Therefore, reducing fuel costs is another important economic driver of clean technology adoption for ship owners, apart from the incentives presented by green policies based on MBMs. How uncertainty in fuel prices impacts the long-term adoption of clean technologies by a ship owner subject to an ETS regulation is an open question. As previously stated, our formulation of the total net costs of the technology measure already include the fuel price; thus, the fuel price has a direct impact on the investment costs of clean technologies. Further, a limitation of this research is the scope of focusing on the investment decision over time of a single firm. This does not allow us to make statements about how the strategic interaction between firms might impact their investment decisions and overall emission reduction efforts in the industry. While Montero (2008) showed that the auction mechanism can still implement the first-best solution under such circumstances, examining the impact of strategic interactions on a firm's optimal investment policy over time and the value of managerial flexibility could be a fruitful avenue for future research.

Appendix

We start by describing the concepts and definitions upon which our proof strategy for the propositions and lemmas of this section are based on.

Basics

The first concept is the notion of stochastic order: a random variable Y is said to be first-order stochastically greater than or equal to random variable X if $P(Y > x) \geq P(X > x)$ for any real number of x, where $P(\cdot)$ denotes the probability of an event. We denote this relation by $Y \geq^{st} X$. In our proof strategy, the following two results from first-order stochastic ordering are applied.

- *$Y \geq^{st} X$ if and only if there exists a coupling of Y and X such that $Y \geq X$.*
- *$Y \geq^{st} X$ if and only if, for all nondecreasing functions u, $E\left[\, u(Y)\,\right] \geq E\left[\, u(X)\,\right]$.*

Further, a random variable Y is said to be second-order stochastically greater or equal than a random variable X if $\int_a^x \left[\, H(z) - F(z)\,\right] dz \geq 0$ for all $x \in \left[\, a,\, b\,\right]$, where $H(\cdot)$ and $F(\cdot)$ are the cumulative distributions of X and Y, respectively. We denote this relation by $Y \geq^{sst} X$. In our proof strategy, the following two results from second-order stochastic ordering are applied. Assume that $E\,[\,Y\,] = E\,[\,X\,]$ and that Y and X have support in $[\,a,\, b\,]$, then

- *$Y \geq^{sst} X$ if and only if X is a mean-preserving spread of Y.*
- *$Y \geq^{sst} X$ if and only if for all convex functions h, $E\left[\, h(X)\,\right] \geq E\left[\, h(Y)\,\right]$.*

Further, X is a mean-preserving spread of Y if and only if there is a random variable ϵ such that $X =^d Y + \epsilon$ with $E\left[\epsilon \mid Y\,\right] = 0$ for all Y. For further details on stochastic order, see e.g. Ross (1996).

Similar to Santiago & Vakili (2005), we utilize the mimicking argument. It is based on the idea that one ship owner exactly replicates the actions of another ship owner who acts optimally, under the assumption that both are subject to the same uncertainty. The advantage of the mimicking argument is that the projects for both scenarios will end up in the same terminal state, and the same investment in clean technologies would have been made on the projects over the regulation horizon. This allows us to reduce the analysis of cost differences between ship owners to the expected terminal penalties they are facing. The cost-to-go function associated with the mimicking actions is denoted by the superscript c. For example, the cost-to-go function in t for a ship owner, who mimics the other one's actions, is denoted as $J_t^c(\cdot)$.

Lastly, due to the regulatory requirement c, there exist two different regions at the terminal stage T. Let $A = \{x : x_T \leq c\} \in X$ denote the region where no penalty has to be paid by the ship owner and let $A' \in X$, the complement set of A, be the region where the ship owner has to pay a penalty. Further, the probability of ending up in region A' at stage T will be denoted by $P(x_T \in A')$. To illustrate, the case of a positive but not certain probability to pay a penalty is defined as $0 < P(x_T \in A') < 1$.

Proof of the results of section 5

The first set of propositions is concerned with deriving the shape of the ship owner's optimal investment policy over the regulation horizon. We do this by first investigating the shape of the cost-to-go function, and then using this result to describe the shape of the optimal investment decision rule in all review stages.

Proposition 5.1: *If the expected final penalty function $E\left[G_T(x_T)\right]$ is monotone nondecreasing in x, then the cost-to-go function at any stage, $J_t(\cdot)$, is also monotone nondecreasing in x.*

Proof: The proof is by backward induction. By assumption $J_T(x_T) = E\left[G_T(x_T)\right]$ is monotone nondecreasing in $x \in X$. Now assume that $J_{t+1}(.)$ is monotone nondecreasing at stage $t+1$, and let x be the state at stage t with an allocation of licenses l. Consider now any $x^- \in [l, x]$. We want to show that $J_t(x) \geq J_t(x^-)$. Let the optimal action i in state x be $\mu(x) = \xi$. Assume that in state x^- the actions of state x are mimicked. Hence, the corresponding cost-to-go function under this assumption is $J_t^c(x^-)$. From this follows that,

$$\begin{aligned}
&J_t(x) - J_t^c(x^-) = \\
&\big[\, D(l) + C(l,x) + v\xi + F(\xi) + \frac{1}{1+r}\, E\,[\, J_{t+1}(x - s\xi + \omega)]\,\big] - \\
&\big[\, D(l) + C(l,x^-) + v\xi + F(\xi) + \frac{1}{1+r}\, E\,[\, J_{t+1}(x^- - s\xi + \omega)]\,\big] = \\
&\big[\, C(l,x) - C(l,x^-)\,\big] + \frac{1}{1+r}\, E\,\big[\, J_{t+1}(x - s\xi + \omega) - J_{t+1}(x^- - s\xi + \omega)\,\big].
\end{aligned}$$

Due to $x \geq x^-$, it directly follows that $C(l,x) - C(l,x^-) \geq 0$ since $\int_l^x P(z)dz \geq \int_l^{x^-} P(z)dz$. Furthermore, monotonicity of $J_{t+1}(\cdot)$ implies that,

$$J_{t+1}(x - s\xi + \omega) - J_{t+1}(x^- - s\xi + \omega) \geq 0 \implies E\,\big[\, J_{t+1}(x - s\xi + \omega) - J_{t+1}(x^- - s\xi + \omega)\,\big] \geq 0.$$

Hence, we can conclude $J_t(x) - J_t^c(x^-) \geq 0$. Since the control ξ and allocated licenses l were not optimal for state x^-, $J_t^c(x^-) \geq J_t(x^-)$ holds. Therefore, $J_t(x) \geq J_t^c(x^-) \geq J_t(x^-)$ and the proof by induction is complete.

Proposition 5.2: *There exist optimal decision rules $\mu_t^*(x)$ which are monotone nondecreasing in x for $t = 0, 1, ..., T-1$.*

Proof: We show this by invoking Theorem 4.7.4 in Puterman (1994, p.107). For Theorem 4.7.4 to hold, the following five conditions have to be fulfilled in the model.

1. $G_t(x,i)$ is nondecreasing in x for all $i \in I_{x_t}$,
2. $q_t(k \mid x,i)$ is nondecreasing in x for all $k \in X$ and $i \in I_{x_t}$,
3. $G_t(x,i)$ is a superadditive function on $X \times I_{x_t}$,
4. $q_t(k \mid x,i)$ is a superadditive function on $X \times I_{x_t}$ for all $k \in X$, and
5. $G_T(x)$ is nondecreasing in x,

where $q_t(k \mid x,i) = \sum_{j=k}^{X} p_t(j \mid x,i)$ represents the probability that the state at review stage $t+1$ exceeds $k-1$ when choosing action i in state x at review period t. First, note that condition 5 holds by assumption. Further, as shown in Proposition 5.1, $J_t(x)$ is monotone nondecreasing in x for every t and therefore by Proposition 4.7.3 in Puterman (1994, p.106) condition 1 and 2 are fulfilled. We are left with showing conditions 3 and 4. According to Puterman (1994, p.103), superadditivity implies for all $x^+ \geq x^-$ (and $i^+ \geq i^-$),

$$g(x^+, i^+) - g(x^+, i^-) \geq g(x^-, i^+) - g(x^-, i^-).$$

Define $g(x, i) = G_t(x, i) = D(x) + C(l, x) + vi + F(i)$, which can be reformulated as,

$$g(x, i) = D(x) + C(l, x) + vi + F(i)$$
$$g(x, i) = h(x) + e(i),$$

with $h(x) = D(x) + C(l, x)$ and $e(i) = vi + F(i)$. Then, by Puterman (1994, p.104), $G_t(x, i)$ is a superadditive function on $X \times I_{x_t}$ and condition 3 is fulfilled. The strategy for condition 4 is similar and utilizing the fact that the dynamics of the system can be equivalently represented by the system equation $f_t(\cdot)$ and the transition probabilities $p_t(\cdot)$. Let $g(x, i)$ be defined as $g(x, i) = E\left[\, f_t(x, i, \omega)\,\right]$. Hence,

$$g(x, i) = E\,[\, x - si + \omega\,]$$
$$g(x, i) = x - si + E\,[\,\omega\,]$$
$$g(x, i) = x - si,$$

since $E[\omega] = 0$ and independent of x and i. This expression can be reformulated as

$$g(x, i) = h(x) + e(i),$$

with $h(x) = x$ and $e(i) = -si$. Therefore, $g(x, i)$ and equivalently also $q_t(k \mid x, i)$ are superadditive functions on $X \times I_{x_t}$ for all $k \in X$. As shown, all five conditions of Theorem 4.7.4 are fulfilled and the proof is complete.

Corollary 5.3: *If there exist an optimal decision rule $\mu_t^*(x)$ which is monotone nondecreasing* *in x for $t = 0, 1, ..., T-1$, then there also exists a control limit b_t, which is a threshold between pollution demand states where the optimal action is to invest in clean technologies and the ones where it is optimal to wait.*

Proof: In Proposition 5.2 the existence of a monotone nondecreasing decision rule in x_t has been established. From this follows that if the optimal action at state x_t is $i_t = 0$ (waiting) then for all $x_t^- \leq x_t$ the optimal action is also $i_t^- = 0$. Similarly, if the optimal action at state x_t is $i_t > 0$ (investing) then for all $x_t^+ \geq x_t$ the optimal action is $i_t^+ \geq i_t$. Hence, we can conclude that there exists a threshold value $b_t \in X$ separating the pollution demand states where the optimal action is to invest in clean technologies and the ones where it is optimal to wait.

Proof of Theorem 1: Theorem 1 follows from Propositions 5.1, Proposition 5.2 and Corollary 5.3.

In addition, we prove the existence of a value of managerial flexibility in the stochastic dynamic programming model.

Proposition 5.3: *Consider the regulation mechanism under two management scenarios. In scenario 1 the ship owner does not have the option to invest and chooses the option to wait at all review stages (which is equivalent to passive management), while in scenario 2, it has the option to either wait or invest. Let Y_t and X_t be the state of pollution demand under Scenario 1 and 2 at stage t, respectively. Then, Y_t is stochastically greater than or equal to X_t.*

Proof: We prove the result by induction. At stage 0, $X_0 = Y_0 = a_0$, hence, the condition is trivially valid. Assume that $Y_t \geq^{st} X_t$. By definition of stochastic order, it is possible to define a coupling between Y_t and X_t so that every sample of Y_t is greater or equal to the sample of X_t, i.e. we can assume $Y_t \geq X_t$. Let i_t^* be the optimal investment decision at stage t under the first scenario. Using the same change in pollution demand ω_t in both scenarios yields $Y_{t+1} = Y_t + \omega_t \geq X_t - si_t^* + \omega_t = X_{t+1}$ and hence $Y_{t+1} \geq X_{t+1}$. It follows that there exists a coupling that every sample of X_{t+1} is not bigger than Y_{t+1}. Thus, $Y_{t+1} \geq^{st} X_{t+1}$ and the proof by induction is complete.

Proof of the results of section 6

Next, we derive the lemmas and propositions from which the theorems in section 3.6 follow directly. The goal of these propositions is to describe the effect of increased uncertainty in the pollution demand and regulatory risks on the cost-to-go function and value of flexibility.

We first turn to the analysis of the regulatory risks impacting the terminal penalty. By assuming that the expected terminal penalty depends on a parameter Θ, we examine the impact of a change in Θ on the cost-to-go function and value of flexibility. Assume there are two distinct parameter values $(\theta, \bar{\theta}) \in \Theta$ which are associated with two regulation mechanisms (mechanism 1 and 2), where θ denotes mechanism 1 with lower variability and $\bar{\theta}$ mechanism 2 with higher variability. The two mechanisms are identical, apart from the different expected terminal penalty due to θ and $\bar{\theta}$. The expected terminal penalty dependent on parameter value θ will be denoted as $E\left[\, G_T(x_T, \theta)\,\right] = J_T(x_T, \theta)$. Similarly, The cost-to-go function corresponding to the parameter value $\bar{\theta}$ in stage t will be denoted with a bar, e.g. $\bar{J}_t(x_t)$. Note, that the mimicking ship owner's the cost-to-go function in stage t, as a function of $\bar{\theta}$, would be denoted as $\bar{J}^c_t(x_t)$.

We now provide two lemmas which will be used in conjunction with the upcoming propositions to prove the theorems concerning the regulatory risks. Comparing two regulation mechanisms 1 and 2, we will show that higher expected terminal costs under mechanism 2 translate to higher costs and a higher option value of managerial flexibility in the starting period $t = 0$ under mechanism 2.

Lemma 6.1: *Assume that $J_T(x_T, \bar{\theta}) \geq J_T(x_T, \theta)$ for all x_T meaning that the expected final penalty under regulation mechanism 1 is always lower than under regulation mechanism 2. Then, the ship owner's cost-to-go function and the PV of regulation costs under mechanism 1 are lower than under mechanism 2. In other words,*

$$\bar{J}_0(x_0) \geq J_0(x_0) \quad \textit{and} \quad \bar{PV}_0(x_0) \geq PV_0(x_0).$$

Proof: Assume that a ship owner's management acts optimally under regulation mechanism 2 and a ship owner affected by mechanism 1 mimics these actions. Under this coupling, the ship owner's actions in these two mechanisms lead to the exactly same terminal demand for pollution x_T. However, for all states, the ship owner under mechanism 1 pays at most as much as the ship owner under mechanism 2. Hence, $\bar{J}_0(x_0) \geq J_0^c(x_0)$. Given that $J_0^c(x_0) \geq J_0(x_0)$, we can conclude that $\bar{J}_0(x_0) \geq J_0(x_0)$. The argumentation for the PV of regulation costs is a simpler version of the above argument.

Lemma 6.2: *Assume that* $J_T(x_T, \bar{\theta}) - J_T(x_T, \theta)$ *is nondecreasing in* x_T. *Then, the value of managerial flexibility under regulation mechanism* 2 *will be higher than under mechanism* 1. *In other words,*

$$P\bar{V}_0(x_0) - \bar{J}_0(x_0) \geq PV_0(x_0) - J_0(x_0).$$

Proof: Assume that a ship owner's management acts optimally under regulation mechanism 1 and a ship owner affected by mechanism 2 mimics these actions. Let X_T denote the terminal demand of a ship owner under mechanism 1 and when mimicking in mechanism 2. Furthermore, let Y_T denote the terminal state under mechanism 1 and 2 with passive management. From Proposition 5.3 we know that $Y_t \geq^{st} X_t$. Using the fact that $J_T(x_T, \bar{\theta}) - J_T(x_T, \theta)$ is nondecreasing in x_T and the properties of stochastic order, we can write,

$$E\left[\, J_T(Y_T, \bar{\theta}) - J_T(Y_T, \theta) \,\right] \geq E\left[\, J_T^c(X_T, \bar{\theta}) - J_T(X_T, \theta) \,\right].$$

Hence,

$$P\bar{V}_0(x_0) - PV_0(x_0) \geq \bar{J}_0^c(x_0) - J_0(x_0).$$

We know that $\bar{J}_0^c(x_0) \geq \bar{J}_0(x_0)$ and from Lemma 6.1 that $\bar{J}_0(x_0) \geq J_0(x_0)$. Since $J_0(x_0)$ is non-negative, it follows that $\bar{J}_0^c(x_0) \geq \bar{J}_0(x_0) \geq J_0(x_0)$, and, thus,

$$P\bar{V}_0(x_0) - PV_0(x_0) \geq \bar{J}_0(x_0) - J_0(x_0).$$

By rearranging terms we arrive at,

$$P\bar{V}_0(x_0) - \bar{J}_0(x_0) \geq PV_0(x_0) - J_0(x_0),$$

and the proof is complete.

