Accelerating shipping's climate change transition, and the role of UK shore power

A thesis submitted to the University of Manchester

for the degree of Doctor of Philosophy in the Faculty of Science and Engineering

2023

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Total word count: 57,829

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Acronyms

AR6	IPCC Sixth Assessment Report
CCC	Climate Change Committee
CII	Carbon Intensity Indicator
CMDC	Clean Maritime Demonstration Competition
CMP	Clean Maritime Plan
CO_2	Carbon dioxide
DNO	District Network Operator
DSV	Dive Support Vessel
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ships Index
EU MRV	European Union Monitoring, Reporting and Verification
ILO	International Labour Organisation
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISO	International Organisation for Standardisation
MCA	Multi-Criteria Analysis
MEPC	Marine Environment Protection Committee
MLP	Multi-Level Perspective
MPSV	Multi-Purpose Supply Vessel
MSA	Multiple Streams Approach
NOx	Nitrogen Oxides
SEEMP	Ship Energy Efficiency Management Plan
SR15	IPCC Special Report on 1.5°C
TEU	Twenty-foot-Equivalent-Unit
TIS	Technological Innovation Systems
UNFCCC	United Nations Framework Convention on Climate Change

Abstract

This thesis investigates how the shipping industry can make a transition so that it plays its fair part in meeting the global Paris Agreement goals on climate change. Shipping has undergone major transitions in the past, such as from sail to steam. The literature posits that addressing climate change will be the sixth such transition, and industry and governments agree that the sector's greenhouse gas emissions must be reduced. However, there are numerous gaps in the literature regarding this potential transition. First, the required scale and speed of transition is contested. Second, there is uncertainty around the combinations of technologies and practice changes that will be necessary. Third, it is unclear what policies and governance structures will be required.

The thesis takes a mixed-method approach to address these gaps, with four analyses at different scales: at global, EU, UK and port levels. The first analysis is a quantitative study of global carbon budgets to establish feasible quantified pathways for Paris-aligned shipping carbon dioxide reductions. Its conclusion that deep emissions cuts are required by 2030 is a timely challenge to existing targets and to the industry's focus on 2050, ahead of a global strategy review in 2023. The second is a novel application of the concept of "committed emissions" to the EU shipping sector, concluding that meeting such targets requires a focus on reducing the operational emissions of existing ships, not just a focus on new fuels. The third investigates one of these operational measures – shore power in the UK – using two transitions frameworks: Technological Innovation Systems and the Multiple Streams Approach. It concludes that political factors are preventing the introduction of policies that could accelerate the deployment of UK shore power and identifies means to overcome these challenges. The fourth is a case-study at the Port of Aberdeen to analyse how, in the face of economic barriers, the financial case for shore power can be improved.

This thesis presents evidence that shipping decarbonisation measures are dependent on policies and actions at local, national and global scales, but that coordination between and within these levels is disjointed and often in conflict. This represents a polycentric governance challenge for shipping. The need for an accelerated transition is urgent, and its delivery in time to meet the Paris climate goals will require stronger integration and alignment of policy regimes at multiple levels.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Copyright Statement

Acknowledgements

There are many people I'd like to thank for their help, advice, encouragement and support:

My fabulous supervisors Alice Larkin and Claire Hoolohan, and in the early days John Broderick. I could not have been luckier.

In the UK ports and shipping world, many thanks to Mark Simmonds, Anna Ziou and Tristan Smith, to Marlene Mitchell, Luigi Napolitano, and Matt North at Port of Aberdeen, and to Jamie Crossan, James Dickinson and Eliott Higgins at Buro Happold. In particular, thank you Tim Morris, I deeply appreciate your support in getting my fieldwork kick-started in that first Covid year.

Everyone at Tyndall Manchester, you cheery, smart, kind people. Singling out James Mason: I fell on my feet being able to work with you these last four years. My deep gratitude too to the EPSRC for funding my PhD, and to Ruth, Fiona and Amanda for their support through the Power Networks Centre for Doctoral Training. Also, a big hurray to my fellow CDT researchers, especially Claire Brown, Tim Capper and Ami Crowther.

Also, our growing network of shipping transitions researchers – particularly Igne, Jonathan and Hanna – I'm learning lots from you all. And to Wessam Abouarghoub, Aykut Őlcer, Lucy Gilliam and Frank Geels, thank you for your friendliness and deeply helpful advice as I was starting out.

In Bradford thanks loads for the top tips over beer to Kevin, Betts, Naomi, Kev and Dave - you wise owls. Thanks too to David, Ayaz and the other cheery souls at Assembly Bradford. And Fred and Elsie too, for being generally fantastic, always.

Finally, all my love and gratitude to Anna, for your advice, encouragement, kindness, distraction and support, even when you had a million other things to do…

(Picture credit: Elsie Watson)

Chapter 1 Introduction

1.1 Climate change – the challenge

The greenhouse effect makes life on Earth possible for humanity and much of nature. Without it, the Earth's surface temperature would be 33°C colder (Mitchell, 1989, Kweku et al., 2018). Scientific study of the greenhouse effect started with the pioneering work of Joseph Fourier in the 1820s (Fourier, 1827), who proposed that the Earth's atmosphere could act as an insulator, making the planet warmer than expected. In the late 1850s, experiments by Eunice Foote (Sorenson, 2011) and John Tyndall (Tyndall, 1860) showed that gases in the atmosphere such as water vapour and carbon dioxide can absorb some of the sun's incoming radiation after it hits the Earth's surface, preventing this heat from returning to space.

However, beyond this 'natural' greenhouse effect, further planetary heating is possible. During the 1890s, Svante Arrhenius predicted that accumulations of greenhouse gases from the burning of fossil fuels would have a discernible effect on global temperatures (Arrhenius, 1896), later concluding that doubling the carbon dioxide in the air would increase the surface temperature of the earth by 4°C (Arrhenius, 1908). This effect was shown in practice by Hansen et al. (1981), who observed global temperature increases of 0.2°C from 1960-1980 that were consistent with theoretical calculations of the temperature rise from measured increases in carbon dioxide in the atmosphere. The work of the Intergovernmental Panel on Climate Change (IPCC) from 1988 has built upon and consolidated this science, and it is now unequivocal that the accumulation of carbon dioxide and other greenhouse gases in the atmosphere is causing our planet's temperature to rise (Masson-Delmotte et al., 2021b).