After having established these two lemmas, we will now deal with deriving the two propositions for increased variability in the regulatory risks. By comparing two regulation mechanisms 1 and 2, our goal is to show that higher variability in the two random variables c and δ under mechanism 2 indeed leads to higher expected terminal costs under mechanism 2.

Proposition 6.1: *Consider two regulation mechanisms with equal expected regulatory intensity δ. Further, assume that the intensity in mechanism 2 is subject to higher uncertainty defined as an independent, zero-mean disturbance ϵ than the requirement in mechanism 1. In other words, $\bar{\delta} =^d \delta + \epsilon$ with $E[\epsilon \mid \delta] = 0$ for all δ and $E[\bar{\delta}] = E[\delta] = \mu_\delta$. Then, the expected terminal penalty of mechanism 2 is higher than of mechanism 1. In other words,*

$$E\left[G_T(x_T, \bar{\delta})\right] \geq E\left[G_T(x_T, \delta)\right].$$

Proof: First note, that by definition $\bar{\delta}$ is a mean-preserving spread of δ and, hence, $\bar{\sigma_\delta} \geq \sigma_\delta$ as desired. Let us consider now any $x_T \in X$ and focus first on the case of $P(x_T \in A') = 1$ where a penalty has to be paid. The expected terminal penalty under mechanism 2 can be rewritten as,

$$E\left[G_T(x_T, \bar{\delta})\right] = E\left[G_T(x_T, \delta + \epsilon)\right].$$

By the law of iterated expectations, it follows that,

$$E\left[G_T(x_T, \delta + \epsilon)\right] = E\left[E\left[G_T(x_T, \delta + \epsilon) \mid \delta\right]\right].$$

Since $G_T(\cdot)$ is strictly convex in region A', we know from Jensen's inequality that,

$$E\left[E\left[G_T(x_T, \delta + \epsilon) \mid \delta\right]\right] \geq E\left[G_T\big(x_T, E[\delta + \epsilon \mid \delta]\big)\right],$$

has to hold. Further, as $E[\delta \mid \delta] = \delta$ and $E[\epsilon \mid \delta] = 0$, we can infer that,

$$E\left[G_T\big(x_T, E[\delta + \epsilon \mid \delta]\big)\right] = E\left[G_T\big(x_T, \delta + E[\epsilon \mid \delta]\big)\right] = E\left[G_T\big(x_T, \delta\big)\right].$$

Hence, we can conclude that,

$$E\left[\,G_T(\,x_T,\,\bar{\delta})\,\right] \geq E\left[\,G_T(\,x_T,\,\delta)\,\right],$$

has to hold in region $x_T \in A'$. It is now possible to extend the proof to the more general case of x_T being either part of subset A or A'. Consider any $x_T \in X$ and suppose that $0 < P(x_T \in A') < 1$. The expected terminal penalty under both mechanisms is given by,

$$E\left[\,G_T(\,x_T,\,\bar{\delta})\,\right] \geq E\left[\,G_T(\,x_T,\,\delta)\,\right].$$

Please note, that,

$$E\left[\,G_T(\,x_T,\,\bar{\delta})\,\right] = P(x_T \in A') * E\left[\,G_T(\,x_T,\,\bar{\delta}) \mid x_T \in A'\,\right] + P(x_T \in A) * 0,$$

and, similarly,

$$E\left[\,G_T(\,x_T,\,\delta)\,\right] = P(x_T \in A') * E\left[\,G_T(\,x_T,\,\delta) \mid x_T \in A'\,\right] + P(x_T \in A) * 0.$$

So, by rearranging terms, we have,

$$P(x_T \in A') * E\left[G_T(\,x_T,\,\bar{\delta}) \mid x_T \in A'\,\right] \geq P(x_T \in A') * E\left[\,G_T(\,x_T,\,\delta) \mid x_T \in A'\,\right].$$

We know that $E\left[\,G_T(\,x_T,\,\bar{\delta})\,\right] \geq E\left[\,G_T(\,x_T,\,\delta)\,\right]$ in region $x_T \in A'$ of the penalty function. Further, for the case under consideration, we know that $0 < P(x_T \in A') < 1$, so,

$$E\left[\,G_T(\,x_T,\,\bar{\delta})\,\right] \geq E\left[\,G_T(\,x_T,\,\delta)\,\right],$$

has to hold. The case of $P(x_T \in A') = 0$ is straightforward and, therefore, the proof is complete.

Proof Theorem 2: Theorem 2 is a direct corollary of Lemma 6.1, Lemma 6.2, Proposition 5.3 and Proposition 6.1.

Proposition 6.2: *Consider two regulation mechanisms with equal expected regulatory requirement* *c. Further, assume that the requirement in mechanism 2 is subject to higher uncertainty defined as an independent, zero-mean disturbance ϵ than the requirement in mechanism 1. In other words, $\bar{c} =^d c + \epsilon$, with $E[\epsilon \,|\, c] = 0$ for all c and $E[\bar{c}] = E[c] = \mu_c$. Then, the expected terminal penalty of mechanism 2 is higher than of mechanism 1. In other words,*

$$E\left[\,G_T(\,x_T,\,\bar{c})\,\right] \geq E\left[\,G_T(\,x_T, c)\,\right].$$

Proof: First note, that by definition $\bar{c}$ is a mean-preserving spread of c and, hence, $\bar{\sigma_c} \geq \sigma_c$ as desired. Since $\bar{c}$ is a mean preserving spread of c and $E[c] = E[\bar{c}] = \mu_c$, we can infer that $c \geq^{sst} \bar{c}$. Define the difference in the expected penalty under both mechanisms as,

$$E\left[\,G_T(\,x_T,\,\bar{c})\,\right] - E\left[\,G_T(\,x_T, c)\,\right] =$$
$$\int_0^b G_T(x_T, z)\, dH(z) - \int_0^b G_T(x_T, z)\, dF(z),$$

with H and F being the cumulative distributions of random variables $\bar{c}$ and c respectively. Further, we know that $G_T(\cdot)$ is strictly convex in the interval $[0, x_T)$ and convex in the interval $[x_t, b]$. Since also $c \geq^{sst} \bar{c}$, we can conclude from the results of second-order stochastic ordering that,

$$\int_0^b G_T(x_T, z)\, dH(z) - \int_0^b G_T(x_T, z)\, dF(z) \geq 0,$$

for all x_T. So, by rearranging terms, we arrive at $E\left[\,G_T(\,x_T,\,\bar{c})\,\right] \geq E\left[\,G_T(\,x_T,\,c)\,\right]$ and the proof is complete.

Proof Theorem 3: Theorem 3 is a direct corollary of Lemma 6.1, Lemma 6.2, Proposition 5.3 and Proposition 6.2.

We will now turn to deriving the two main propositions for the impact of increased variability in the pollution demand on the cost-to-go function and the value of managerial flexibility. Similar to before, we will compare two distinct scenarios, where ω denotes scenario 1 with lower variability and $\bar{\omega}$ denotes scenario 2 with higher variability. The two scenarios are identical (i.e., the same mechanism) apart from the different variability of ω and $\bar{\omega}$. A key difference in the analysis is that the ship owners are not subject to the same demand uncertainty across the review stages. Hence, the mimicking argument does not ensure that the projects end up in the same terminal state; thus, the analysis does not reduce to assessing the expected terminal penalties at stage T. However, note that the replication of actions ensures that investment levels and allocated licenses are the same for the ship owner acting optimally and the mimicking ship owner in every stage t.

Proposition 6.3 *Consider a ship owner facing a regulation mechanism under two pollution demand variability scenarios. Further, assume that the pollution demand in scenario 2 is subject to higher uncertainty defined as an independent, zero-mean disturbance ϵ than the demand in scenario 1. In other words, $\bar{\omega}_t =^d \omega_t + \epsilon$ for all t with $E[\epsilon \mid \omega_t] = 0$ for all ω_t and $E[\bar{\omega}_t] = E[\omega_t] = 0$. Then, the ship owner's cost-to-go function and the PV of regulation costs at stage 0 under scenario* 1 *are lower than under scenario* 2*. In other words,*

$$\bar{J}_0(\bar{x}_0) \geq J_0(x_0) \quad \textit{and} \quad \bar{PV}_0(\bar{x}_0) \geq PV_0(x_0).$$

Proof: Assume that a ship owner's management acts optimally under scenario 2 and a ship owner affected by scenario 1 mimics these actions. First note that at stage 0 both ship owners are on the same initial state $\bar{x}_0 = x_0$. So, at every review stage t, the expected demand for pollution for both ship owners is the same, as $\bar{i}_t = i^c_t$ and $E[\bar{x}_{t+1} \mid \bar{x}_0] = E[x^c_{t+1} \mid x_0]$, where $\omega = \sum_{t=0}^{t} \omega_t$. Furthermore, given the Markov Property and mimicking, at each stage t, both ship owners face $\bar{l}_t = l^c_t$; thus, $D(\bar{l}_t) = D(l^c_t)$, $F(\bar{i}_t) = F(i^c_t)$, and $v\bar{i}_t = vi^c_t$. Therefore, under the mimicking assumption and by forward induction, the difference in the costs per stage t for the ship owners facing the two distinct scenarios is only affected by the costs to reduce emissions $C(\cdot)$. That is,

$$E\left[G_t(\bar{x}_t, \mu(\bar{x}_t), \bar{\omega}_t)\right] - E\left[G_t(x^c_t, \mu(x^c_t), \omega_t)\right] =$$
$$E\left[C_t(\bar{l}_t, \bar{x}_t)\right] - E\left[C_t(l^c_t, x^c_t)\right].$$

Note that $\bar{l}_t = l^c_t$ and by assumption $C(\cdot) \geq 0$. Due to convexity of $C(\cdot)$ and since $\bar{\omega}_t$ is a mean-preserving spread of ω_t, for all t, we have,

$$E\left[C_t(\bar{l}_t, \bar{x}_t)\right] - E\left[C_t(l^c_t, x^c_t)\right] \geq 0.$$

At the terminal stage T, suppose that both ship owners have a positive probability to pay a penalty, i.e., $0 < P(\bar{x}_T \in A') < 1$ and $0 < P(x_T^c \in A') < 1$. Consider now the difference in the terminal penalty, defined as,

$$E\left[\, G_T(\,\bar{x}_T \mid \bar{x}_0)\,\right] - E\left[\, G_T(\,x_T^c \mid x_0)\,\right].$$

Note that ω second-order stochastically dominates $\bar{\omega}$. Also, $G_T(\cdot)$ is a non-decreasing convex function in x_T. Therefore,

$$E\left[\, G_T(\,\bar{x}_T \mid \bar{x}_0)\,\right] - E\left[\, G_T(\,x_T^c \mid x_0)\,\right] \geq 0.$$

Taking both results together, we can infer that, at stage 0, $\bar{J}_0(\,\bar{x}_0) - J_0^c(\,x_0) \geq 0$ has to hold. We know that $J_0^c(\,x_0) \geq J_0(\,x_0)$ and $J_0(\,x_0) \geq 0$. Therefore, we can conclude that $\bar{J}_0(\,\bar{x}_0) \geq J_0(\,x_0)$, which is what we wanted to show. The argumentation for the PV of regulation costs is a simpler version of the above argument.

Proposition 6.4 *Consider a ship owner facing a regulation mechanism under two pollution demand variability scenarios. Further, assume that the pollution demand in scenario 2 is subject to higher uncertainty defined as an independent, zero-mean disturbance ϵ than the demand in scenario 1. In other words, $\bar{\omega}_t = \omega_t + \epsilon$ for all t, with $E\,[\,\epsilon \mid \omega_t\,] = 0$ for all ω_t and $E\,[\,\bar{\omega}_t\,] = E\,[\,\omega_t\,] = 0$. Then, the value of managerial flexibility under scenario* 2 *will be higher than under scenario* 1*. In other words,*

$$\bar{PV}_0(\bar{x}_0) - \bar{J}_0(\bar{x}_0) \geq PV_0(x_0) - J_0(x_0).$$

Proof: Assume that a ship owner's management acts optimally under scenario 1 and a ship owner affected by scenario 2 mimics these actions. From Proposition 5.3, we know that $Y_t \geq^{st} X_t$. Furthermore, due to the mimicking assumption, it is possible to define a coupling between passive and active management. Hence, the difference in value of managerial flexibility between the two scenarios is given by,

$$\left[\, \bar{PV}_t(\bar{x}_t) - \bar{J}_t^c(\bar{x}_t)\,\right] - \left[\, PV_t(x_t) - J_t(x_t)\,\right].$$

The argumentation is similar to Proposition 6.3. Due to the mimicking assumption, it suffices to assess the difference with respect to $C(\cdot)$ and $G_T(\cdot)$ for both scenarios. The convexity of such functions together with $Y_T \geq^{st} X_T$ imply that,

$$\big[\, P\bar{V}_0(\bar{x}_0) - PV_0(x_0) \,\big] - \big[\, \bar{J}_0^c(\bar{x}_0) - J_0(x_0) \,\big] \geq 0.$$

Rearranging the terms yields,

$$\big[\, P\bar{V}_0(\bar{x}_0) - \bar{J}_0^c(\bar{x}_0) \,\big] - \big[\, PV_0(x_0) - J_0(x_0) \,\big] \geq 0.$$

We know that $\bar{J}_0^c(x_0) \geq \bar{J}_0(x_0)$ and $J_0(x_0) \geq 0$. From this follows that,

$$P\bar{V}_0(\bar{x}_0) - \bar{J}_0(\bar{x}_0) \geq P\bar{V}_0(\bar{x}_0) - \bar{J}_0^c(\bar{x}_0) \geq PV_0(x_0) - J_0(x_0).$$

Thus, we can conclude that,

$$P\bar{V}_0(x_0) - \bar{J}_0(x_0) \geq PV_0(x_0) - J_0(x_0),$$

and the proof is complete.

Proof Theorem 4: Theorem 4 is a direct corollary of Proposition 5.3, Proposition 6.3, and Proposition 6.4.

References

Bøckman, T., Fleten, S.-E., Juliussen, E., Langhammer, H. J., & Revdal, I. (2008). Investment timing and optimal capacity choice for small hydropower projects. *European Journal of Operational Research*, *190*(1), 255–267.

Boomsma, T. K., Meade, N., & Fleten, S.-E. (2012). Renewable energy investments under different support schemes: A real options approach. *European Journal of Operational Research*, *220*(1), 225–237.

Chen, Y., & Tseng, C.-L. (2011). Inducing clean technology in the electricity sector: Tradable permits or carbon tax policies? *The Energy Journal*, *32*(3), 149–174.

Di Corato, L., & Montinari, N. (2014). Flexible waste management under uncertainty. *European Journal of Operational Research*, *234*(1), 174–185.

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty.* Princeton Press.

Drake, D. F., Kleindorfer, P. R., & Van Wassenhove, L. N. (2016). Technology choice and capacity portfolios under emissions regulation. *Production and Operations Management*, *25*(6), 1006–1025.

Drake, D. F., & Spinler, S. (2013). Sustainable operations management: An enduring stream or a passing fancy? *Manufacturing & Service Operations Management*, *15*(4), 689–700.

EC. (2021). *Commission proposal: Revision of the EU emissions trading system.* European Commission. Retrieved from `https://eur-lex.europa.eu/resource.html?uri=cellar:618e6837-eec6-11eb-a71c-01aa75ed71a1.0001.02/DOC_1&format=PDF`

Greenstone, M., Kopits, E., & Wolverton, A. (2013). Developing a social cost of carbon for US regulatory analysis: A methodology and interpretation. *Review of Environmental Economics and Policy*, *7*(1), 23–46.

Gu, Y., Wallace, S. W., & Wang, X. (2019). Can an emission trading scheme really reduce CO_2 emissions in the short term? Evidence from a maritime fleet composition and deployment model. *Transportation Research Part D: Transport and Environment*, *74*, 318–338.

Huang, X. N., Tan, T., & Toktay, L. B. (2021). Carbon leakage: The impact of asymmetric regulation on carbon-emitting production. *Production and Operations Management*, *30*(6), 1886–1903.

IMO. (2018). *Adoption of the initial IMO strategy on reduction of GHG emissions from* *ships and existing IMO activity related to reducing GHG.* International Maritime Organization. Retrieved from https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf

IPCC. (2014). *AR 5: Climate change 2014: Mitigation of climate change* (Tech. Rep.). Intergovernmental Panel on Climate Change. Retrieved from https://www.ipcc.ch/report/ar5/wg3/

Kachi, A., Mooldijk, S., & Warnecke, C. (2019). *Carbon pricing options for international maritime emissions* (Report). New Climate Institute. Retrieved from https://newclimate.org/wp-content/uploads/2019/04/Carbon-pricing-options-for-international-maritime-emissions.pdf

Kort, P. M., Murto, P., & Pawlina, G. (2010). Uncertainty and stepwise investment. *European Journal of Operational Research*, *202*(1), 196–203.

Krass, D., Nedorezov, T., & Ovchinnikov, A. (2013). Environmental taxes and the choice of green technology. *Production and Operations Management*, *22*(5), 1035–1055.

Krysiak, F. C. (2008). Prices vs. quantities: The effects on technology choice. *Journal of Public Economics*, *92*(5-6), 1275–1287.

Lagouvardou, S., Psaraftis, H. N., & Zis, T. (2020). A literature survey on market-based measures for the decarbonization of shipping. *Sustainability*, *12*(10), 3953.

Lukas, E., & Welling, A. (2014). Timing and eco(nomic) efficiency of climate-friendly investments in supply chains. *European Journal of Operational Research*, *233*(2), 448–457.

MEPC. (2009). *Guidelines for voluntary use of the ship energy efficiency operational indicator (EEOI).* International Maritime Organization. Retrieved from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Technical%20and%20Operational%20Measures/MEPC.1_Circ.684_Guidelines%20for%20Voluntary%20use%20of%20EEOI.pdf

MEPC. (2021). *Resolution MEPC.328(76).* International Maritime Organization. Retrieved from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.328(76).pdf

Montero, J.-P. (2008). A simple auction mechanism for the optimal allocation of the commons. *American Economic Review*, *98*(1), 496–518.

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy* *of Sciences*, *114*(7), 1518–1523.

Pizer, W., Adler, M., Aldy, J., Anthoff, D., Cropper, M., Gillingham, K., ... Wiener, J. (2014). Using and improving the social cost of carbon. *Science*, *346*(6214), 1189–1190.

Plambeck, E. L. (2012). Reducing greenhouse gas emissions through operations and supply chain management. *Energy Economics*, *34*(1), 64–74.

Popp, D., Newell, R. G., & Jaffe, A. B. (2010). Energy, the environment, and technological change. In B. H. Hall & N. Rosenberg (Eds.), *Handbook of the economics of innovation* (Vol. 2, pp. 873–937). Elsevier.

Psaraftis, H. N. (2016). *Green transportation logistics.* Springer, Switzerland.

Psaraftis, H. N. (2018). Decarbonization of maritime transport: To be or not to be? *Maritime Economics & Logistics*, *23*(1), 1–19.

Psaraftis, H. N., Zis, T., & Lagouvardou, S. (2021). A comparative evaluation of market based measures for shipping decarbonization. *Maritime Transport Research*, *2*, 100019.

Puterman, M. L. (1994). *Markov decision processes: Discrete stochastic dynamic programming.* John Wiley & Sons.

Ross, S. M. (1996). *Stochastic processes* (Vol. 2). John Wiley & Sons.

Royal Academy of Engineering. (2013). *Future ship powering options* (Tech. Rep.). Royal Academy of Engineering. Retrieved from `https://www.raeng.org.uk/publications/reports/future-ship-powering-options`

Santiago, L. P., & Vakili, P. (2005). On the value of flexibility in R&D projects. *Management Science*, *51*(8), 1206–1218.

Smith, T. W., Jalkanen, J., Anderson, B., Corbett, J., Faber, J., Hanayama, S., ... Aldous, L. (2014). *Third IMO GHG study 2014.* Interational Maritime Organization. Retrieved from `http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf`

T&E. (2020). *Maritime ETS public consultation* (Report). Transport & Environment. Retrieved from `https://www.transportenvironment.org/wp-content/uploads/2021/07/Maritime%20ETS%20public%20consultation%20briefing.pdf`

Trigeorgis, L., & Tsekrekos, A. E. (2018). Real options in operations research: A review. *European*

Journal of Operational Research, *270*(1), 1–24.

UNCTAD. (2021). *Review of maritime transport 2021* (Report). United Nations Conference on Trade and Development. Retrieved from `https://www.transportenvironment.org/wp-content/uploads/2021/07/Maritime%20ETS%20public%20consultation%20briefing.pdf`

Wang, W., Ferguson, M. E., Hu, S., & Souza, G. C. (2013). Dynamic capacity investment with two competing technologies. *Manufacturing & Service Operations Management*, *15*(4), 616–629.

Zhao, J. (2003). Irreversible abatement investment under cost uncertainties: Tradable emission permits and emissions charges. *Journal of Public Economics*, *87*(12), 2765–2789.

Chapter 4

Benchmarking energy efficiency of ship designs: Implications for maritime policies

Franz Buchmann

Abstract

Improving the energy efficiency of ship designs is a key policy objective to drive the green transition of the maritime industry. Regulations intended to support this objective are usually designed to focus on subgroups of vessels and comparisons against minimum requirements. Due to this perspective, the current potential for energy efficiency improvements in the maritime industry remains elusive. It is argued that opportunities for energy efficiency improvements are largely determined by two factors that vary across shipping sectors, namely, the scope for improvements through the adoption of best practices within sectors and the technological conditions across sectors. A general framework for benchmarking the energy efficiency of ship designs is proposed, and a nonparametric metafrontier approach is employed to account for the heterogeneity in ship designs. Relative efficiency measures are derived for a sample of over 6,000 vessels from the container, tanker, and dry bulk shipping sectors. This paper suggests that the sectors can benefit from diverse additional instruments due to differences in the scope for improvements and technological conditions. Further, the study offers a refined perspective for energy efficiency comparisons in the maritime industry, which can improve the effectiveness of existing regulations by addressing unwanted side effects and introducing competitive market forces.

4.1 Introduction

Ambitious commitments to the green transition of marine transport are urgently needed in the maritime industry. A prime example of such commitments is the recent announcement that A.P. Møller-Mærsk would operate the world's first carbon-neutral liner vessel in 2023. Further, Mærsk plans to incorporate dual-fuel technology in the ship designs of all future newly built vessels, with the ultimate target of having a carbon-neutral fleet by 2050 (Mærsk, 2021). Despite being considered the most environmentally friendly mode of freight transportation, it is estimated that shipping emitted a staggering $1,056$ million tonnes of CO_2 in 2018, accounting for 2.86% of global CO_2 emissions that year (Faber et al., 2020). To put this in perspective, if the maritime industry were a country, it would have been the sixth-largest emitter of carbon dioxide in 2019, directly ahead of Germany (Crippa et al., 2020). Even more concerning, marine emissions are forecasted to follow an increasing trajectory, going against the vision of sustainable marine transport.

A main policy focus to foster the green transition of the industry and reach emission reduction targets lies on technology to improve the energy efficiency of the global fleet. In 2018, the International Maritime Organization (IMO) defined the target to reduce CO_2 emissions per transport work by at least 40% by 2030, pursuing efforts towards 70% by 2050[1] (IMO, 2020). Theoretical frameworks conceptualizing the transition of mobility and transportation systems have long highlighted improvements in technological energy efficiency[2] as a key action to reach such ambitions (Banister, 2008) and as a focal policy approach (Dalkmann & Brannigan, 2007). From a managerial perspective, a focus on energy efficiency is a cost-efficient measure, as the major share of maritime emissions comes from energy consumption. In addition, energy-optimizing technologies are seen as a potential source of future competitive advantage, considering more costly alternative fuels or additional market-based policy measures (Green Ship, 2020).

To drive the process of energy-efficiency improvements, the IMO has the objective to foster continuously the adoption and development of energy-optimizing technologies in ship designs through its policies. Generally speaking, delivering on this policy objective largely entails exhausting the

[1] Compared to 2008 as the baseline.

[2] Note that throughout the paper, I refer to the technical energy efficiency of the ship design as technological energy efficiency to avoid confusion with the term technical efficiency used in the data envelopment methodology.

potential of utilized technologies in existing ship designs and expanding the space of existing ship designs through technological development and innovation. The most important policy measure in force aimed at satisfying the objective is the mandatory Energy Efficiency Design Index (EEDI), adopted in 2011 (MEPC, 2011). In a nutshell, the EEDI regulation prescribes minimum energy efficiency standards that a newly built vessel must fulfill, depending on the year and shipping sector in which it operates. Furthermore, the EEDI only applies to vessels built after 2013; thus, it encompasses a unique and rather small subset of the global fleet. In summary, the regulatory approach compares a specific group of vessels against a sector-specific minimum standard.

I remark that such a perspective is not well suited to assess the current potential for improvements in technological energy efficiency in the maritime industry, which is of interest to policy makers, as it informs their policy objective. I argue that this potential is mostly determined by two factors. The first factor is the scope for improvements through the adoption of existing best-practice ship designs within sectors. This scope is likely not uniform across shipping sectors due to differences in prevailing market conditions and market dynamics in the different sectors. The second factor is the technological conditions across shipping sectors, limiting technology choice at the design stage. Further, limiting conditions might make it more challenging for a sector to adopt existing industry best practices and, thus, curb its scope for efficiency improvements.

Information about these two factors in the different shipping sectors is crucial for policy makers to evaluate current instruments and to develop additional instruments. Many studies have questioned the EEDI regulation's effectiveness to stimulate continuous improvements in technological energy efficiency due to the policy design and unintended side effects, such as speed reductions at the design stage (Ančić et al., 2018; Polakis et al., 2019; Vladimir et al., 2018). Hence, it is questionable whether the policy measures in their current form are sufficient to satisfy the policy objective and additional instruments are most likely needed. A key barrier to designing new measures is that their effectiveness is dependent on the situational context and their interaction with measures previously adopted (Givoni, 2014; Justen, Fearnley, et al., 2014). Similar to O'Donnell et al. (2008), I suggest that the presented analysis can act as a quantitative decision support tool for designing such new instruments through providing a granular picture of the sector-specific contexts.

This research has the objective to assess the scope for efficiency improvements within sectors and the technological conditions across sectors of the maritime industry. A key claim of the study is that by shifting the view from comparisons against minimum standards to best practices and by utilizing a general framework for the energy efficiency of ship designs instead of a specialized index for certain subgroups, it is possible to present a thorough assessment of these two factors. The study derives estimates for the relative performance of vessels based on best-practice benchmarks and describes their distribution in the respective sectors. Based on these estimates, it is possible to shed light on the scope for improvements through the adoption of existing ship designs and the technological conditions in the shipping sectors. A challenge is that vessels in different shipping sectors are designed for distinct purposes (e.g., the type of cargo they transport); thus, vessel designs differ substantially across sectors. One must consider this heterogeneity in ship designs to make meaningful comparisons across sectors. Such comparisons are insightful, as they highlight the importance of acknowledging the sector-specific contexts when evaluating existing and developing new measures. Therefore, the study strives to describe the differences in situational contexts in the considered shipping sectors.

This research proposes a general framework for comparing the energy efficiency of vessel designs and employs a metafrontier approach based on data envelopment analysis (DEA) to account for the heterogeneity in ship designs. This approach enables the assessment of the scope for efficiency improvements within sectors and to make industry-wide comparisons across sectors. DEA is a popular method for assessing the environmental efficiency of decision-making units in various empirical contexts (see, e.g., Sueyoshi et al. (2017) or Zhou et al. (2018)) and of entities in the maritime supply chain in particular (Nguyen et al., 2016; Wanke & Barros, 2016; Woo et al., 2019). In these studies, the focus is on production processes and the related productive efficiency of decision-making units, including, for example, ports or shipping companies. While yielding important insights into productivity and related pollutant emissions, such a perspective is unsuitable to investigate the phenomenon of interest. This study focuses on individual vessels and their energy transformation processes. I collected a novel data set of over $6,000$ vessels from the container, tanker, and dry bulk shipping sectors with detailed information about the idiosyncratic ship design characteristics.

The study contributes by providing a detailed picture of the current potential to improve technological energy efficiency in the container, tanker, and dry bulk shipping sectors, which have the highest absolute CO_2 emissions. The results indicate that the scope for improvements by adopting existing best-practice ship designs ranges, on average, between 6.4% to 17.4% depending on the sector. In addition, there are substantial differences in the technological conditions across sectors. Based on these insights, the study contributes by providing two main implications for marine policies designed to support the policy objective. First, it discusses how the adoption of the presented approach could improve the effectiveness of existing policy instruments, such as the EEDI, by addressing unwanted side effects and introducing competitive market forces. Second, due to the observed heterogeneity in sector-specific contexts, it suggests that the considered sectors can benefit from different additional policy measures.

The remainder of the paper is structured as follows. Section 2 describes technological energy efficiency in the maritime context, and the related literature is reviewed in Section 3. Section 4 presents the methodology by outlining the data collection and validation process alongside the data analysis strategy. The results and insights from applying the approach to the empirical data are examined in Section 5. Section 6 discusses the key findings and their implications for maritime policies. The study is concluded by evaluating the limitations and providing open areas for future research.

4.2 Technological energy efficiency in the maritime industry

In general terms, the energy efficiency of a transportation unit can be defined as the ratio of total energy consumed for propulsion to the travelled distance of load over a certain time. The measurement of the two components depends on the context, e.g., whether the load is freight or passengers. In transportation, total energy consumed is often expressed in terms of fuel consumption by the unit of interest. In the maritime regulation context, the rationale behind measures of energy efficiency is to produce a ratio of the impact to the environment (expressed in carbon emissions) to the benefit for society (expressed in transport work) due to the cargo transportation. Hence, the technological energy efficiency of a specific vessel is, in general, defined as (Molland et al., 2017),

$$EE\ Index = \frac{Total\ CO_2\ Emissions}{Transport\ Work} = \frac{Installed\ Power \times Fuel\ Consumption \times Fuel\ CF}{Capacity \times Speed}. \quad (4.1)$$

In equation (4.1), the total energy consumed depends on the installed power and the fuel oil consumption per unit of power, which together determine the total fuel oil consumption for propulsion. To reflect the fact that different fuels have different impacts on the environment, the numerator is measured in total carbon emissions; thus, the total fuel oil consumption is scaled with a carbon conversion factor (CF) depending on which type of fuel the vessel is combusting. Further, the main determinants for the numerator are the specific main engines (ME) and auxiliary engines (AE) installed onboard.

Intuitively, the transport work in the denominator expresses the aforementioned cargo-transporting capabilities. It can be interpreted as how much cargo — measured in capacity — can be theoretically transported how many nautical miles — measured by speed — in one hour by the vessel. Thus, measures of energy efficiency are defined as aggregate ratios expressing a vessel's carbon emissions per capacity-mile. Although equation (4.1) is referred to as an indicator of energy efficiency by the industry, to be technically precise, it is rather a measure of the carbon intensity. This study refers to the expression as a measure of energy efficiency to be consistent with the nomenclature used in maritime regulations and to avoid confusion for the reader. It is important to highlight that this rationale describes the technological energy efficiency, and the observed operational energy efficiency will likely be different due to deviations from theoretical conditions. This study focuses on technological energy efficiency due to the high relevance to existing and planned policies.

Based on this rationale, there are multiple different indices stipulated by the IMO — the main regulatory body in the maritime industry — expressing the technological energy efficiency of the ship design. The most relevant are the Estimated Index Value (EIV), the EEDI, and the recently adopted Energy Efficiency Existing Ship Index (EEXI). The main difference between these indices is the scope of vessels they cover and how they are calculated. To illustrate, attaining an EEDI rating is mandatory for all newly built vessels above 400 gross tonnage (GT) and is a one-off certification. The formula for calculating the attained EEDI rating is complex due to the inclusion of various adjustment and correction factors, and it requires detailed information from sea trial runs. Further, the regulation based on the EEDI prescribes minimum standards the vessel must fulfill to be considered compliant.