These temperature rises to date are primarily due to emissions of carbon dioxide from burning fossil fuels – coal, oil and gas – with annual emissions from anthropogenic sources of over 36 billion tonnes in 2021 (Friedlingstein et al., 2022). Carbon dioxide concentrations are now at their highest levels for 800,000 years (Blunden et al., 2018), and average global surface temperatures have increased by 1.1°C since the late 19th century as a result

(Masson-Delmotte et al., 2021b), with annual variations and the long-run trend shown in Figure 1-1.

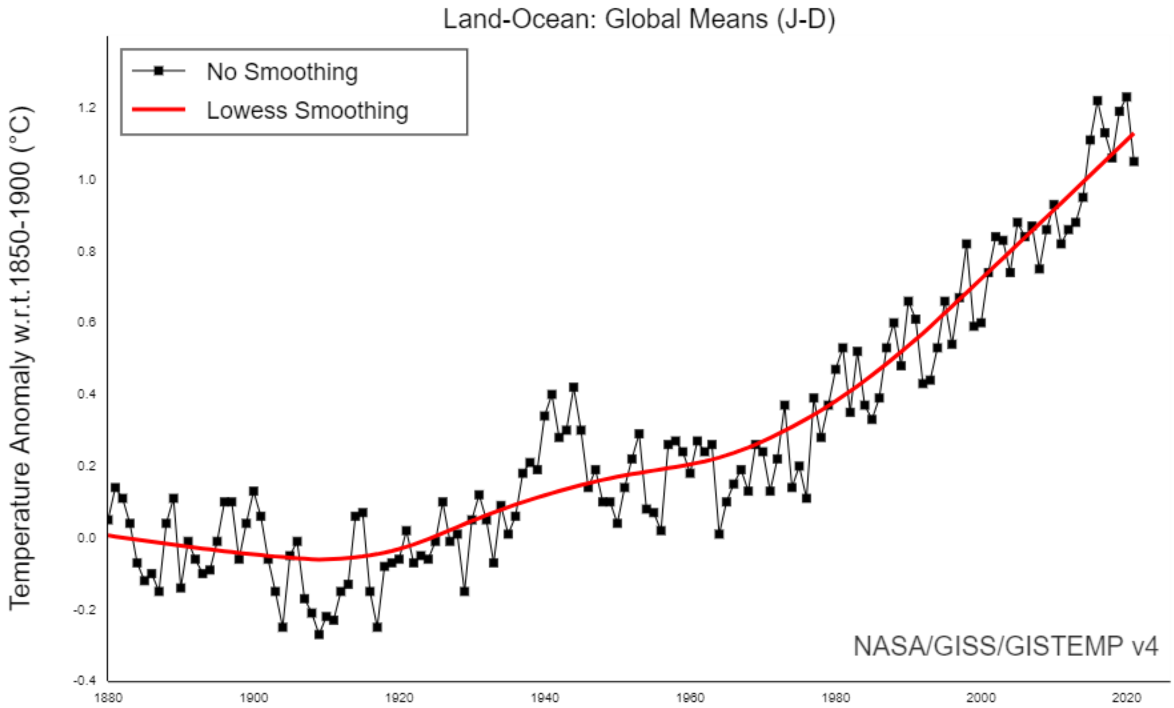

Figure 1-1 Global Annual Mean Surface Air Temperature Change.

Source: (NASA, 2022)

This planetary heating is causing the Earth's climate to change (IPCC, 2021). These changes are an urgent and increasing threat to humanity and nature. Impacts being experienced already include sea-level rise, ocean acidification, biodiversity loss and greater frequency or intensity of extreme heat events, drought, coral bleaching and floods, and these impacts will worsen as temperatures rise further (IPCC, 2022c). Further, temperature rises also increase the risk of passing "tipping points", where abrupt and potentially irreversible changes occur, such as Amazon rainforest dieback, ice-sheet melt and slow-down in Atlantic ocean currents, with feedback loops and cascading interactions between these events (Lenton et al., 2019).

In response to the threats from climate change, the World's governments have agreed and ratified the 1992 United Nations Framework Convention on Climate Change, whose goal is to "*prevent dangerous human interference with the climate system*" (United Nations, 1992b). The meaning of “dangerous” is subjective, and subsequent intergovernmental processes have focussed on what are appropriate actions for nations to take in response, through for example the Kyoto Protocol in 1997 (UNFCCC, 1997), and the Paris Agreement in 2015 (United Nations, 2015). The Paris Agreement commits the 194 parties who have ratified it to “*pursue efforts to limit the temperature increase to 1.5°C*” (UNFCCC, 2022).

The imperative to keep the global mean temperature rise below 1.5°C is stark. For example, at 1.5°C, 14 per cent of the world’s population would be exposed to severe heat waves at least every five years, with this figure rising to 37 percent at 2°C heating (IPCC, 2022b). In addition to incremental increases in damages, temperature rises also increase the likelihood of passing climate ‘tipping points’. Such tipping points refer to instances where, beyond certain warming thresholds, changes become self-perpetuating, with substantial and widespread impacts (Armstrong McKay et al., 2022). Understanding of these risks is growing, with recent research suggesting that passing six climate tipping points becomes likely between 1.5°C and 2°C, including permafrost thaw and the collapse of the West Antarctic and Greenland ice sheets (Armstrong McKay et al., 2022). Probabilities for these risks are still uncertain, but - in line with the well-established precautionary principle (United Nations, 1992a) - as they would have catastrophic and usually irreversible impacts, a strongly precautionary approach to prevent them is advisable (Stirling et al., 1999).

The actions required to limit temperature rises to 1.5°C are set out in detailed analysis by Working Group III of the Intergovernmental Panel on Climate Change, most recently the Special Report on 1.5°C (SR15) (IPCC, 2022b) and the Sixth Assessment Report (AR6) (IPCC, 2022a). SR15 and AR6 use the concept of carbon budgets to guide policy action. Because of the approximately linear relationship between cumulative carbon emissions and temperature rise (Matthews et al., 2018), it is possible to calculate cumulative future emissions of carbon dioxide (carbon budgets) which would be consistent with meeting a specified likelihood of exceeding a given temperature goal, for given assumptions for emissions of other greenhouse gases. SR15 and AR6 then set out carbon dioxide emissions pathways compatible with such carbon budgets. These pathways vary in the speed and timing of emissions reduction trajectories, depending for example on the extent to which carbon dioxide removal technologies are assumed to be deployed. However, the conclusion of these reports is that very steep global emissions reduction trajectories are required, with the AR6 report stating that meeting the 1.5°C goal requires 43% reductions in carbon dioxide emissions by 2030, with net zero carbon dioxide emissions by the early 2050s (IPCC, 2022a). These reports are also clear that meeting such goals will require concerted action and collaboration from all countries and sectors of the global economy. One of these sectors is shipping, the focus of this thesis.