To incentivize the continuous development and adoption of cleaner technologies, these minimum requirements become more stringent over time and are based on the so-called reference line. The sector-specific reference lines are derived from a regression curve fit of existing vessels' EIV above 400 GT and delivered between 1999 and 2009. The EIV is a simplified version of the EEDI comprising the main determinants outlined in equation (4.1). The main purpose of the EIV was to infer the reference lines for the EEDI regulation, but it can be calculated for most vessels due to its simplicity. Because the industry is lacking a technological energy efficiency index for existing vessels, it is also currently used for this purpose, and its reporting is compulsory in the Monitoring, Reporting, and Verification (MRV) emission inventory of the European Union (EU). To fill this gap, the Maritime Environment Protection Committee introduced the EEXI at the 75$^{\text{th}}$ meeting in November 2020. The EEXI is expected to enter into force in 2023, and the regulation is intended as an EEDI counterpart for all existing vessels. The guidelines for calculating the EEXI will be similar to those of the EEDI procedure, with some adjustments due to limited data access from the ships' design stage (DNV, 2020).

All these indices have in common that they are aggregate, vessel-centric measures of energy efficiency. However, comparing or benchmarking vessels with different indices is not directly meaningful, due to the different calculation procedures and definitions. Even benchmarking vessels with the same index within a sector is problematic, as the indices are dependent on size. In general, a vessel's rating is negatively correlated with the capacity and, thus, two vessels with the same energy efficiency value can have drastically different ship designs. Further, using one of the aggregate measures for benchmarking purposes means relying on some implicit assumptions. Most importantly, one is implicitly assuming that it is possible to scale a vessel's size and machinery linearly, i.e., constant returns to scale are assumed. However, regulations prescribe minimum propulsive power requirements to avoid safety issues, and there are technical constraints limiting the size of a vessel type, making this assumption at least questionable in this context.

4.3 Literature review

As a departing point, I remark that previous studies have examined the technological energy efficiency on a vessel level, with special attention to the current main policy measure, the EEDI. Overall, this stream of literature has highlighted the limited effectiveness of the EEDI to stimulate improvements in the energy efficiency of ship designs for different marine sectors. One reason for this is that design speed reductions by reducing the main engine power are in general seen as an easy way to comply with the EEDI regulation (Psaraftis, 2019; Molland et al., 2017; Stevens et al., 2015). While reducing the operational speed can constitute a cost-efficient way to lower the GHG emissions of the world fleet (Lindstad et al., 2011), a focus on design speed reductions limits the role of energy-optimizing technologies (Ančić et al., 2018). In addition, design speed reductions lead to safety concerns in adverse weather conditions due to under powering, especially for vessels with slower speeds, e.g., bulk carriers (Polakis et al., 2019).

Another identified reason is that the prescribed minimum energy efficiency standards seem insufficient to incentivize the implementation of energy-optimizing technologies in different marine sectors. Ančić et al. (2018) argued that the EEDI is not expected to further advance design improvements for bulk carriers, partly due to the majority of newly built vessels today already being compliant with the most stringent requirements. Similarly, Attah and Bucknall (2015) conclude that the regulation will most likely not lead to improvements in future LNG ship designs, as the propulsion technology installed on the majority of new builds is already compliant with future standards. Lastly, the existing EEDI requirements are relatively inconsequential for the design of ultra-large container vessels due to their size (Vladimir et al., 2018). Indeed, in a study ranking EEDI-compliant solutions that reduce emissions under realistic operational conditions for Aframax tankers, Lindstad and Bø (2018) report that a ship design reducing emissions the most would not be selected as a solution due to the high capital costs of associated energy-optimizing technologies. Hence, additional policy instruments or initiatives, would be needed on top of the EEDI to foster their adoption.

A key point of the study is in line with Sueyoshi et al. (2017), who argue that technology innovation in engineering must be linked to managerial, societal, and regulatory perspectives to address environmental challenges, such as improving energy efficiency on a large scale. The use of DEA is considered to provide such a methodological linkage between engineering knowledge and the social sciences, and there are numerous applications to energy and environment topics (Sueyoshi et al., 2017; Zhou et al., 2018). Although empirical studies have been conducted for various modes of transport, this study is broadly related to the literature examining the productive efficiency of entities in the maritime supply chain. Here, previous studies have mostly investigated the relative efficiency of ports or terminals (Luna et al., 2018; Martinez-Budria et al., 1999; Nguyen et al., 2016; Roll & Hayuth, 1993; Wanke & Barros, 2016) and shipping companies (Panayides et al., 2011; Woo et al., 2019) in different empirical contexts.

Of special interest is the recent and growing literature stream incorporating negative impacts of pollution in their analysis to derive measures of environmental efficiency. For example, Quintano et al. (2020) estimate the eco-efficiency of 24 container ports in Europe and evaluate determinants by utilizing a two-step DEA approach to address unobserved heterogeneity in port behaviors. By estimating the CO_2 emissions of 28 Spanish port authorities based on a fleet activity-based approach, Tovar and Wall (2019) conclude that CO_2 emissions could have been decreased to an average of 63% of their observed levels. Gong et al. (2019) estimate the efficiency of 26 shipping companies based on different efficiency measures. They remark that the DEA efficiency measures with or without adjusting for negative environmental impacts are similar, but different from measures based on a output–emission ratio. This is an important differentiation: in the aforementioned studies, the usual research object is the productive efficiency of an economic production process while considering environmental aspects. Through this lens, pollution is seen as an undesirable output due to pollution-generating technologies, and firms can devote resources to their mitigation. However, in this empirical context, the focus lies on the energy efficiency of the transportation activities from a marine policy lens.

Previous literature has also examined the energy efficiency of the transportation sector in different regional contexts (Cui & Li, 2014; Omrani et al., 2019; Saidur et al., 2007). These studies most often employ a top-down approach, focusing on the economy-wide energy efficiency of transportation systems. For example, in a study estimating the energy efficiency of the transportation sector for 30 provincial regions in China, Wu et al. (2016) report that the passenger transportation system performs relatively better than the freight transportation system in terms of energy efficiency. Makridou et al. (2016) inter alia showed that the transportation sector across European countries, while being one of the most efficient, energy-intensive sectors, failed to improve its energy efficiency performance over the period 2000–2009, mainly due to not having adopted industry best practices. In contrast to the economy-wide perspective, this paper employs a bottom-up approach, focusing on the individual vessels and their design parameters affecting technological energy efficiency. This enables a granular analysis of the current potential for efficiency improvements within the shipping sectors, in addition to industry-wide comparisons across sectors. The design parameters are thoroughly described in the following section, which is concerned with the data sources and data transformation strategy.

4.4 Method

4.4.1 Data and measures

The subsequent analysis focuses on the container, tanker, and dry bulk shipping sectors, which account for roughly 90% of total maritime cargo transportation capacities (Faber et al., 2020). Following the classification in the EU-MRV, the tanker sector is further split into the gas carrier, oil tanker, and chemical tanker sector, setting the scope of this paper to five shipping sectors. Within these sectors, the analysis is limited to the vessels included in the EU-MRV regulation's public database for the reporting year 2019 (EU, 2015). Because this mandatory regulation requires individual vessels to report one of the aforementioned technological energy-efficiency indices, it allows validating the collected data for the ship design parameters and to identify potential data outliers. For the individual ship design parameters, the Clarkson World Fleet Register (CWFR) and the Thomson Reuters Eikon Shipping (TRES) database, which contain detailed vessel specifications and machinery information, have been utilized. The EU-MRV sample and these registers have been matched by the vessels' IMO numbers, yielding a sample of 6,482 vessels with complete and consistent information about the vessel-specific main engine characteristics, speed, and capacity. The summary statistics for the collected ship design parameters are summarized in Table (4.1), and a brief description of the individual variables is given below.

TABLE 4.1: Summary statistics per shipping sector

Variables	Bulk carrier	Chemical tanker	Container ship	Gas carrier	Oil tanker
Observations	2,577	961	1,294	236	1,414
Outputs					
Capacity	66,440.10	33,915.15	49,032.87	23,230.27	102,167.81
	(41,808.33)	(16,045.44)	(36,380.43)	(17,147.79)	(64,094.99)
Speed	14.28	14.53	22.15	15.94	14.88
	(0.61)	(0.85)	(2.66)	(1.29)	(0.88)
Inputs					
ME Power	7,138.40	5,769.55	26,326.07	6,343.89	9,917.24
	(2,465.10)	(1,918.55)	(16,921.14)	(3,062.59)	(3,791.71)
ME SFOC	172.63	173.07	172.14	171.60	171.11
	(3.36)	(5.08)	(3.70)	(8.32)	(3.67)
ME Carbon Factor	3.11	3.11	3.11	3.09	3.11
	(0.00)	(0.06)	(0.01)	(0.13)	(0.01)
AE Power	450.28	379.03	1188.53	401.50	566.43
	(115.62)	(114.34)	(571.81)	(150.19)	(147.71)
AE SFOC	195.32	193.90	195.36	192.68	194.95
	(2.13)	(3.32)	(3.26)	(7.41)	(2.22)
AE Carbon Factor	3.12	3.13	3.12	3.12	3.12
	(0.01)	(0.03)	(0.02)	(0.07)	(0.02)

Note: Table (4.1) reports the mean of output and input variables with the standard deviation in parentheses.

The two main variables on the output side are *Capacity* and *Speed*. In line with maritime regulation, *Capacity* is defined as a vessel's deadweight tonnage for bulk carriers, chemical tankers, oil tankers, and gas carriers and as 70% of the deadweight tonnage for container ships (MEPC, 2018). Intuitively, deadweight tonnage indicates the maximum weight-carrying capacity of a vessel, excluding its own light weight and, thus, is used as a measure for the cargo-carrying capacity of a vessel. The *Speed* variable is the service speed of a vessel, describing a vessel's average speed under normal load and weather conditions, and it is measured in nautical miles per hour (knots).

As highlighted in section (4.2), the two main determinants of a vessel's total carbon emissions are the main and auxiliary engines. For the main engine (ME), the three main determinants of carbon emissions are *ME Power*, *ME SFOC*, and *ME Fuel Carbon Factor*. The total main engine's power is defined as 75% of the sum of power generated by the main engine(s) and transferred to the main propulsor(s) and is measured in kilowatts (kW). The *ME SFOC* variable is defined as the specific fuel oil consumption (SFOC) of the main engine, indicating the grams of fuel consumed per kilowatt-hour (g/KWh) and can be interpreted as a measure of the engine's fuel efficiency. Lastly, the amount of carbon emissions emitted also depends on the type of fuel consumed by the main engine. In the data set, the type of fuel is a categorical variable with five levels: diesel/gas oil (DGO), heavy fuel oil (HFO), liquefied natural gas (LNG), ethanol, and methanol. To reflect the carbon content of a certain unit of the different fuel types, the categories must be transformed into numerical values. For this purpose, the study follows the approach outlined in the EEDI regulation and uses the provided conversion factors to transform the categorical fuel type to the *ME Fuel Carbon Factor* variable, which states the grams of CO_2 per gram of fuel ($gCO_2/gfuel$) (MEPC, 2018). Note that in case the main engine is a dual-fuel engine, I follow Faber et al. (2020) and assume that the engine uses the alternative fuel as the primary fuel.

In the same vein, the three main determinants for the carbon emissions of the auxiliary engines (AE) are *AE Power*, *AE SFOC*, and *AE Fuel Carbon Factor*. However, the data quality for the vessel-specific auxiliary engines characteristics is much lower than for the main engine, requiring some assumptions to derive the auxiliary engines' characteristics. For the auxiliary engines' power variable, the study uses the two formulas defined in MEPC (2018) to calculate the *AE Power* from the total propulsion power of a vessel. In this context, the estimate expresses the required auxiliary engine power for propulsion and accommodation to supply the capacity at the defined speed while the vessel is engaged in voyage. Due to the low data quality for the *AE SFOC* variable, the study uses the values provided in Table 19 of Faber et al. (2020) to derive an estimate of the auxiliary engines' specific fuel oil consumption, dependent on the engines' age and fuel type. Lastly, in the data set, the fuel type used by the auxiliary engines is only reported for roughly 64% of the vessels. To obtain a complete data set, a nonparametric, iterative imputation method based on random forests, which is described in Stekhoven and Bühlmann (2012), was applied to impute the missing categorical values of the auxiliary fuel type variable. For this task, information about the auxiliary engine model, the main engine characteristics, and vessel-specific characteristics have been used as predictors in the iterative approach, with 500 decision trees per iteration. In Table (4.2) the results from the imputation procedure are depicted alongside the observed frequencies for the subset of complete observations and the resulting full data set.

TABLE 4.2: Auxiliary fuel type imputation results

	All		*Complete*		*Imputed*	
	Obs.	Share	Obs.	Share	Obs.	Share
HFO	6,165	95.11%	3,963	95.40%	2,202	94.61%
DGO	309	4.76 %	183	4.41%	126	5.39%
LNG	8	0.12 %	8	0.19%	0	0%

Note: Table (4.2) reports the results for the auxiliary fuel type imputation based on random forests, with 500 decision trees per iteration.

Overall, the difference between the observed frequencies of the subsets of complete and imputed observations is only minor; thus, the imputation procedure seems to yield appropriate results. More formally, the out-of-bag prediction error is 0.0255, indicating that on average, only 2.55% of the out-of-bag observations have been labelled incorrectly by the random forest classifier. Note that the high accuracy of the imputation method is not surprising given the high prevalence of the HFO fuel type in the data. Nevertheless, the method yields a more accurate prediction than more naive methods like, e.g., assuming that all missing auxiliary fuel type observations are of the category HFO.

4.4.1.1 Data validation

The data collection process for the vessels in the sample is validated to ensure that the collected information about their inputs and outputs is a good representation of their actual design characteristics. This is done to verify that the collected data points from the secondary databases do not contain data mistakes on a large scale. One key advantage of focusing on the EU-MRV subsample for the considered shipping sectors is the possibility to validate the preceding data collection and assumptions. In the EU-MRV data set, for each vessel, the ship-specific EIV or EEDI value is reported, indicating the technological energy efficiency of the ship design. Therefore, for each vessel, either the EIV or EEDI value (with all correction and adjustment factors assumed to be 0) is computed with the collected data according to the formulas outlined in the EEDI guidelines (MEPC, 2018). The estimates are then compared to the reported EEDI or EIV value in the EU-MRV data set by forming the following ratio,

$$Ratio = \frac{Computed\ Index\ Value}{Reported\ EEDI/EIV\ Value}. \tag{4.2}$$

Intuitively, a ratio of 1 means that the computed index value based on the collected ship design parameters coincides with the reported value of technological energy efficiency. Hence, a ratio close to 1 is feasible to validate the data collection process. The results of the data validation for the two technological energy efficiency indices are presented in Table (4.3) alongside the standard error of the mean (SEM), indicating how far the sample mean is likely to fall from the true population mean.

Overall, the ratios are close to 1 across shipping sectors, suggesting that the collected data and assumptions appear to be a good reflection of the actual vessel characteristics. Over the whole sample, on average, the ratio is a mere 1.02, indicating that the derived estimates are only 2% higher than the actual reported values. This is especially observed for vessels with an EIV as a measure of their energy efficiency. For these vessels, the reported index is adjacent to the estimated index, with an average ratio of 1.01. For vessels having obtained an EEDI rating, the computed measure overestimates the actual rating on average by roughly 6%. This result is not surprising;

Table 4.3: Data validation results

	Obs.	Mean ratio	Median ratio	SEM
Overall	6,272	1.02	1.00	0.003
Estimated Index Value (EIV)	4,722	1.01	1.00	0.003
Bulk carrier	1,910	1.03	1.02	0.004
Chemical tanker	695	1.01	1.00	0.008
Container ship	985	1.02	1.00	0.007
Gas carrier	150	1.00	1.00	0.020
Oil tanker	982	0.97	0.99	0.005
Energy Efficiency Design Index (EEDI)	1,550	1.06	1.01	0.006
Bulk carrier	567	1.05	1.00	0.009
Chemical tanker	248	1.06	1.04	0.021
Container ship	288	1.07	1.01	0.013
Gas carrier	82	1.06	1.04	0.021
Oil tanker	365	1.06	1.01	0.009

Note: Sample size in Table (4.3) differs, as the energy efficiency index values (EEDI or EIV) are not reported for all vessels in the EU-MRV database.

the approach does not consider potential vessel-specific correction or adjustment factors incorporated into the EEDI formula like, e.g., reduction factors for innovative technologies or correction factors for ice-class ships. In general, these factors reduce the attained EEDI rating, so it is to be expected that the simplified approximation overestimates the actual rating. There are also only minor differences in the estimates across ship types, which is reassuring.

However, this assessment does not rule out the existence of idiosyncratic data mistakes and outliers, which could bias the results in the subsequent data envelopment analysis. To address this potential issue, all observations with a ratio outside the bounds of the interquartile rule for both indices have been labelled potential outliers, and the robustness of the derived results with respect to these observations is evaluated in section (4.5.3) (Upton & Cook, 1996, p.56).

4.4.2 Data analysis

The strategy to analyze the data consists of three main elements. The first is a general theoretical framework for benchmarking the energy efficiency of ship designs to formulate empirical models. The second is a nonparametric metafrontier method based on DEA to estimate the relative efficiency of vessels within sectors and to make efficiency comparisons across sectors. The third features bootstrapping techniques to correct for the inherent bias of the DEA estimator, which is dependent on the sample and not uniform across sectors. The individual elements of the strategy are thoroughly outlined in sections (4.4.2.1) to (4.4.2.5).

4.4.2.1 General theoretical framework

Departing from the general rationale for measures of energy efficiency in the maritime industry, I note that equation (4.1) can be interpreted in the following way: a vessel uses fuel energy to provide the cargo transportation service defined as transport work. Because the environmental impact not only depends on the amount of fuel consumed but also on the type of fuel, the input side is expressed in carbon emissions. Hence, it transforms energy as an input into travelled distance of cargo as an output. It is possible to derive a more granular and multi-faceted picture of the inputs and outputs by partitioning the elements of equation (4.1), which is depicted in Figure (4.1). To illustrate, one can see that on the input side, a vessel's k total carbon emissions can be disaggregated into the carbon emissions of the main and auxiliary engines installed onboard. The engine's carbon emissions depend mostly on the determinants outlined in section (4.4.1). This representation provides a general theoretical framework for all vessels based on the maritime rationale for technological energy efficiency and enables the formulation of multiple possible input-output combinations to represent the transformation process. Further, the framework ensures that a vessel only gets benchmarked against comparable units and allows for sector-specific comparisons, which are described in the following section.

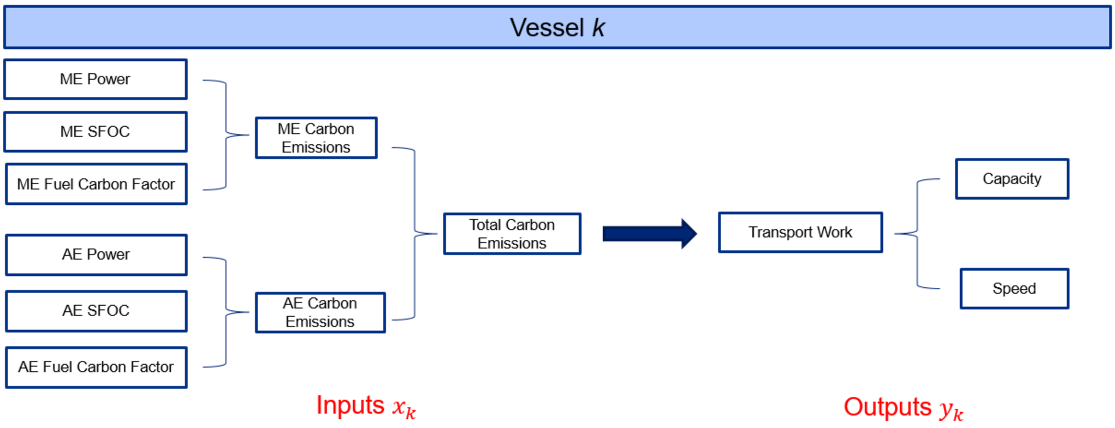

FIGURE 4.1: General framework - Input-output combinations of a vessel

4.4.2.2 Sector-specific frontiers

Consider observations on $k = 1, ..., N$ transportation units, with each unit k comprising a vector of inputs $x_k = (x_{1k}, ..., x_{pk}) \in \mathbb{R}^p_+$ and a vector of outputs $y_k = (y_{1k}, ..., y_{qk}) \in \mathbb{R}^q_+$. The sample is composed of observations from $g = 1, ..., G$ distinct sectors (groups) of size N_g and $\sum_{g=1}^{G} N_g = N$ has to hold. Further, the combination of inputs and outputs of unit k is denoted as (x_k, y_k). The underlying technology set $T(g)$ for each sector g is defined by,

$$T(g) = \{(x, y) \in \mathbb{R}^p_+ \times \mathbb{R}^q_+ \mid x \text{ can produce } y \text{ in sector } g\}. \tag{4.3}$$

Note that the true technology sets are unknown; thus, the nonparametric data envelope estimator proposed by Charnes et al. (1978) is utilized to derive an estimate $\hat{T}(g)$ of $T(g)$ for each sector. The approach is based on the minimum extrapolation principle of the observed input-output combinations, satisfying free disposability and convexity as technological assumptions. Further, no rescaling is assumed, i.e., varying returns to scale, resulting in a flexible inner approximation of the true technology set based on a minimum set of assumptions. In short, $\hat{T}(g)$ is a piece-wise linear, non-decreasing, and concave estimate of $T(g)$ with $\hat{T}(g) \subseteq T(g)$. The estimate for $\hat{T}(g)$ is then given by,

$$\hat{T}(g) = \{(x, y) \in \mathbb{R}^p_+ \times \mathbb{R}^q_+ \mid \exists \lambda \in \mathbb{R}^{N_g}_+ : x \geq \sum_{k \in N_g} \lambda_k x_k,\ y \leq \sum_{k \in N_g} \lambda_k y_k,\ \sum_{k \in N_g} \lambda_k = 1\}. \tag{4.4}$$

Intuitively, equation (4.4) describes the observed best practices for transportation units in sector g and will be referred to as the estimated efficient sector-specific frontier. To quantify the technical efficiency of the individual transportation units relative to the efficient frontiers, a radial output-based efficiency measure is utilized. More formally, the output-based efficiency F_k^g of firm k with (x_k, y_k) relative to technology set $T(g)$ is defined as,

$$\hat{D}_k^g = max\, \{F \in \mathbb{R}_+ \mid (x_k, y_k/F) \in \hat{T}(g)\}. \tag{4.5}$$

This function indicates the maximum radial expansion of the output vector y_k given the inputs x_k for unit k. Note that inserting equation (4.4) into equation (4.5) yields for the DEA approach a typical linear programming problem, which is thoroughly outlined in Charnes et al. (1978) and Bogetoft (2013). Further, a unit can be considered efficient with respect to the sector-specific frontier if and only if $\hat{D}_k^g = 1$ (O'Donnell et al., 2008).

4.4.2.3 Industry metafrontier

Under the stated formulation, each sector is associated with a different technology set. This is due to the fact that the transportation units (i.e., vessels) are designed for different purposes like, e.g., the kind of cargo they are transporting or the routes on which they are deployed. This restricts the technology choice at the design stage, and the boundaries of the restricted technology sets $T(g)$ determine the sector-specific frontiers[3]. Thus, the observed transportation units form distinct sector groups, each of which has their respective technological conditions. Relying on a traditional DEA approach considering only one common technology set does not reflect the different technological conditions across sectors and might yield unrealistic estimates of efficiency scores. The metafrontier approach provides an appropriate methodology to compare the efficiency of transportation units belonging to different sectors (Battese et al., 2004; O'Donnell et al., 2008). From the restricted sector-specific technology sets, it is possible to formulate an industry metatechnology set containing all feasible input-ouput combinations defined by,

$$T = \{(x, y) \in \mathbb{R}_+^p \times \mathbb{R}_+^q \mid x \text{ can produce } y\}. \tag{4.6}$$

[3]Note that the constraints are not limited to technical constraints but can also be due to any other characteristic of the physical, social, and economic environment influencing ship designs (O'Donnell et al., 2008).

Based on the same set of assumptions as for $\hat{T}(g)$, it is then possible to derive an estimate $\hat{T}$, which I will refer to as the metatechnology frontier. Similarly, the output efficiency of observation k with respect to the metafrontier can be measured by,

$$\hat{D}_k = max\,\{F \in \mathbb{R}_+ \mid (x_k, y_k/F) \in \hat{T}\}. \tag{4.7}$$

Intuitively, the metafrontier measures the efficiency of a transportation unit given that there are no restrictions in the technology choice at the design stage and under the assumption that all units have access to the same technologies. This allows the formulation of a measure of how close the sector-specific frontiers are to the industry metafrontier. This measure is referred to as the metatechnology ratio, and for units belonging to sector g with input-output combinations (x, y) is defined by,

$$MTR(x, y) = \frac{D(x, y)}{D^g(x, y)}. \tag{4.8}$$

The ratio indicates how limiting the technological conditions in sector g are when compared to the unrestricted metatechnology containing all observed ship design technologies in the sample. To illustrate, a ratio of 0.8 means that, given the input vector, the maximum output that can be achieved by a transportation unit in sector g is 80% of the feasible output using the metatechnology. A lower metatechnology ratio indicates that the technology set in sector g is more restricted and, thus, the technological conditions are more limiting.

4.4.2.4 Sample bias

I remark that while a unit with an estimated efficiency score $\hat{D}_k^g > 1$ is objectively inefficient, such a conclusion cannot be made for the efficient units with $\hat{D}_k^g = 1$ spanning the estimated efficient frontiers. As highlighted, the true technology sets $T(g)$ and, thus, the true efficiency scores D_k^g are unknown and are estimated by the DEA estimator. However, because the estimated technology set $\hat{T}(g)$ is a subset of $T(g)$, the estimator is biased (but consistent) and yields upward-biased efficiency score estimates $\hat{D}_k^g$. The same argument applies to the efficiency scores with respect to the metatechnology T. This is especially problematic for the comparison of different sectors, each having their individual technology set estimate (Zhang & Bartels, 1998). To illustrate, Simar and Wilson (2000) remark that the bias decreases in sample size and density around a frontier point and increases in the curvature of the frontier. Intuitively, one can expect the bias to be relatively small in a situation where a large sample with homogeneous units faces a frontier with a mild curvature.

Note that the sample size varies between the five sectors, and this is likely also the case for the density and frontier curvature. Thus, the bias cannot be expected to be uniform across sectors, and a comparison of efficiency scores derived from the idiosyncratic sector models would be highly questionable in this application. Results from the asymptotic theory about the sampling distribution can only be applied to derive a bias-corrected DEA estimator for a simple single input and output model. Therefore, the study resorts to bootstrapping techniques to derive bias-corrected efficiency measures and to construct confidence intervals for the (true) efficiency scores D_k^g. In particular, the study follows the algorithm for bootstrapping in nonparametric frontier models proposed by Simar and Wilson (1998) (please refer to Daraio and Simar (2007) on page 61–62 for a detailed description of the procedure). The required bandwidth choice for the kernel density estimator has been determined according to the robust normal reference rule (Silverman, 1986). Lastly, this procedure should also mitigate the effects of the reduced sample size due to focusing on the EU-MRV subsample, and it yields 95% confidence intervals for the unobservable true efficiency scores.

4.4.2.5 Empirical models

Based on the general framework presented in section (4.4.2.1), various multiple inputs-outputs models can be formulated. Table (4.4) summarizes the main candidate models with the respective input and output sets. From a conceptual viewpoint, the study hypothesizes that *"Model 3"* is most appropriate in this application for the following reasons. First, in the data collection process, several assumptions had to be made for determinants of the auxiliary engines. Using the aggregate measure for the auxiliary engines mitigates the potential influence of idiosyncratic errors in the decomposed determinants. Second, the main engine is responsible for around 80% of a vessel's carbon emissions and is of key importance for a vessel's energy efficiency. Hence, a granular representation of the main engine's characteristics in the benchmarking model is conceptually feasible.

TABLE 4.4: Empirical models

Model 1	**Model 2**	**Model 3**	**Model 4**
Outputs			
Capacity	Capacity	Capacity	Capacity
Speed	Speed	Speed	Speed
Inputs			
ME Carbon Emissions	ME Power	ME Power	ME Power
AE Carbon Emissions	ME SFOC	ME SFOC	ME SFOC
	ME Carbon Factor	ME Carbon Factor	ME Carbon Factor
		AE Carbon Emissions	AE Power
			AE SFOC
			AE Carbon Factor

To ensure the obtained results are not driven by the model formulation and are robust to alternative specifications, a sensitivity analysis is conducted in section (4.5.3).

4.5 Results

4.5.1 Results for sector frontiers

In this section, sector-specific frontiers are constructed to compare the performance of each vessel with the performance of other vessels within the sector according to the methodology described in section (4.4.2.2). Table (4.5) presents the results for the uncorrected (standard) and bias-corrected average technical efficiency scores, alongside the 95% confidence intervals and the average bias estimate. Note that the average effect of the bias correction on efficiency scores is in general small, ranging from 0.5% to 1.9%. The first observation is that the bias and, thus, the confidence intervals are not decreasing in sample size across sectors. To illustrate, the bulk carrier group is the sector

Table 4.5: Technical efficiency score results with respect to sector-specific frontiers

Sector	Original eff. score	Bias-corrected eff. score	Lower bound	Upper bound	Mean bias
Bulk carrier	0.838	0.826	0.813	0.836	0.012
Chemical Tanker	0.866	0.852	0.839	0.863	0.014
Container ship	0.941	0.936	0.931	0.940	0.005
Gas carrier	0.848	0.829	0.805	0.846	0.019
Oil tanker	0.852	0.841	0.830	0.851	0.011

with the largest sample size, but its average bias of 1.2% is higher than the container shipping sector's average bias of 0.5%. This is most likely due to the observations in the container shipping sector being more homogeneous than those in the bulk carrier sector. Hence, there appears more variability in the input-output structure of bulk carriers and, thus, more diversity in ship designs from an energy efficiency perspective. Further, for all considered sectors, the uncorrected average efficiency scores are located outside the constructed confidence intervals. This emphasizes the utility of bias-correction in this application and the risk of using uncorrected efficiency scores, especially if one would be interested in the relative performance of the individual observations (De Borger et al., 2008; Fallah-Fini et al., 2012).

I will now turn to the interpretation of the derived results. In general, efficiency scores smaller than one represent the magnitude of improvements that could be achieved in the outputs without requiring additional inputs. The scope for efficiency improvements ranges, on average, from 6.4% to 17.4%, depending on the sector. To illustrate, on average, bulk carriers could increase their output capacity and speed by 17.4% without requiring additional machinery or energy inputs. In contrast, container ships, on average, can only improve their outputs by 6.4% given the inputs. The scope for average efficiency improvements in the other three sectors appears rather similar, ranging from 14.8% to 17.1%, but focusing on a single point-wise measure only yields an incomplete picture of the analysis. To provide a more detailed description, the distribution of bias-corrected efficiency scores per sector is presented in Figure (4.2) in the appendix. To illustrate, the efficiency score distributions for the oil and chemical tanker sectors appear concentrated around the average efficiency score, and few observations are located close to the frontier. On the other hand, in the gas carrier sector, the global maximum is around a value of 0.77, and there is a larger dispersion of efficiency score values, with many observations located close to the sector frontier.

Based on the preceding interpretation, one might conclude that if one sector has a higher average efficiency than another, it implies that the sector is more efficient. However, the results of Table (4.5) only present the relative performance of vessels compared to their sector-specific frontiers, which might differ in location. Hence, the efficiency scores derived from benchmarks against different sector frontiers cannot be directly compared with each other. The results for the metafrontier analysis, allowing for industry-wide comparisons across sectors, are reported in the following section.

4.5.2 Results for metafrontier

In this section, the industry metafrontier enveloping the group frontiers is constructed to enable comparisons of relative performance across sectors according to the methodology in section (4.4.2.3). For this purpose, all observations were pooled to compute a common industry metafrontier representing the current state of ship design technologies across all considered sectors. Table (4.6) shows the average bias-corrected efficiency scores with respect to the group frontiers and the metafrontier, as well as the metatechnology ratios, for each sector.