1.2 Climate change and shipping

Shipping has a pivotal role in meeting global climate goals, in two main respects: due to its essential role in the supply of goods in the global economy, and as a major consumer of fossil fuels.

First, ships transport large proportions of the world's iron ore, grain, chemicals, consumer products, coal, oil and gas: over 80% of international goods trade by tonnage is by ship (UNCTAD, 2021). Much of the world's supply chains and economies therefore rely heavily upon shipping – as witnessed by the deeply negative economic impacts caused by delays to shipments of goods when the Evergiven container ship ran aground and blocked the Suez Canal in 2021 (Lee and Wong, 2021). So, as the world makes a transition to a zero-carbon energy system, the types, journeys and quantities of energy, products and materials traded will change, and the shipping sector will have a central but also changed role in enabling these new trade flows, in a transformed global energy system (Sharmina et al., 2017).

Second, the shipping sector is itself a major consumer of fossil fuels, primarily through using heavy fuel oils for propulsion in ships' engines, emitting large quantities of carbon dioxide (Faber et al., 2020). Global shipping emissions are split into two components – international and domestic – with international emissions being the responsibility of the International Maritime Organisation, and domestic emissions the responsibility of individual nations. There are different methodologies for apportioning global emissions to these categories; the recommendation from the IMO's 4th Greenhouse Gas Emissions report is for a method which splits global shipping emissions 740 $MtCO_2$ to international, 315 $MtCO_2$ to domestic. In total, the shipping sector's emissions are equivalent to around 3% of the world's total

(Faber et al., 2020), with only five countries having higher emissions – China, USA, India, Russia and Japan (Friedlingstein et al., 2022). The sector is therefore a major contributor to climate change, and consequently will need to play its part in meeting the Paris 1.5°C goal, requiring it to make a rapid transition in the types and quantities of fuels it uses.

1.3 Shipping transitions

Major transitions in shipping are possible, and have happened in the past (Pettit et al., 2018). The transition from sail to steam began in the 19th century, with the majority of the transition between 1860 and 1900 (Geels, 2002, Pettit et al., 2018). From the 1950s, there was an accelerated switch away from coal-fired steam propulsion to diesel engines using heavy fuel oil. Shipping transitions are also not solely concerned with methods of propulsion – in the late 1960s there were dramatic reductions in the costs of shipping cargo following the rapid introduction of containers, replacing the loading and unloading of cargoes by hand (Levinson, 2016). This containerisation has transformed global logistics in the following decades, and been a core enabler of growth in global trade (El-Sahli, 2013), with container traffic increasing from zero to 423 million tonnes by 1996, and more than quadrupling to 1,934 million tonnes by 2021 (Clarksons, 2021).

In the 21st century, shipping needs to make another transition – to keep its cumulative greenhouse gas emissions within Paris-compatible limits, and ultimately become zero-carbon. There are however three attributes that distinguish this transition from previous ones. First, previous transitions occurred because of technological breakthroughs that conferred economic advantages. In this transition, it is major political and social pressure, rather than an economic imperative, that is driving change. Second, for the sector to play its part in meeting globally agreed climate change goals, this transition will need to occur faster than in previous transitions, in an industry that is now of much greater size and complexity. Third, this time there is no obvious silver-bullet or saviour technology – it is likely that a multitude of actions across technology, practices, culture, economics and politics will be required in combination to deliver this transition.

The transition is underway. The International Maritime Organisation (IMO) is the United Nations agency charged with coordinating efforts to address issues of safety and pollution. Its environmental focus has historically been on preventing oil spills (IMO, 2023a), but over time it has expanded its remit to include issues such as ballast water, ship recycling and anti-fouling paints (David et al., 2015, Jain et al., 2013, IMO, 2002) and sulphur and nitrogen emissions to air via the MARPOL Annex VI regulations (Čampara et al., 2018). The focus on compliance with these air pollution regulations predominantly through the use of low sulphur oils or scrubbers was a missed opportunity to also address greenhouse gas emissions (Faber, 2020, Krantz et al., 2022), but increasingly, the IMO's remit has focussed on climate change. In 2018 it set out an initial Greenhouse Gas strategy (IMO, 2018d), and it has begun to roll-out a series of regulatory measures aimed at improving the energy efficiency of vessels.

However, despite this increasing attention from the IMO, and also from industry coalitions (Getting to Zero Coalition, 2021), industry bodies (ICS, 2021) and Governments (UK Government, 2019b), shipping's carbon dioxide emissions have been relatively constant in the last decade, with improvements in energy efficiency being countered by demand growth (IMO, 2020). Like a super-tanker, the shipping sector is slow in changing direction. This slow pace reflects the complexity of the sector, and deeply embedded practices (Stopford, 2009) - both within the industry, and in its links to the wider system of global trade. In addition, shipping's emissions at sea are low visibility and receive less attention from policy makers and the general public (Poulsen et al., 2018). But a further cause is that the direction of transition and the means to achieve it is deeply contested, with three unresolved questions at three levels, around the scale and speed of transition, required technology and practice change, and governance.

Regarding the first question, the scale and speed at which transition is required is uncertain. The IMO have set a target of "at least" 50% reductions in greenhouse gas emissions on 2008 levels by 2050 (IMO, 2018d). But is this sufficient? Some nations have challenged the need for even 50% reductions (IMO, 2018b, IMO, 2018e), others argue for greater levels of ambition (IMO, 2018a).

Second, the technologies and practice changes that will be needed are uncertain. What is the relative role for new fuel technologies, versus measures to improve energy efficiency, or measures which reduce the need for shipping transport (Bouman et al., 2017, Mallouppas and Yfantis, 2021)? Just within the category of fuels, a smorgasbord of potential options are available – such as ammonia, batteries, hydrogen, methanol and biofuels (Balcombe et al., 2019, DNV, 2022b).