Overall, the average metatechnology ratios range from 82.8% to 95.0% across sectors. To give the reader a specific example, the average technical efficiency in the chemical tanker sector with respect to the group frontier is 0.852. This means that, on average, chemical tankers could improve their outputs by 14.8% without requiring additional machinery or energy inputs. When compared to the industry metafrontier, the average technical efficiency of chemical tankers drops to 0.705. Thus, the potential for output improvements (given the inputs) is twice as high for chemical tankers when considering the unrestricted industry metafrontier instead of the restricted sector frontier. Another

Table 4.6: Summary of the technical efficiency corresponding to each sector in the pooled dataset

	Technical efficiency group frontier		Technical efficiency meta-frontier		Metatechnology ratio	
Sector	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Bulk carrier	0.826	0.045	0.725	0.054	0.878	0.045
Chemical Tanker	0.852	0.045	0.705	0.048	0.828	0.035
Container ship	0.936	0.046	0.890	0.076	0.950	0.062
Gas carrier	0.829	0.081	0.740	0.054	0.898	0.073
Oil tanker	0.841	0.053	0.752	0.069	0.895	0.069

Note: Table (4.6) reports the bias-corrected efficiency scores. Differences in the estimated bias for each vessels with respect to the group frontier and metafrontier leads in rare instances (0.7% of total observations) to metatechnology ratios marginally greater than one.

way of stating this observation is by looking at the average metatechnology ratio, which is 0.828 for the chemical tanker sector. On average, given the machinery and energy inputs, the maximum output that can be achieved by a chemical tanker is 82.8% of the output that is feasible given the current state of ship design technologies in the maritime industry. In contrast, the average metatechnology ratio for the container shipping sector is 0.95. This large value also implies that the container shipping sector's frontier is more tangent to the industry metafrontier than the chemical tanker sector's frontier. Hence, the container shipping sector plays a bigger role in spanning the unrestricted industry metafrontier than the chemical tanker sector. A similar observation can be made for gas carriers, where the average metatechnology ratio is 0.898. Although the average potential for improving outputs with respect to the sector frontier is 17.1%, their maximum output that can be achieved is already 89.8% of the feasible output; thus, the sector frontier is adjacent to the industry metafrontier.

Lastly, the results from the pooled metafrontier model allow for a test of whether there are any statistically significant differences in the efficiency scores of the considered sectors. For this, the Kruskal–Wallis test is utilized to test whether efficiency scores of the sector samples originate from the same distribution (Kruskal & Wallis, 1952). The test rejects the null hypothesis that the mean ranks of the sectors are the same at the 1% level. Thus, it can be concluded that there are statistically significant differences between the efficiency scores of vessels in the different sectors. This further validates the usefulness of the metafrontier framework in this application to compare the relative performance across considered sectors.

4.5.3 Sensitivity analysis and robustness

In this section, the robustness of the derived relative performance measures is assessed. This is an important task, as it is known that estimated relative efficiency scores are sensitive to a variety of factors, which might jeopardize the generalizability of the derived results (Cooper et al., 2004). In this study, two of the main concerns are the sensitivity of the computed results with respect to the empirical model formulation and potential idiosyncratic data mistakes.

Because the theoretical framework outlined in Figure (4.1) allows for multiple input and output set formulations, one can ex ante only hypothesize about the appropriate model specifications based on contextual reasoning. However, this choice has direct implications for the estimated efficiency scores and the precision of the DEA estimator. In general, increasing the dimensionality of the technology set by increasing the number of input/output variables leads to, ceteris paribus, (weakly) increasing efficiency scores. In addition, the sample bias is increasing in the number of output/input variables, requiring much larger sample sizes to derive precise estimates (Simar & Wilson, 2008). Therefore, the efficiency scores for the alternative model formulations summarized in Table (4.4) were computed as a robustness check.

Outliers due to idiosyncratic data mistakes are another prime concern when using the DEA approach. Especially, if such an outlier is located at the frontier, its existence might impact the relative performance of several other observations through, e.g., facilitating unrealistic convex combinations to span the frontier (Bogetoft, 2013). Thus, the sensitivity of efficiency scores was evaluated for all models in Table (4.4) by excluding all potential data mistakes identified in section (4.4.1.1) as an additional robustness check. Table (4.7) summarizes the average standard efficiency scores for these robustness checks alongside the results for Model 3 for comparison.

Table 4.7: Sensitivity analysis with respect to model specification and data validation outliers

	Model 1 eff. scores		Model 2 eff. scores		Model 3 eff. scores		Model 4 eff. scores	
Sector	All obs.	Outliers excluded	All obs.	Outliers excluded	All obs.	Outliers excluded	All obs.	Outliers excluded
Bulk carrier	0.819	0.821	0.838	0.839	0.838	0.840	0.840	0.841
Chemical Tanker	0.861	0.877	0.866	0.884	0.866	0.884	0.874	0.893
Container ship	0.940	0.948	0.940	0.949	0.941	0.950	0.947	0.952
Gas carrier	0.833	0.842	0.848	0.851	0.848	0.852	0.850	0.866
Oil tanker	0.849	0.883	0.852	0.887	0.852	0.888	0.853	0.888

Note: Table (4.7) reports uncorrected efficiency scores for the considered models with all observations and with outliers excluded. The conclusion does not change when considering bias-corrected efficiency scores.

In general, the average efficiency scores across sectors are, as expected, increasing in the number of input and output variables and are only minorly different from the results of Model 3. This observation confirms that the derived results are not driven by the empirical model choice based on contextual reasoning. The biggest deviation from the presented results can be observed in Model 1 for the bulk carrier sector, with an absolute difference in average efficiency scores of 1.9%. Similarly, when excluding outliers, the average efficiency scores are increasing across sectors compared to the models with all observations. This can be explained by the reduced number of observations when constructing the sector-specific frontiers, which (weakly) increases the efficiency scores, as well as the potential bias due to the reduced sample size. However, the changes in average efficiency scores are overall only moderate across sectors. The largest absolute difference in average efficiency scores ranges from 3.4% to 3.6% for the oil tanker sector. This can be explained by the fact that in this sector, more outliers are located at the frontier. However, this does not imply that all excluded outliers are idiosyncratic data mistakes, as the presented data validation approach does not capture the correction and adjustment factors incorporated in the EEDI formula. Hence, it is a rather cautious evaluation by removing all potential idiosyncratic data mistakes to ensure the robustness of the analysis. To conclude, the results from the sensitivity analysis show only slight deviations from the presented results, which is reassuring.

4.6 Final discussion

In this section, I thoroughly evaluate the presented results and discuss their implications for policy makers that strive to foster continuously the adoption and development of clean technologies in vessel designs. The study aims to assess the scope for improvements through the adoption of existing ship designs and the technological conditions for the container, tanker, and dry bulk shipping sectors. For this purpose, a general framework for benchmarking the energy efficiency of ship designs is proposed. Further, the nonparametric metafrontier approach is employed in combination with bootstrapping techniques to derive robust relative efficiency measures by considering the heterogeneity across shipping sectors due to different restrictions.

The first result is that the scope for improvements through the adoption of existing best-practice ship designs substantially differs across sectors. Based on the results from the sector-specific frontier analysis, this scope within sectors ranges between 6.4% in the container shipping and 17.4% in the dry bulk sectors. A potential explanation for these variations are the differences in the market structure and dynamics of the different shipping sectors. The dry bulk sector is considered characterized by many buyers and suppliers of shipping services for mostly intermediary goods, including ore, iron, and coal, with low entry barriers, and it is often referred to as a perfect competition market structure (Stopford, 2009). Therefore, the sector is driven by price considerations and not environmental concerns. In contrast, containerized cargo in container shipping is of high value and close to the end consumers. While there is significant market concentration on the supplier side, there are major consumer brands on the buyer side concerned with the brand loyalty of their customers. Because environmental awareness is rising among end consumers, consumer brands are under pressure to improve the carbon footprint of their whole supply chains and demand this from their suppliers of maritime transport (Poulsen et al., 2016). It seems plausible that container shipping has already adopted more best practices in their ship designs and, in turn, has a lower scope for efficiency improvements than a price-driven sector, like dry bulk shipping.

The second result is that there are also differences in the technological conditions across sectors. This is based on the results from the metafrontier analysis measuring how close the restricted sector-specific frontiers are to the unrestricted metafrontier representing the current state of ship design technologies in the industry. The metatechnology ratios representing the technological conditions range between 0.828 and 0.950 across sectors. The container shipping sector has the highest ratio, implying that the sector frontier is closely located to the industry frontier. This can be explained by the fact that most container ships due to their high speed populate a unique space in the technology set, which does not permit direct comparisons with ship designs from other sectors. The chemical tanker sector has the lowest metatechnology ratio, implying that the maximum achievable output by a chemical tanker given the inputs is, on average, 82.8% of the feasible output from an industry perspective. This indicates that their technological conditions are more limiting compared to the other sectors; thus, their scope for efficiency improvements is curbed by potential restrictions in design choices.

4.6.1 Policy implications

I will now turn to discussing the policy implications of the presented analysis. First, it is plausible that the presented approach can improve the effectiveness of existing technological energy efficiency regulations in the maritime industry. As discussed, previous studies have highlighted that mandatory compliance with the EEDI regulation may rather lead to speed reductions than the adoption of energy-optimizing technologies at the design stage (Polakis et al., 2019). In the current approach, a vessel's requirement is determined by its size and, thus, reducing a vessel's speed given the size is seen as an easy way to comply with the EEDI regulation (Molland et al., 2017). However, such unintended side effects reduce the direct expected effect of the policy measure and its effectiveness in fulfilling the policy objective (Justen, Schippl, et al., 2014). In contrast, the proposed DEA approach uses a measure considering radial expansions in both capacity and speed given the inputs. Hence, speed reductions by reducing the main engine's power would lead to a change in the reference against which the vessel is compared and alter the requirement.

In addition, the comparisons against a fixed reference line entail a binary pass–fail criterion to assess a vessel's compliance. This implies that the current regulation in itself does not provide any incentive to outperform the minimum requirements and does not incorporate any feedback from the shipbuilding market (Ančić & Šestan, 2015). Such feedback mechanisms can improve the effectiveness of policy measures by introducing competitive market forces. When shifting the focal point of comparisons from minimum standards to best practices, the requirement dynamically tightens when new innovative ship designs arrive in the market, forcing others to improve further the technological energy efficiency of their ship designs. Further, it directly allows for a more flexible ranking of vessels instead of a binary pass–fail criterion, which would be more appropriate (Ančić et al., 2018)). To conclude, policy measures based on the presented approach could arguably be more effective to foster continuously improvements in the energy efficiency of ship designs by addressing currently observed side effects and introducing competitive market forces.

In light of the previous discussion, it seems questionable whether current measures like the EEDI and the planned EEXI are sufficient to reach the ambitious policy target; it is likely that additional instruments are needed. I argue that, plausibly, the considered sectors benefit from different additional measures to foster continuous improvements in technological energy efficiency. Previous studies examining policy packaging to address transport policy challenges have stressed that a policy measure's performance can never be assessed in isolation and crucially depends on the situational context in which it is implemented (Givoni, 2014). As shown, in the maritime industry, there is substantial heterogeneity in the scope for improvements within sectors and the technological conditions across sectors. Hence, future measures to enhance the intended effects of the existing measures must be cognizant of this heterogeneity in situational contexts (Justen, Fearnley, et al., 2014).

This theoretical perspective resonates with the metafrontier framework, offering a quantitative decision support tool to design instruments by allowing policy makers to assess the potential payoffs of different initiatives (O'Donnell et al., 2008). To illustrate, in the dry bulk sector, there is still a significant scope for improvements through the adoption of existing best practices within the sector. Therefore, initiatives and measures targeted at shipbuilders and owners to improve the technological energy efficiency of their ship designs by adopting already-utilized technologies can be fruitful here. In contrast, in the container shipping sector, the potential for improvements through the adoption of best practices in the sector and the industry is small; thus, expanding the space of existing ship designs is needed here. Additional policy instruments should support the development and introduction of new and innovative technologies like, for example, alternative fuels in container ship designs to enable further improvements in technological energy efficiency for the sector. Hence, by taking a sector-specific perspective when designing additional instruments, policy makers can potentially more effectively and targeted foster continuous improvements in energy efficiency than with a general industry-wide view.

4.6.2 Limitations and future research

It is important to highlight that the presented analysis relates to the energy efficiency of vessels from a ship design perspective. This efficiency measure might in practice be substantially different from the observed operational energy efficiency due to deviations from theoretical conditions or due to practices like slow steaming, referring to operating a vessel significantly below its design speed to reduce fuel costs. Comparing and benchmarking the operational energy efficiency of vessels is a highly relevant topic for the maritime industry, which is exemplified by the carbon intensity indicator (CII) regulation, which was formally adopted in 2021 by the IMO. However, key challenges to benchmark the operational energy efficiency of vessels is the inherent noise in recorded operational data and the necessity to control for uncontrollable external factors, such as weather conditions, which are a major influence on ship fuel consumption (ICS, 2018). These two issues would need to be addressed by potential future studies to derive realistic measures of vessels' relative performance across sectors.

Lastly, I remark that the analysis does not encompass all technological components related to the fuel efficiency of a ship design. Most notably, energy-saving technologies reducing the auxiliary engine's power by generating electricity (e.g., waste heat recovery and photovoltaic power generation systems) or reducing the required main engine's power (e.g., air lubrication and wind propulsion systems) are not considered. This is due to the lack of available data concerning these variables. These variables would be particularly important to consider if one is interested in the specific efficiency scores of individual vessels, in addition to the presented sector averages. Future research concerned with deriving such comprehensive comparisons of vessels in certain categories or vessel classes is feasible, as it can yield important insights into the specific characteristics of efficient ship designs. This could assist decision makers in the maritime industry in their technology choices and help identify the most effective ship designs for driving the green transition of the maritime industry.

Appendix

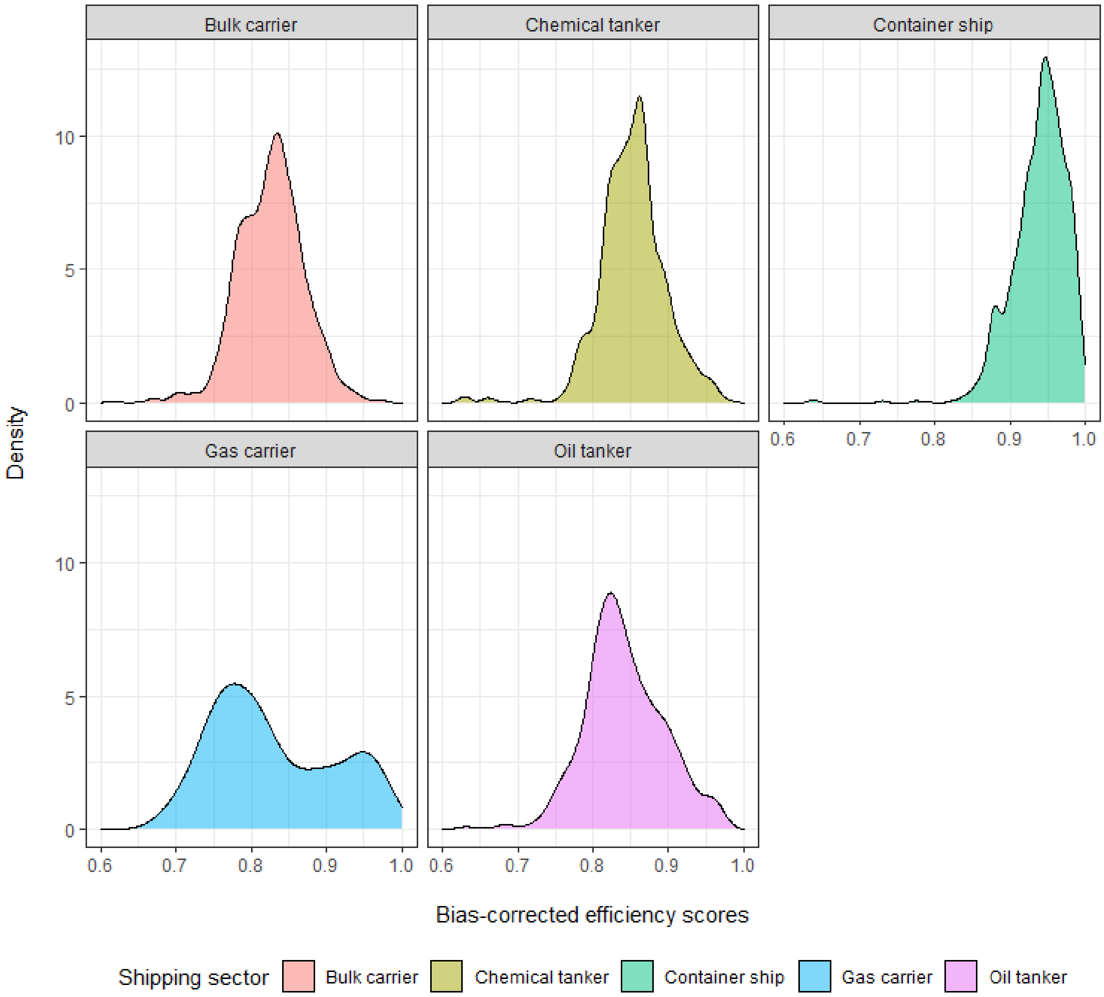

FIGURE 4.2: Density plots of bias-corrected efficiency scores per sector

References

Ančić, I., & Šestan, A. (2015). Influence of the required EEDI reduction factor on the CO_2 emission from bulk carriers. *Energy Policy*, *84*, 107–116.