Third, it is uncertain which policies and governance structures will be necessary to drive the transition, and how can they be delivered and supported. Is regulation more important than market-based mechanisms such as carbon pricing (Psaraftis et al., 2021)? Can effective governance for decarbonisation be delivered through the IMO (Bach and Hansen, 2023), or is there a greater role for policy from nations or nation groups such as the EU (Psaraftis and Kontovas, 2020a)? To what extent are industry coalitions necessary to break through regulatory inertia (Rayner, 2021)? Or will layered, polycentric combinations of all of these be required (Gritsenko, 2017)?

This thesis addresses these three contested and linked questions, with the aim of elucidating how the shipping sector's climate transition might be accelerated.

1.4 The contribution of this thesis

This thesis aims to address gaps in academic and policy-maker knowledge around shipping's contested low-carbon energy transition through four linked pieces of research, using a mixed-method, multi-level approach. The gaps in the academic literature are discussed in Chapter 2.

The first two pieces of research (presented in Chapter 3 and 4) aim to provide greater clarity on the scale and pace of transition required in shipping, and what combinations of technology and practice change will be necessary to align with the Paris Climate Agreement. The first analysis builds on existing literature on long-term shipping targets to make a novel contribution that deep emissions reductions this decade is an absolute priority for the shipping sector. The second analysis applies the concept of "committed emissions" to the shipping sector for the first time, with the novel contribution that emissions reductions from the existing fleet this decade is a central element of a Paris-compatible shipping transition, not just a focus on new fuels in new ships.

The third and fourth pieces of research aim to better understand the cultural, economic and political barriers to the accelerated deployment of measures to reduce shipping emissions, and how they can be overcome, through an analysis of one particular technology, shore power. Shore power connects ships to land-side electricity grids, allowing at-berth vessel energy use to be provided by shore-side electricity, rather than from burning fuel oils in the ship's auxiliary engines. Shore power is chosen because it is an option that can deliver both reductions in greenhouse gas emissions and local air quality improvements, and is also deployable now, but one whose global deployment remains slow. It is also an option which has broader links to the wider shipping transition – it is an enabling technology for the greater deployment of hybrid and fully-electric vessels, and it is synergistic with greater uptake of e-fuels such as ammonia. A deeper understanding of the barriers to uptake of shore power can help understand both how its own deployment can be accelerated, but also provide insight into how barriers to wider shipping decarbonisation can be overcome. The UK is chosen as a focus for this shore power analysis, given the slow deployment of this technology in the UK to date, despite the UK's leadership role on the urgency of climate action, exemplified by its practical use of carbon budgets within UK climate legislation (LSE, 2020). The third analysis' novel contributions are to apply two transitions methodologies in combination to the UK shipping sector for the first time, to spotlight that it is political factors blocking the accelerated deployment of UK shore power, and to identify means to overcome these barriers. The fourth analysis builds on the global shore power literature's tendency to focus on one policy instrument to identify combinations of policy instruments which can improve shore power project viability.

These four pieces of research are set out in published or submitted journal articles and are presented here as four concurrent chapters.

The next section sets out four research questions underpinning this research, with a brief description of the approach taken to address them. Detailed methodological issues are discussed in Chapter 2 and the relevant Chapters 3-6.

1.5 Research Questions

This thesis aims to address four linked questions, each of which are predominantly addressed in one of Chapters 3-6:

- What contribution should shipping make towards meeting the Paris Agreement goal to limit global warming to 1.5°C? (Chapter 3)

- Which technologies and practices, deployed at what time scales, could enable the shipping sector to meet Paris-compatible pathways? (Chapter 4)

- Why has shore power been slow to deploy in the UK, despite the UK's position as a leader on climate change mitigation and given shore power's technological maturity, and clear environmental and social benefits, and what solutions might overcome barriers to its deployment? (Chapter 5)

- What are the main financial and technical requirements for a UK shore-power project, how are they interlinked and what can be learnt and applied more broadly to the shipping transition?" (Chapter 6)

A broad gap in knowledge in shipping is around the scale and pace of change required to meet globally agreed climate targets, and what technologies and practices could help meet this challenge. The first research question therefore asks: "*What contribution should shipping make towards meeting the Paris Agreement goal to limit global warming to 1.5°C?"* This question is interrogated via the use of quantitative analysis of global carbon budgets, and principles around budget allocation, to derive Paris-compatible pathways for future international shipping carbon dioxide emissions.

The second research question then analyses the implications of this research, by asking "*Which technologies and practices, deployed at what time scales, could enable the shipping sector to meet Paris-compatible pathways*?" This question is addressed by extending the use of the concept of "committed emissions" to the shipping sector for the first time. Committed emissions refer to the future emissions from the business-as-usual operations for the remaining lifetimes of existing infrastructure (Tong et al., 2019, Davis et al., 2010). Committed emissions can be expected to be a larger issue for parts of the global economy with long-lived assets (such as ships), compared with shorter-lived products such as cars or laptops. The study uses the committed emissions concept in a quantitative analysis to elucidate the relative importance of measures to address the emissions from new versus existing ships.

This committed emissions analysis concludes that business-as-usual committed emissions from existing ships are very large, and measures that reduce the emissions of existing ships in this decade are an essential element of the shipping sector playing its part in avoiding a global temperature rise of 1.5°C. These measures include technologies such as shore power.

Another broad gap in knowledge in shipping concerns why deploying technologies and implementing policies to address shipping emissions have been slow to materialise (see Chapter 2 for detail), and how this could be addressed. The third and fourth research questions cover different aspects of this issue.

The third research question asks: "*Why has shore power been slow to deploy in the UK, despite the UK's position as a leader on climate change mitigation and given shore power's technological maturity, and clear environmental and social benefits, and what solutions might overcome barriers to its deployment?"* This question is answered using a case study involving a qualitative study based around 40 industry-stakeholder interviews, to analyse the barriers and solutions to UK shore-power deployment, using two analytical frameworks from the transitions literature: Technological Innovation Systems (TIS) and the Multiple Streams Approach (MSA). Key political, cultural, and economic barriers and interventions are identified.

Finally, these barriers and solutions to shore-power are explored in practice - the fourth research question asks: "*What are the main financial and technical requirements for a UK shore-power project, how are they interlinked and what can be learnt and applied more broadly to the shipping transition?"* This was analysed via a feasibility study and construction of an outline business case, through quantitative and qualitative analysis, for a shore power installation at multiple berths at the Port of Aberdeen, a mid-sized, multi-function UK port. This analysis sets out optimal locations for shore power installation, a preferred technical option, and assesses how different policy interventions from Government, combined with actions from the port and from ship operators and owners, would affect the project's financial viability.

1.6 Summary

This chapter has set out the urgent global need to reduce greenhouse gas emissions, to minimise the impacts of climate change on humanity and nature. It has positioned shipping as a major sector in the global economy, needing to make a rapid transition in the types and quantities of fuels it uses as part of addressing this global challenge. It highlights that transitions in shipping have happened in the past, and that a transition regarding climate change is underway, however this transition is contested and uncertain, with unresolved questions around the scale and speed of transition, required technology and practice change, and governance.

The chapter then set out four research questions (see Table 1-1-1) around this contested transition that the thesis addresses, to illuminate how shipping's climate change transition can be accelerated. It then stated that the thesis builds on existing academic literature to make five novel contributions. First, it sets out clear pathways required by the sector to meet globally agreed climate goals. Second, it elucidates priority actions and changes to technology and practice to these pathways. These first two findings conclude that there is an urgent need for emissions reductions this decade, and for a greater focus on non-fuel decarbonisation options – this is a challenge to recent years' consensus in shipping policy making, whose emissions reductions focus has been on 2050 and new fuels. Third, it details the impediments to the accelerated deployment of one such technology in the UK – shore power – which are caused by governance failures between and within the levels of global, national and local policy making. Fourth it sets how such barriers could be overcome. Fifth, it links these global-national-local analyses to make recommendations that are pertinent to the low-carbon energy transition in shipping more broadly.

The rest of this thesis is formatted in journal format, following the instructions for this format set out in the University of Manchester's Presentation of Theses Policy, June 2022. The four papers presented here are clear and discrete elements of work, addressing different aspects of the UK and global policy agendas for shipping decarbonisation, but also have common links and themes, explored in the discussion section. The prime justification for the decision to use the journal format was that policy at both global and UK level on shipping decarbonisation is in flux and rapidly changing, after a preceding decade of comparative quiet. The intention in this PhD has therefore been to publish results in journals as soon as possible, and disseminate these results to key stakeholders, so as to be able to inform live and emerging policy and industry debates around appropriate policy responses to the imperatives around climate change mitigation for shipping.

At the time of thesis-submission, two papers have been published, one has been submitted, one is in review. Titles and author-contributions are set out in Table 1-1-1 below. This work has also been cited in Government and policy-maker documents, for example in a UK Government submission to the IMO (IMO, 2022c), the Science Based Targets Initiative (Bonello et al., 2022), a submission to IMO by IMarEST (IMO, 2022a), the IPCC's AR6 WGIII report (IPCC, 2022a), the UK Parliamentary Office for Science and Technology (UK Parliament, 2022), the UK Climate Change Committee annual progress report (CCC, 2021) , and the UK Government's call-for-evidence on shore power (Department for Transport, 2022a). The initial Aberdeen analysis was used as the basis for a successful funding bid to the UK Government's Clean Maritime Demonstration Competition.

Relevant literature, an assessment of gaps in the literature and methods are predominantly covered within the specific journal papers in Chapters 3-6. Additional and overarching material on context, choice of methodological approach and literature review is now set out in Chapter 2.

Table 1-1-1 Thesis journal articles

Chapter	Paper	Author contributions (as set out in papers)	Primary research question addressed
3	Bullock, S., Mason, J., Larkin, A., 2022. The urgent case for stronger climate targets for international shipping. *Climate Policy,* Volume 22 Issue 3.	SB, JM and AL designed the study. SB led the writing with input from all authors who edited all drafts. SB, JM and AL contributed jointly on methodology.	1. What contribution should shipping make towards meeting the Paris Agreement goal to limit global warming to 1.5°C?
4	Bullock, S., Mason, J., Broderick, J. and Larkin, A., 2020. Shipping and the Paris climate agreement: a focus on committed emissions. *BMC Energy*, *2*(1), pp.1-16.	SB, JB and AL designed the study. SB was responsible for data analysis, model design, and led the writing with input from all authors who edited all drafts. JM contributed to model design. JB, JM, SB and AL contributed jointly on methodology for evaluating carbon budgets.	2. Which technologies and practices, deployed at what time scales, could enable the shipping sector to meet Paris-compatible pathways?
5	Bullock, S., Hoolohan, C., Larkin, A., 2023. Accelerating shipping decarbonisation: a case study on UK shore power (Submitted)	SB: Conceptualization, Investigation, Methodology, Data curation, Writing – original draft. CH: Conceptualization, Writing – review & editing, Supervision. AL: Conceptualization, Writing – review & editing, Supervision.	3. Why has shore power been slow to deploy in the UK, and what solutions might overcome barriers to its deployment?
6	Bullock, S., Higgins, E., Crossan, J., Larkin, A, 2023. Improving shore power project economics at the Port of Aberdeen. *Marine Policy*, Volume 152, 105625.	SB: Methodology, Investigation, Writing - Original Draft, Conceptualization; EH & JC: Methodology, Investigation, Writing – Review and Editing, Conceptualization; AL: Writing – Review and Editing, Supervision.	4. What are the main financial and technical requirements for a UK shore-power project, how are they interlinked and what can be learnt and applied more broadly to the shipping transition?

Chapter 2 Context and methods

The premise of the first chapter is that to meet global climate change goals, a rapid transition is required in the shipping system. However, it is uncertain what this should entail, and how it might occur. This chapter sets out a rationale for choice of methodological approach for analysing this potential shipping transition, situated within a review of clusters of related literature.

This thesis is informed by four sets of overlapping literatures: on climate change, transitions studies, shipping and shore power, as shown in Figure 2-1.