Ančić, I., Theotokatos, G., & Vladimir, N. (2018). Towards improving energy efficiency regulations of bulk carriers. *Ocean Engineering*, *148*, 193–201.

Attah, E. E., & Bucknall, R. (2015). An analysis of the energy efficiency of LNG ships powering options using the EEDI. *Ocean Engineering*, *110*, 62–74.

Banister, D. (2008). The sustainable mobility paradigm. *Transport Policy*, *15*(2), 73–80.

Battese, G. E., Rao, D. P., & O'donnell, C. J. (2004). A metafrontier production function for estimation of technical efficiencies and technology gaps for firms operating under different technologies. *Journal of Productivity Analysis*, *21*(1), 91–103.

Bogetoft, P. (2013). *Performance benchmarking: Measuring and managing performance.* Springer.

Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research*, *2*(6), 429–444.

Cooper, W. W., Li, S., Seiford, L. M., & Zhu, J. (2004). Sensitivity analysis in DEA. In *Handbook on data envelopment analysis* (pp. 75–97). Springer.

Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Solazzo, E., Monforti-Ferrario, F., ... Vignati, E. (2020). *Fossil CO_2 emissions of all world countries - 2020 report* (Tech. Rep.). European Commission. Retrieved from https://edgar.jrc.ec.europa.eu/booklet/Fossil_CO2_emissions_of_all_world_countries_booklet_2020report.pdf

Cui, Q., & Li, Y. (2014). The evaluation of transportation energy efficiency: An application of three-stage virtual frontier DEA. *Transportation Research Part D: Transport and Environment*, *29*, 1–11.

Dalkmann, H., & Brannigan, C. (2007). *Transport and climate change. Module 5e. Sustainable transport: A sourcebook for policy-makers in developing cities.* Federal Ministry for Economic Cooperation and Develompent. Retrieved from https://city2030.org.ua/sites/default/files/documents/GIZ_SUTP_SB5e_Transport-and-Climate-Change_EN.pdf

Daraio, C., & Simar, L. (2007). *Advanced robust and nonparametric methods in efficiency analysis: Methodology and applications.* Springer.

De Borger, B., Kerstens, K., & Staat, M. (2008). Transit costs and cost efficiency: Bootstrapping non-parametric frontiers. *Research in Transportation Economics*, *23*(1), 53–64.

DNV. (2020). *EEXI – Energy efficiency existing ship index.* Retrieved from `https://www.dnv.com/maritime/insights/topics/eexi/index.html#`

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauerhof, E., & Yuan, H. (2020). *Fourth IMO greenhouse gas study 2020* (Tech. Rep.). International Maritime Organization. Retrieved from `https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf`

Fallah-Fini, S., Triantis, K., Jesus, M., & Seaver, W. L. (2012). Measuring the efficiency of highway maintenance contracting strategies: A bootstrapped non-parametric meta-frontier approach. *European Journal of Operational Research*, *219*(1), 134–145.

Givoni, M. (2014). Addressing transport policy challenges through policy-packaging. *Transportation Research Part A: Policy and Practice*, *60*, 1–8.

Gong, X., Wu, X., & Luo, M. (2019). Company performance and environmental efficiency: A case study for shipping enterprises. *Transport Policy*, *82*, 96–106.

Green Ship. (2020). *The retrofit project* (Report). Green Ship of the Future. Retrieved from `https://greenship.org/wp-content/uploads/2020/05/GSF-Retrofit-Project.pdf`

ICS. (2018). *Reducing CO_2 emissions to zero: The "Paris Agreement for Shipping". implementing the initial strategy on reduction of GHG emissions from ships* (Tech. Rep.). Retrieved from `https://www.ics-shipping.org/wp-content/uploads/2020/08/reducing-co2-emissions-to-zero-the-paris-agreement-for-shipping.pdf`

IMO. (2020). *Energy efficiency measures.* Retrieved from `https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx`

Justen, A., Fearnley, N., Givoni, M., & Macmillen, J. (2014). A process for designing policy packaging: Ideals and realities. *Transportation Research Part A: Policy and Practice*, *60*, 9–18.

Justen, A., Schippl, J., Lenz, B., & Fleischer, T. (2014). Assessment of policies and detection of unintended effects: Guiding principles for the consideration of methods and tools in policy-packaging. *Transportation Research Part A: Policy and Practice*, *60*, 19–30.

Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal* *of the American Statistical Association*, *47*(260), 583–621.

Lindstad, E., Asbjørnslett, B. E., & Strømman, A. H. (2011). Reductions in greenhouse gas emissions and cost by shipping at lower speeds. *Energy Policy*, *39*(6), 3456–3464.

Lindstad, E., & Bø, T. I. (2018). Potential power setups, fuels and hull designs capable of satisfying future EEDI requirements. *Transportation Research Part D: Transport and Environment*, *63*, 276–290.

Luna, J. H., Mar-Ortiz, J., Gracia, M. D., & Morales-Ramírez, D. (2018). An efficiency analysis of cargo-handling operations at container terminals. *Maritime Economics & Logistics*, *20*(2), 190–210.

Makridou, G., Andriosopoulos, K., Doumpos, M., & Zopounidis, C. (2016). Measuring the efficiency of energy-intensive industries across European countries. *Energy Policy*, *88*, 573–583.

Martinez-Budria, E., Diaz-Armas, R., Navarro-Ibanez, M., & Ravelo-Mesa, T. (1999). A study of the efficiency of Spanish port authorities using data envelopment analysis. *International Journal of Transport Economics*, *26*(2), 237–253.

MEPC. (2011). *Inclusion of regulations on energy efficiency for ships in MARPOL Annex VI.* International Maritime Organization. Retrieved from `https://imointernetcdn.azureedge.net/localresources/en/OurWork/Environment/Documents/TechnicalandOperationalMeasures/ResolutionMEPC.203(62).pdf`

MEPC. (2018). *2018 guidelines on the method of calculation of the attained energy efficiency design index (EEDI)) for new ships.* International Maritime Organization. Retrieved from `https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.308(73).pdf`

Molland, A. F., Turnock, S. R., & Hudson, D. A. (2017). *Ship resistance and propulsion.* Cambridge University Press.

Mærsk. (2021). *A.P. Møller - Mærsk will operate the world's first carbon neutral liner vessel by 2023 – seven years ahead of schedule.* Retrieved from `https://www.maersk.com/news/articles/2021/02/17/maersk-first-carbon-neutral-liner-vessel-by-2023`

Nguyen, H.-O., Nguyen, H.-V., Chang, Y.-T., Chin, A. T., & Tongzon, J. (2016). Measuring port efficiency using bootstrapped DEA: The case of Vietnamese ports. *Maritime Policy & Management*, *43*(5), 644–659.

Omrani, H., Shafaat, K., & Alizadeh, A. (2019). Integrated data envelopment analysis and cooperative game for evaluating energy efficiency of transportation sector: A case of Iran. *Annals of Operations Research*, *274*(1-2), 471–499.

O'Donnell, C. J., Rao, D. P., & Battese, G. E. (2008). Metafrontier frameworks for the study of firm-level efficiencies and technology ratios. *Empirical Economics*, *34*(2), 231–255.

Panayides, P. M., Lambertides, N., & Savva, C. S. (2011). The relative efficiency of shipping companies. *Transportation Research Part E: Logistics and Transportation Review*, *47*(5), 681–694.

Polakis, M., Zachariadis, P., & de Kat, J. O. (2019). The energy efficiency design index (EEDI). In *Sustainable shipping* (pp. 93–135). Springer.

Poulsen, R. T., Ponte, S., & Lister, J. (2016). Buyer-driven greening? Cargo-owners and environmental upgrading in maritime shipping. *Geoforum*, *68*, 57–68.

Psaraftis, H. N. (2019). Decarbonization of maritime transport: To be or not to be? *Maritime Economics & Logistics*, *21*(3), 353–371.

Quintano, C., Mazzocchi, P., & Rocca, A. (2020). Examining eco-efficiency in the port sector via non-radial data envelopment analysis and the response based procedure for detecting unit segments. *Journal of Cleaner Production*, *259*, 120979.

Roll, Y., & Hayuth, Y. (1993). Port performance comparison applying data envelopment analysis (DEA). *Maritime Policy & Management*, *20*(2), 153–161.

Saidur, R., Sattar, M., Masjuki, H. H., Ahmed, S., & Hashim, U. (2007). An estimation of the energy and exergy efficiencies for the energy resources consumption in the transportation sector in Malaysia. *Energy Policy*, *35*(8), 4018–4026.

Silverman, B. W. (1986). *Density estimation for statistics and data analysis* (1st ed.). Routledge.

Simar, L., & Wilson, P. W. (1998). Sensitivity analysis of efficiency scores: How to bootstrap in nonparametric frontier models. *Management Science*, *44*(1), 49–61.

Simar, L., & Wilson, P. W. (2000). Statistical inference in nonparametric frontier models: The state of the art. *Journal of Productivity Analysis*, *13*(1), 49–78.

Simar, L., & Wilson, P. W. (2008). Statistical inference in nonparametric frontier models: Recent developments and perspectives. In H. O. Fried, C. A. Knox Lovell, & S. S. Schmid (Eds.), *The measurement of productive efficiency and productivity growth* (pp. 421–521). Oxford

University Press.

Stekhoven, D. J., & Bühlmann, P. (2012). Missforest — Non-parametric missing value imputation for mixed-type data. *Bioinformatics*, *28*(1), 112–118.

Stevens, L., Sys, C., Vanelslander, T., & Van Hassel, E. (2015). Is new emission legislation stimulating the implementation of sustainable and energy-efficient maritime technologies? *Research in Transportation Business & Management*, *17*, 14–25.

Stopford, M. (2009). *Maritime economics* (3rd ed.). Routledge.

Sueyoshi, T., Yuan, Y., & Goto, M. (2017). A literature study for DEA applied to energy and environment. *Energy Economics*, *62*, 104–124.

Tovar, B., & Wall, A. (2019). Environmental efficiency for a cross-section of Spanish port authorities. *Transportation Research Part D: Transport and Environment*, *75*, 170–178.

Upton, G., & Cook, I. (1996). *Understanding statistics*. Oxford University Press.

Vladimir, N., Ančić, I., & Šestan, A. (2018). Effect of ship size on EEDI requirements for large container ships. *Journal of Marine Science and Technology*, *23*(1), 42–51.

Wanke, P., & Barros, C. P. (2016). New evidence on the determinants of efficiency at Brazilian ports: A bootstrapped DEA analysis. *International Journal of Shipping and Transport Logistics*, *8*(3), 250–272.

Woo, S.-H., Lai, P.-L., Chen, Y.-H., & Yang, C.-C. (2019). Meta-frontier function approach to operational efficiency for shipping companies. *Maritime Policy & Management*, *46*(5), 529–544.

Wu, J., Zhu, Q., Chu, J., Liu, H., & Liang, L. (2016). Measuring energy and environmental efficiency of transportation systems in China based on a parallel DEA approach. *Transportation Research Part D: Transport and Environment*, *48*, 460–472.

Zhang, Y., & Bartels, R. (1998). The effect of sample size on the mean efficiency in DEA with an application to electricity distribution in Australia, Sweden and New Zealand. *Journal of Productivity Analysis*, *9*(3), 187–204.

Zhou, H., Yang, Y., Chen, Y., & Zhu, J. (2018). Data envelopment analysis application in sustainability: The origins, development and future directions. *European Journal of Operational Research*, *264*(1), 1–16.

Chapter 5

Conclusion of the Ph.D. project

The focal point of inquiry in this Ph.D. project is the green transition of the maritime industry, which is at the heart of the concurrent sustainability crisis. Maritime transport is the backbone of internationalized trade; thus, sustainable international shipping is a key puzzle piece to safeguard the natural environment in which we are all living and secure the livelihood of future generations. This thesis concentrates on the role of the maritime industry in the climate change problem, which is one of the most pressing sustainability issues, including how the industry can support global efforts to reach international climate change goals. The project investigated two key drivers of the green transition of the industry, namely, clean technology adoption and environmental policies. In particular, the overarching objective of the thesis was to examine thoroughly the interplay between clean technology adoption and environmental policies to drive the green transition of the maritime industry. For this purpose, the thesis consists of three distinct research articles, each contributing to the overarching objective and providing important insights and implications for the decarbonization of the maritime industry.

The study presented in chapter 2 demonstrated the relationship between technology and operational levers and environmental performance as the subject of inquiry. Technology and operational drivers are key levers that decision makers can utilize to improve energy efficiency and to comply with environmental policies. Hence, this research examines how technology and operational levers impact the environmental performance of vessels by utilizing the empirical setting of the EEDI regulation. An important conjecture was that this impact might vary across the range of environmental performances. This is relevant, as the policy measure prescribes minimum performance standards, thus targeting primarily the units with poor environmental performance. We develop a set of hypotheses to answer the research questions and empirically test them with statistical methods. A key result of the study is that the impact of technology and operational levers on environmental performance is indeed heterogeneous, and their relationship is complex. The presented results yield theoretical insights for examining the drivers of performance and their implications. Further, the detailed analysis provides practical implications for decision makers seeking to reduce their carbon footprint through technology and operational drivers.

Chapter 3 focused on the impact of an ETS designed to reach industry-wide emission reduction targets through ship owners' investments in clean technologies. Two important features of the investment decision problem in the context of the green transition are that it is an inherently dynamic problem subject to an uncertain environment. The study examines how a ship owner's investment policy over time is shaped under an ETS for the maritime industry. Second, we investigate the impact of increased regulatory and demand uncertainties on this investment policy. For this purpose, the study develops and analyzes a discrete multi-stage decision model in a stochastic environment. The analytical results suggest that the optimal investment policy must balance the costs of investing in clean technology today and the expected future cost reductions due to an increase in carbon efficiency. In addition, the analytical results suggest that an environment with increased regulatory and demand uncertainties has a substantial impact on a ship owner's investment policy over time. Our study contributes to scientific knowledge by enriching the theoretical understanding of the investment decision problem under uncertainty in the context of environmental policies. Lastly, the study provides important insights for policy makers about how design choices around a global ETS for the maritime industry impact incentives for ship owners to adopt clean technologies.

A key objective of environmental policies in the maritime industry is to improve the energy efficiency of ship designs through clean technology adoption. Chapter 4 assesses the opportunities for energy efficiency improvements. The study argues that the current potential is mostly determined by two factors: the scope for improvements by adopting best practice ship designs within sectors and the technological conditions across sectors limiting technology choice at the design stage, thus, curbing the scope for efficiency improvements. To derive an empirical estimate of these factors, the study develops a general framework for the energy efficiency of ship designs in the maritime industry and applies quantitative benchmarking methods on a sample of over 6,000 vessels. A main result of the study is that these two factors vary considerably across the shipping sectors; thus, the situational contexts for energy efficiency improvements differ across the shipping sectors. Based on the results, the study provides important implications for marine policies by suggesting how existing policy measures can be improved and how the sectors can benefit from different additional policy measures.

The remainder of the conclusion is structured as follows: section (5.1) synthesizes the key findings from the three research papers. Afterwards, section (5.2) discusses the limitations of the Ph.D. project and suggests potential avenues for future research to deepen the understanding of the interplay between environmental policies and clean technology adoption in the context of the green transition. Lastly, section (5.3) concludes the project by assessing the status quo of the green transition of the maritime industry through the lens of this thesis.

5.1 Main results and implications for the green transition

This section synthesizes the main findings of the three distinct research articles and discusses the implications for theory and practice. In particular, I seek to outline the insights gained about the two drivers of the decarbonization of the industry on which this thesis focused. As highlighted in section (1.3), a main driver of the green transition of the maritime industry is the adoption of clean technologies. In particular, the adoption of alternative fuels is of special importance, and the thesis generated multiple insights into their role in the decarbonization process. The results in chapter (2) suggest that the adoption of alternative fuels is a strong lever for ship owners to improve technical energy efficiency and to comply with the minimum performance standards mandated by the EEDI regulation. Hence, the thesis provides empirical evidence from the existing fleet that alternative fuels can be a key driver for ship owners to improve their environmental performance, and it encourages further efforts in their development and adoption. Apart from the practical relevance, this insight also contributes to the Sustainable Operations Management (SOM) literature by complementing previous analytical work focusing on the adoption of clean transportation technologies to reduce carbon footprints.