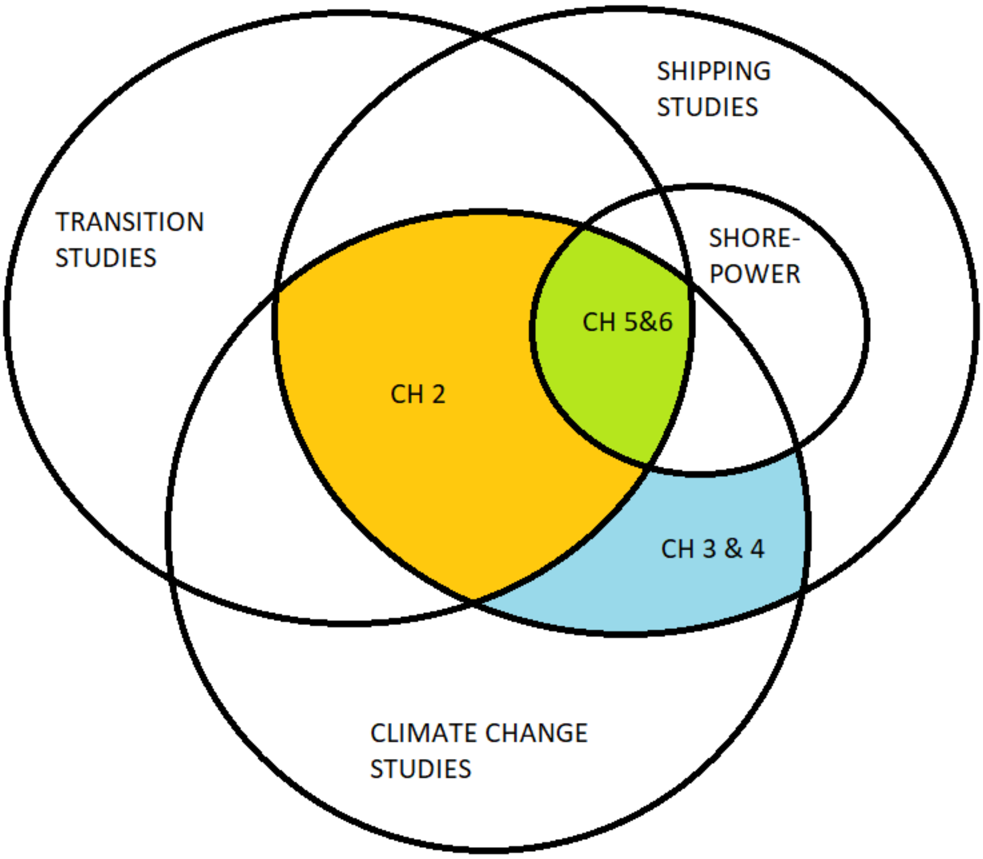

Figure 2-1: Overlapping shipping, climate and transition literatures

Climate change literature informs the framing for this thesis, set out in Chapter 1. The various intersections of climate change, shipping, transitions, and shore power have their own focussed literatures. This Chapter sets out an overview of existing research at these intersections, showing how it is used to underpin the empirical work presented in Chapters 3-6, and providing an overview of the conceptual framing for the thesis. Specific studies are reviewed in more detail in the relevant chapters, with a summary of location of literature assessments indicated in Table 2-1.

Table 2-1: Geographic scale and literature coverage for chapters 2-6

Chapter/ Section	Chapter description	Scale	Primary underpinning literatures
2.1, 2.2 and 2.3	Methods overview	All	Transition studies; shipping transitions studies
3 and 2.4	Scale and pace of change	Global	Climate change; climate change and shipping
4 and 2.5	Technologies and practice	Global/ regional	Climate change and shipping
5 and 2.6	National shore power transition	National	Shore power; particularly its overlap with transitions and climate
6 and 2.7	Local shore power case study	Local	Shore-power

The literature on transitions and shipping transitions informs the overall research design, as described in the following sections. Section 2.1 presents a broad justification for an analytical approach based on a series of linked studies at different levels. Section 2.2 then gives an overview of the shipping system using the Multi-Level Perspective. Section 2.3 continues with a discussion of how shipping transitions have occurred in the past, the factors involved in future transitions, and gaps in the shipping transitions literature. This leads to a choice of focus and methodological approaches. Sections 2.4 to 2.7 then summarises and discusses each of these approaches in relation to existing literature, introducing the analysis to be undertaken in each of Chapter 3-6.

2.1 Justification for a mixed-method, multi-level approach

Shipping is an example of a complex socio-technical system, operating at interconnected global, national and local scales (Geels, 2002, Pettit et al., 2018). In order to gain a fuller picture of how and why shipping transitions occurs, a multi-scalar analytical approach is required. Socio-technical systems are the combinations of technologies, institutions, practices and actors that deliver functions for society (Markard et al., 2012). Socio-technical transition studies analyse changes in how these functions, such as healthcare or mobility, are fulfilled (Zolfagharian et al., 2019). Characteristics of such transitions are that they have uncertain outcomes, involve multiple forms of inertia which must be overcome, have polycentric processes of change, and lead to profound (rather than incremental) change to system functions or how they are delivered (Köhler et al., 2018).

The focus on socio-technical systems is important, because it emphasises that transitions and systems are not just about technologies, but involve complex interactions between multiple elements of society. Andrews-Speed (2016) argues that "*…technology and society are not separate spheres of activity or policy, but are highly inter-dependent. Technology can determine behaviour in society and societies can make choices concerning technology. Individual technologies have cultural symbolic value, as indeed does the whole notion of technological progress. Thus societies and technology co-evolve*" (p217).

Sustainability transitions are a widely studied sub-set of socio-technical transitions, involving changes to systems to ensure broad sustainability goals are achieved (Markard et al., 2012, Geels, 2011). In sustainability transitions change is driven purposively (Smith et al., 2005, Kuzemko et al., 2016), with long-term goals to inform and drive the transition, rather than change emerging solely from ongoing processes and developments (Köhler et al., 2018). Literature on sustainability transitions research is wide and deep (van den Bergh et al., 2021), with a diverse agenda of active lines of research inquiry, such as on power, agency and politics, ethics, governance and the geography of transitions (Köhler et al., 2019, Truffer et al., 2022). This sits alongside the broader transitions literature (Sovacool and Hess, 2017, Cherp et al., 2018, Zolfagharian et al., 2019) and its own research agendas (Geels et al., 2018, Sovacool et al., 2020). The potential shipping transition studied in this thesis is an example of a sustainability transition, part of the wider transition required across all sectors to address the challenges and risks of climate change.

There are many analytical approaches for assessing transitions, with Sovacool and Hess (2017) identifying 96 theories and conceptual approaches used in the transitions literature. Some of the leading approaches include Energy Technology Innovation (Grubler and Wilson, 2014), Technological Innovation Systems (TIS) (Hekkert et al., 2007), Strategic Niche Management (Kemp et al., 1998), Transition Management (Rotmans et al., 2001), modelling-based approaches (Köhler et al., 2018), Techno-economic Paradigm theory (Freeman and Louçã, 2001), and the Multi-Level Perspective (MLP) (Geels, 2002). Three major review articles, by Panetti et al. (2018), Zolfagharian et al. (2019) and Markard et al. (2012) conclude that within the much larger group of possible approaches "*four major strands of inquiry"* (Panetti et al., 2018) predominate in terms of the frequency and breadth of their application – the Multi-Level Perspective, Technological Innovation Systems, Strategic Niche Management and Transition Management.