Furthermore, alternative fuels appear of major importance not only to climate-conscious ship owners but also to policy makers in the maritime industry. A main policy objective is to foster the continuous improvements of energy efficiency from a ship design perspective. The adoption and development of alternative fuel technologies plays a critical role in this objective, as they are key enablers of future opportunities for energy efficiency improvements in the industry by increasing the space of available ship designs. As shown in chapter (4), the scope for energy efficiency improvement through the adoption of best practice ship designs within sectors varies significantly across the different sectors. It appears that some sectors have already adopted higher levels of clean technologies in their ship designs, thus leaving only a small scope for improvements with existing best practices. Here, the adoption and development of alternative fuels can expand the scope of existing ship designs and enable further improvements in energy efficiency. Therefore, the thesis suggests that policy makers should support these efforts with their policy measures to ensure that their policy objective can be satisfied in the long-run.

One of the most promising approaches at the disposal of policy makers for the green transition is an environmental policy based on MBMs. The discussion in section (1.3) highlighted that a main challenge in the adoption of alternative fuels is the high up-front economic costs that would be required for their widespread adoption. It is generally accepted in the maritime industry, that MBMs can play an important role here by enforcing the *"polluter-pays"* principle, thus providing economic incentives for ship owners to invest in clean technologies. Chapter (3) marks an important contribution to this discussion about MBMs for the maritime industry by providing a long-term perspective on the impact of a maritime ETS. The analytical results around the ship owner's optimal investment policy suggest that a global maritime ETS designed to reach industry-wide reduction targets can indeed incentivize investments in clean technologies over a time horizon. More importantly, a key insight is that such an ETS can yield incentives for large technology investments by ship owners in the beginning of the regulation horizon, as they would be required for the widespread adoption of alternative fuels. Hence, these insights suggest that a maritime ETS provides a first-mover advantage to ambitious ship owners and can be an important component in the green transition of the industry.

Without such incentives, it is possible that ship owners will resort to less costly technology levers to comply with existing policy measures. As previously stated, main engine adjustments to reduce fuel consumption have the reputation of being easy and effective measures to comply with the EEDI regulation for ship owners. However, the empirical results of chapter (2) overall highlight the limits that main engine adjustments have in improving the technical energy efficiency and in complying with the mandated minimum performance standards. Moreover, this lever does not explain performance variations for vessels with poor performance, which are of major importance to climate-conscious ship owners. It appears these vessels would require more extensive retrofits implementing clean technology solutions to reduce their environmental impacts significantly. However, as discussed, the decision to retrofit an existing vessel might be especially under pressure for vessels with poor performance. Because modern vessels have a lifetime of up to 30 years, the thesis reveals an important potential challenge for the green transition concerning how to reduce the negative impact of existing vessels with relatively poor performance.

The other main driver of the green transition of the maritime industry, on which the thesis focuses, are environmental policies. A common theme throughout the thesis is that it seems questionable how well the existing energy efficiency framework can drive the green transition of the industry. A main reason highlighted by previous research is that an existing main, mandatory measure of the framework — the EEDI regulation — does not sufficiently stimulate the adoption of clean technologies due to adverse effects and the focus on minimum performance standards. Therefore, chapter (4) revisited the current regulatory approach to energy efficiency and provided an alternative perspective for marine policies. The study contributes to transportation research by providing a comprehensive framework for comparing the energy efficiency of ship designs in the maritime industry based on best-practice benchmarks. Further, chapter (4) yields important insights for policy makers on how some common downsides associated with C & C regulations, like the EEDI regulation, could be addressed by the presented perspective. To illustrate, by shifting the view from minimum requirements to best practices, the regulatory approach could incentivize bold technology advancements by first movers and relax some difficulties associated with setting the appropriate performance standard for policy makers in the industry.

Because existing policy measures in their current form appear insufficient, future environmental policies are most likely a key driver of the green transition. However, a general insight of the thesis is that their potency for driving the decarbonization of maritime transport will depend on the design choices made around these measures. More precisely, the empirical results in chapter (4) show that the current situational contexts for energy efficiency improvements in ship designs differ across the various shipping sectors of the maritime industry. Therefore, the thesis argues that policy makers should be aware of these different contexts when designing additional instruments to ensure their effectiveness. The thesis informs maritime policy makers by providing insights into how the different sectors could benefit from different additional initiatives and providing a quantitative tool for policy planning in the maritime industry.

Similarly, the implementation of an MBM like an ETS is no guarantee for the green transition of the maritime industry and its impact will depend on its design. Currently, it is unclear whether an MBM will be implemented on a global scale for the industry or how it will be designed, which leaves many open questions. The results in chapter (3) show that a global METS, which incorporates the industry-wide emission reduction targets and a credible commitment to these targets in its policy design, can yield strong incentives to invest in clean technologies. This result not only provides theoretical insights for the investment decision problem under uncertainty in the context of an ETS, but it also yields important policy implications for the design of a global maritime ETS to decarbonize the industry. Further, the results posit that the value of managerial flexibility and incentives to invest in clean technologies are not eroded by increased regulatory and demand uncertainties. This is a key insight for the industry, as the green transition process over time is inherently fraught with uncertainty, and future developments are often unforeseeable. Hence, a well-designed maritime ETS can be robust to these uncertainties and does not put a high informational burden on policy makers to yield feasible outcomes.

5.2 Limitations and future research

Despite its multiple theoretical and practical insights for the green transition of the maritime industry, the Ph.D. project has certain limitations due to its scope, on which this section reflects. By outlining these limitations, the thesis seeks to provide potential avenues for future research related to the thesis' main objective of further fostering the understanding of how to drive the green transition of the maritime industry.

The first limitation is that the presented studies mostly relate to the direct carbon emissions of maritime transport, due to their focus on ship owners and policy makers as key stakeholders. According to the classification of the GHG protocol, these emissions can be referred to as scope 1 emissions, covering the direct emissions of company-owned and controlled resources (WBCSD, 2004). In contrast to other industries, the majority of emissions from shipping companies stem from scope 1 due to the combustion of fuels to provide transportation services. To give the reader a specific example, A.P. Møller-Mæersk stated in their Sustainability Report 2020 that 64% of their total GHG emissions can be attributed to scope 1 emissions (Mærsk, 2020). However, a complex topic like the green transition of the maritime industry ultimately requires the decarbonization of the whole value chain. This is referred to as scope 3 emissions, including the up- and downstream emissions associated with company activities.

A scope 3 emissions perspective can yield important additional insights for the area of inquiry of this thesis. To illustrate, the total climate impact of any alternative fuel not only depends on the direct emissions due to fuel consumption (tank-to-wake) but also on the carbon footprint associated with the production, processing, and delivery of the fuel (well-to-tank) (Hwang et al., 2020). Similarly, a vessel generates a negative impact on the climate not only while in use but also at the beginning and end of its life-cycle. Previous work has already hinted at the severe socio-environmental issues (Hsuan & Parisi, 2020) related to the recycling of vessels to recover raw materials. Naturally, addressing emissions across the value chain requires the collaboration and interaction of multiple stakeholders in the industry and would demand a broader focus than the ship owner's or policy maker's perspective. Hence, examining the interplay of the various stakeholders in the maritime industry to reach regulatory emission reduction targets or investigating how policy makers can adopt such a perspective in their policy measures to drive decarbonization across the marine value chain appear exemplary, fruitful areas for future research.

A second limitation of the project is that it mostly focuses on the policy measures related to technical energy efficiency in the energy efficiency framework, due to examining the adoption of clean technologies as a key driver of the green transition. While an energy-efficient ship design is the foundation of a low carbon footprint during a vessel's operations, it is no guarantee. If a vessel with an energy-efficient ship design is operated poorly, the observed fuel consumption and, in turn, operational energy efficiency can significantly deviate from the technical energy efficiency (see, e.g., Adland et al., 2018, for an example). Thus, research on how good operational practices impact measures for operational energy efficiency or compliance with the forthcoming CII regulation is feasible in the future. Further, as outlined in section (1.3), the relationship between clean technology adoption and policy measures for operational energy efficiency is more complex if the ship owner is not the operator, owing to the arising split incentives problem. Recent empirical research on the container shipping sector has already highlighted that chartered vessels have higher carbon emissions than owner-operated vessels (Dirzka & Acciaro, 2021). Interestingly, the forthcoming CII regulation also demands ship owners comply with the regulation. Hence, future research could examine the arising principal agent problem in the context of the CII regulation and shed light on the potential implications for compliance with the regulation or clean technology adoption.

5.3 Is the green transition on its way?

The last section of the thesis relates back to the quote at the beginning by taking stock of the current progress made by the maritime industry to combat climate change. Is the industry on a green pathway to decarbonize maritime transport to support global climate change goals? At the writing of this thesis, the 26th UN Climate Change Conference of the Parties (COP 26) was hosted in Glasgow, with the key goal of securing global net-zero emissions by mid-century and keeping the 1.5 degrees goal within reach. Realizing this goal will require extraordinary joint efforts by the global community given the current situation. To illustrate, a main conclusion of the IPCC's sixth assessment report released in August 2021 is that without immediate and large-scale reductions in GHG emissions, it will be impossible to limit global warming to 1.5 degrees or even 2.0 degrees (IPCC, 2021). Regarding the status quo of the green transition in the maritime industry, the recently released Industry Transition Strategy report from the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (CZCS) gives a sobering outlook. According to the report, the industry is currently on a path to around a 20% *increase* in GHG emissions in 2050 compared to today (CZCS, 2021). This outlook stands in stark contrast to both the mid-century net-zero emissions target of COP 26 and the level of ambition stated in the initial IMO GHG strategy. So what is needed for the green transition of the maritime industry to become a reality through the lens of the Ph.D. project?

One key cornerstone is that the regulatory framework for energy efficiency is effective in stimulating clean technology adoption to improve the energy efficiency of the global fleet. For this purpose, at MEPC 75, the phase III requirements for the EEDI were strengthened by moving them forward from 2025 to 2022 for multiple ship types and mandating more stringent reduction targets for container ships (MEPC, 2020). Furthermore, the introduction of a possible phase IV for the EEDI is currently a subject of discussion at the IMO. While being a step in the right direction, these actions do not address the highlighted problems associated with the strategy of the regulator (ex ante) mandating minimum performance standards. Therefore, it seems concerning that the forthcoming policy measures in 2023 intended to strengthen the existing framework for energy efficiency are utilizing the same regulatory approach. In particular, for the EEXI regulation — the EEDI counterpart for existing vessels — the easiest way for existing vessels to comply with the mandated standards might be engine power limitations to reduce a vessel's fuel consumption and, in turn, carbon emissions. However, speed reductions may lead to a variety of potential side effects, like an increase in the world fleet to meet the demand for shipping or even an increase in total global emissions by inducing demand shifts to more CO_2-intensive modes of transport (Psaraftis, 2019).

Another key component of the green transition is the widespread availability and adoption of alternative fuels in the maritime industry. Since the beginning of the Ph.D. projects in 2018, the adoption of alternative fuels has gained significant traction. To illustrate, according to the Clarkson Shipping Intelligence Network, in August 2021, roughly 3.5% of the existing fleet and 30% of the vessel order book (by GT) have the capabilities to use alternative propulsion. Currently, the most frequently adopted alternative fuel is LNG, as the technology is mature, and it has a robust global bunkering infrastructure. While LNG can considerably reduce the environmental impacts of air pollution, LNG is still a fossil fuel and can only serve as a transition fuel until other fuel options become widely available. Another alternative fuel currently receiving much attention is methanol. To illustrate, in August 2021, Mæersk announced that they ordered eight new large ocean-going container vessels with the capabilities of using methanol fuel to accelerate the decarbonization of their fleet (Mærsk, 2021). In contrast to LNG, methanol can be a carbon-neutral fuel if it is produced with renewable electricity and biogenic carbon. There is still much uncertainty concerning the carbon-free fuel options hydrogen and ammonia, which could be the key technology enablers for the vision of decarbonized maritime transport. Either fuel option would require sizable investments by stakeholders in the industry to make their widespread adoption and availability a reality in the future.

The last component discussed here is a global carbon-pricing mechanism for the maritime industry, operationalized through an MBM to establish the polluter pays principle. Such a mechanism can be a key driver of the green transition by providing economic incentives for the adoption of clean technologies and, in particular, alternative fuels. Moreover, an MBM can generate the necessary funds to subsidize the extraordinary investments needed and create a level playing field for the industry. However, the effectiveness of an MBM, like an ETS (but also a bunker levy scheme), to support the green transition will crucially depend on their stringent policy design. As previously discussed, the mechanism for the allocation of licenses, the geographical scope of the ETS, and the supply of licenses over time are just a few practical design choices that could have a drastic impact on the investment incentives under an ETS. Further, due to the long lifetime of ships' it is important that an MBM be implemented soon to still reach the mid-century emission reduction targets. It is the hope of the author that the discussions and calls to action of COP 26 can rekindle the work and development of a global MBM for the maritime industry as soon as possible at the IMO.

To conclude, there is still a green pathway for the maritime industry but the time window of opportunity for reaching global climate change goals is closing soon; thus, profound changes are needed in the industry to support these goals and reach their own ambitions. Note that the current level of ambition outlined in the IMO GHG strategy is lower than the stipulated goal of net-zero emissions by mid-century of COP 26. It is likely that the IMO will have to raise its level of ambition in the revised IMO GHG strategy in 2023. In this revised strategy, it is the author's belief that a clear commitment to the green transition is required by the policy maker, which is reflected in the design and enforcement of regulatory measures. Such a commitment is not only important to attach real consequences if ambitions are not met, but also to act as reassurance for ambitious ship owners in the industry that their decarbonization efforts will not put them at a disadvantage compared to less ambitious ship owners. I hope this Ph.D. project can do its part to provide guidance in the green transition of the maritime industry through its insights and to spark future academic research in this direction to support further the industry in its vision to decarbonize maritime transport.

References

Adland, R., Cariou, P., Jia, H., & Wolff, F.-C. (2018). The energy efficiency effects of periodic ship hull cleaning. *Journal of Cleaner Production*, *178*, 1–13.

CZCS. (2021). *Industry transition strategy report* (Report). Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. Retrieved from `https://cms.zerocarbonshipping.com/media/uploads/documents/MMMCZCS_Industry-Transition-Strategy_Oct_2021.pdf`

Dirzka, C., & Acciaro, M. (2021). Principal-agent problems in decarbonizing container shipping: A panel data analysis. *Transportation Research Part D: Transport and Environment*, *98*, 102948.

Hsuan, J., & Parisi, C. (2020). Mapping the supply chain of ship recycling. *Marine Policy*, *118*, 103979.

Hwang, S. S., Gil, S. J., Lee, G. N., Lee, J. W., Park, H., Jung, K. H., & Suh, S. B. (2020). Life cycle assessment of alternative ship fuels for coastal ferry operating in Republic of Korea. *Journal of Marine Science and Engineering*, *8*(9), 660.

IPCC. (2021). *AR6 climate change 2021: The physical science basis* (Tech. Rep.). Intergovernmental Panel on Climate Change. Retrieved from `https://www.ipcc.ch/report/ar6/wg1/`

MEPC. (2020). *Procedures for sampling and verification of the sulphur content of fuel oil and the Energy Efficiency Design Index (EEDI).* International Maritime Organization. Retrieved from `https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.324%2875%29.pdf`

Mærsk. (2020). *Sustainability report 2020* (Report). A.P. Møller-Mærsk. Retrieved from `https://www.maersk.com/about/sustainability/reports`

Mærsk. (2021). *A.P. Moller-Marsk accelerates fleet decarbonisation with 8 large ocean-going vessels to operate on carbon neutral methanol.* Retrieved from `https://www.maersk.com/news/articles/2021/08/24/maersk-accelerates-fleet-decarbonisation`

Psaraftis, H. N. (2019). Decarbonization of maritime transport: To be or not to be? *Maritime Economics & Logistics*, *21*(3), 353–371.

WBCSD. (2004). *The greenhouse gas protocol - A corporate accounting and reporting standard* (Tech. Rep.). World Business Council for Sustainable Development. Retrieved from `https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf`

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