The predominant four and also the wider set of 96 approaches are not only different in methodological approach, but also operate at different scales. Geels et al. (2016) group potential approaches for analysing complex systems into three levels of scale. First, global quantitative models, for example normative, modelling-based approaches, that can set explicit goals and assess how these goals might be met. Second, sectoral or national analyses using transitions studies, that can ascertain progress and barriers at the level of a given sector, nation or technology. Third, from the bottom-up, locally-focussed action research, using local, experimental approaches, that assess what works in practice on the ground.

Geels et al. (2016) argue that although each level of analysis offers valuable insights, attempts to integrate these levels into one all-encompassing integrated theory are not possible, given fundamental differences in philosophical and ontological outlook. In addition, such an all-encompassing theory to analyse such processes and their sub-elements would be exceptionally complex. To avoid the complexity of an all-encompassing theory, Geels et al. (2016) advocate that insights from individual approaches should be combined through ‘bridging’. This bridging approach is expounded by Turnheim et al. (2015) who suggest a three-fold method where the results of analyses at these three levels can be combined to derive a multi-dimensional assessment of how a transition might be accelerated, with the three sets of results informing each other and the overall assessment. A bridging approach can thus add value when seeking to understand complex transitions. This thesis takes the view that analysing shipping transitions should use such a combination of linked and different analytical approaches, rather than either using just one approach at one level, or by attempting one grand overarching integrated theory. This pluralization of approaches is observed by Truffer et al. (2022) as a core emergent component of recent research across the sustainability transitions field. Further, Geels et al. (2016) argue that this combined three-fold analytical approach “*offers different kinds of knowledge that together may underpin a multi-facetted transition approach in polycentric governance systems*” (p581) – this is particularly relevant here, given the strong polycentric global-national-local nature of governance in shipping (Gritsenko, 2017, Lister, 2015, Stopford, 2022).

In this thesis therefore, a mixed-method, multi-level approach is employed. Different approaches align with different methods, and lend themselves to understanding transitions at different scales. Here, therefore, the approach used selects complementary methods that reveal different qualities of transition at different scales. First, at a macro level, quantitative modelling methods are used to assess what overarching goals are necessary for shipping’s transition (Chapter 3) and to analyse how such goals could be met (Chapter 4). Second, qualitative case-studies are combined with methodological frameworks from the socio-technical transitions literature to analyse the broad political, economic and cultural factors affecting the speed of transition in one element of the shipping sector (Chapter 5). Third, a bottom-up case study of a demonstrator project assesses the specific challenges faced by a locally-based initiative (Chapter 6). Specific methods and approaches are set out in more detail in Sections 2.4-2.7.

This multi-level and mixed-method approach helps with understanding the ongoing nature of this shipping transition, by providing insights around the interlinkages between the different levels and aspects of the challenge. Transition studies often focus on tensions between incumbents and new entrants (Geels and Schot, 2007, Arranz, 2017), tensions around framing of problems (Roberts and Geels, 2018), and tensions around appropriate policy instruments (Wieczorek and Hekkert, 2012, Rogge and Reichardt, 2016). These 'meso' level studies (Chapter 5) can be complemented by modelling approaches at the macro level that give greater clarity on the direction and speed of change required (Chapters 3 and 4), and by bottom-up studies that give practical examples of how tensions and collaboration between actors are playing out at present (Chapters 5 and 6). Such a combination can provide a greater understanding of the likelihood of the sector delivering the scale of action required, and what actions are likely to accelerate change.

A remaining question is how to derive appropriate linked, macro, meso and micro focuses and approaches. Jasanoff, in interview with Sovacool and Hess (2017), argues that "*one's research question will determine which theories apply…the theory comes from the material, the material doesn't come from the theory*" (p740), with her approach summarised by Sovacool and Hess as "*empirical material and research questions ought to drive theory selection*". In order to derive appropriate approaches from the material and research questions, it is first necessary to take some steps back, and provide some overview analysis, to guide the choice of methodological approach. Initially, section 2.2 describes the existing structure and practices in the shipping system. Then, main attributes of previous transitions in shipping are outlined, alongside an analysis of the literature on both historic and current shipping transitions (section 2.3). This pinpoints areas of focus for this thesis, whose rationale and approaches are then summarised in sections 2.4 to 2.7, and set out in full detail in Chapters 3-6.

2.2 Shipping as a socio-technical system

2.2.1 Introducing the Multi-Level Perspective

The Multi-Level Perspective (MLP) is a widely used heuristic framework in the socio-technical transitions literature for obtaining a broad overview of a system and its components (Geels, 2002). As a framework with a wide scope, it is therefore a strong option as an initial approach to survey the terrain in shipping. For example, other approaches are often criticised for having too narrow a perspective – such as the TIS approach not addressing structural change (Geels, 2011). In addition, after many years of development, the literature on socio-technical transitions has "*increasingly coalesced*" (Sorrell, 2018) around the MLP, with Sovacool et al. (2020)'s review of directions for future socio-technical research describing the MLP as a "core framework" for analysing transformative change. MLP is not without its critiques. Early critiques, such as over-emphasis on technologies (Shove and Walker, 2010), and lack of focus on power (Lawhon and Murphy, 2012) have led to multiple rejoinders, refinements and additions to the MLP approach (Geels, 2011, Geels, 2018), to the point where the theory is now far more sophisticated (but with Sorrell (2018) offering the critique that the MLP is now too cumbersome to be manageable). Some remaining critiques are that the MLP can be weak in ascribing causality, or determining which of the many factors in play would have the most effect on future transitions (Sorrell, 2018), and Gordon Walker's comment in Sovacool and Hess (2017)'s paper that MLP and transitions literature in general "*.. is very good in looking back at the processes involved in past transitions. But it comes a bit unstuck when it tries to… propose processes of change and agency*". Consequently, MLP is used here as a well-established and useful tool to provide an overview of the current state of the shipping system, but other methods – set out and justified in Chapter 5 - will be used to analyse the potential for and barriers to accelerated transition. The overview that MLP provides is used as the context for the four research papers which follow in Chapters 3-6, building on previous shipping MLP analyses (Geels, 2002, Pettit et al., 2018, Wells et al., 2018).

The MLP describes a system as consisting of three linked levels. First, a regime – which expresses the dominant institutional rationality (Fuenfschilling and Binz, 2018) of a system, which in combination with technologies, practices, actors and their interactions deliver a given societal function (Fuenfschilling and Truffer, 2014). Regimes are often constituted of ingrained, entrenched, locked-in co-dependence between actors, technologies and practices (Seyfang and Smith, 2007). Second, niches: protected spaces where innovations may grow and eventually challenge or be integrated into existing regimes (Raven et al., 2016). Third, the landscape, providing the overarching set of political, social, economic and environmental conditions that affect whether regimes strengthen or weaken, and niches grow or fade (Geels and Schot, 2007, Arranz, 2017). Sections 2.2.3-2.2.5 describe the three levels of the shipping system using the MLP, but first section 2.2.2 delineates the boundaries of the shipping system under analysis.

2.2.2 Defining the shipping system

The transitions literature notes that it is difficult to be precise in delineating exactly where a system begins and ends (Genus and Coles, 2008, Fuenfschilling and Binz, 2018). For example, the function of the shipping system could be defined as being the efficient and safe transportation of goods. However, the shipping system also combines with other transportation systems to deliver goods. For example, oil products can be transported by pipeline or tanker; food products can be transported by truck, rail or ship. Goods are often transported using multiple modes – for example bioenergy products harvested in the USA, moved by truck to a port, then by sea to the UK, then by rail to its final user. Shipping is therefore linked with other transport systems to deliver the broad function of transportation of goods, and similarly, all transport systems are linked with other systems as part of an overarching global economic system. The shipping sector also involves the transportation of people – however ferries and passenger vessels only represent 0.4% of the world fleet by tonnage (UNCTAD, 2022). The shipping sector also involves transport of goods on rivers, canals and lakes. The shipping sector is further distinguished from the broader maritime sector – which is concerned with all sea-based economic activities, also including areas such as aquaculture, fishing, offshore wind and oil exploration, as well as the transport of cargo. Clarity on boundaries is essential. For this thesis, the primary function of shipping is defined as the sea-transport of goods, and the 'shipping system' is defined as fulfilling the function of sea-transportation of goods required for the efficient operation of the global economy.

Sea-transport is pivotal in the global economy – over 80% of international trade in goods by weight is by sea (UNCTAD, 2022). In 2021, global seaborne trade totalled 12 billion tonnes, with each tonne of cargo transported on average 5,000 miles (Clarksons, 2021). 80% of seaborne trade is in transporting containers, oil, coal, gas, chemicals, iron ore, grain, steel and forestry products – see Table 2-2. Transport of fossil fuels is particularly important to the maritime sector – the value of oil tankers and gas carriers alone is $244 billion, representing 25% of the value of all vessels (UNCTAD, 2021). The amount of cargo transport-miles has doubled in the last twenty years, to 60,000 billion cargo tonne-miles (UNCTAD, 2022).

Table 2-2: Seaborne freight by cargo type, 2021.

Product	Million tonnes	%
Containers	1,934	16
Crude Oil	1,984	16
Oil products	999	8
Coal	1,210	10
Gas	514	4
Iron ore/Steel	1,886	16
Metals/Minerals	893	7
Grain	512	4
Forest products	383	3
Chemicals	376	3
Other	1,344	11
TOTAL	12,035	100

Source: (Clarksons, 2021).

The types of ship transporting these goods is very varied, and different metrics can be used to show the relative importance of different vessel classes. Table 2-3 shows the main ship types grouped according to their greenhouse gas emissions, as this thesis is concerned with a climate-related transition in shipping.

Table 2-3: Greenhouse gas emissions by vessel type, 2018

Ship type	2018 GHG emissions, ($MtCO_2e$)	%
Container	232	22
Bulk carrier	193	19
Oil tanker	159	15
Chemical tanker	82	8
Liquified gas tanker	71	7
General cargo	58	6
All other ship types[1]	245	24
TOTAL	1040	100

Source: (Faber et al., 2020), table 35.

[1] Other ship types include tugs, fishing vessels, cruise ships, ferries, Ro-Ros, vehicle carriers, offshore vessels.

Other metrics could also be used – such as gross value added (which would increase the perceived importance of container ships), deadweight tonnage or total tonne miles. Table 2-3's main utility is in showing that three vessel classes – container, bulk and oil tanker – constitute over half of the sector's greenhouse gas emissions.

Sections 2.2.3-2.2.5 now briefly outline the landscape, regime and niche elements in shipping, with their combination shown in Figure 2-2.

2.2.3 Landscape factors in the shipping system

There are various typologies of different potential landscape effects that might impact on regimes or niches. Arranz (2017) differentiates between three broad categories: “indicators”, such as greenhouse gas concentrations; “unintentional pressures” – purposeful activities that don't specifically target the regime under analysis, such as market liberalisation; and “intentional pressures”, such as actions deliberately aimed at influencing a regime, for example the 1970s oil embargoes. By contrast, Geels and Schot (2007) categorise landscape changes according to their type of impact, defining five types: regular, hyper-turbulence, specific shock, disruptive and avalanche. These types vary in their frequency, scope, amplitude and speed, with for example “specific shock" having high amplitude and speed, and low frequency and scope.

Landscape factors affecting shipping include geo-political shocks, for example the changes to sea-transportation of grain and oil following the 2022 Russian invasion of Ukraine. They involve the longer-run impact of broad global economic trends. For example, the pace of growth of the global economy and the variation in the price of fossil fuels both affect levels of sea transport of goods. Changes to how the global economy operates, such as through changes to global value chains and the impacts of digitalisation, also affect levels and patterns of sea-transport. Landscape impacts also encompass societal imperatives, such as the need for improved vessel safety following oil spills and increasing societal pressure to act on air pollution and climate change.

2.2.4 Regime factors in the shipping system

There is some ambiguity in the literature concerning the definition of the regime, and how it relates to the system. For this section, a broad definition of regime is used. It is taken here to be a triple combination of (i) (networks of) actors, (ii) dominant technologies and practices and (iii) prevailing formal and informal rules ("institutions"). Figure 2-2's description of landscape, niche and regime elements, based on the analysis in Pettit et al. (2018) broadens their analysis of the regime to break it down into three core elements of actors, technology/practice and institutions, with institutions defined as the informal and formal rules encompassing the range of beliefs, values, practices, capabilities, and also more formal regulations, standards and laws, enacted and constructed by the actors within a system (Fuenfschilling and Binz, 2018, Geels, 2011).

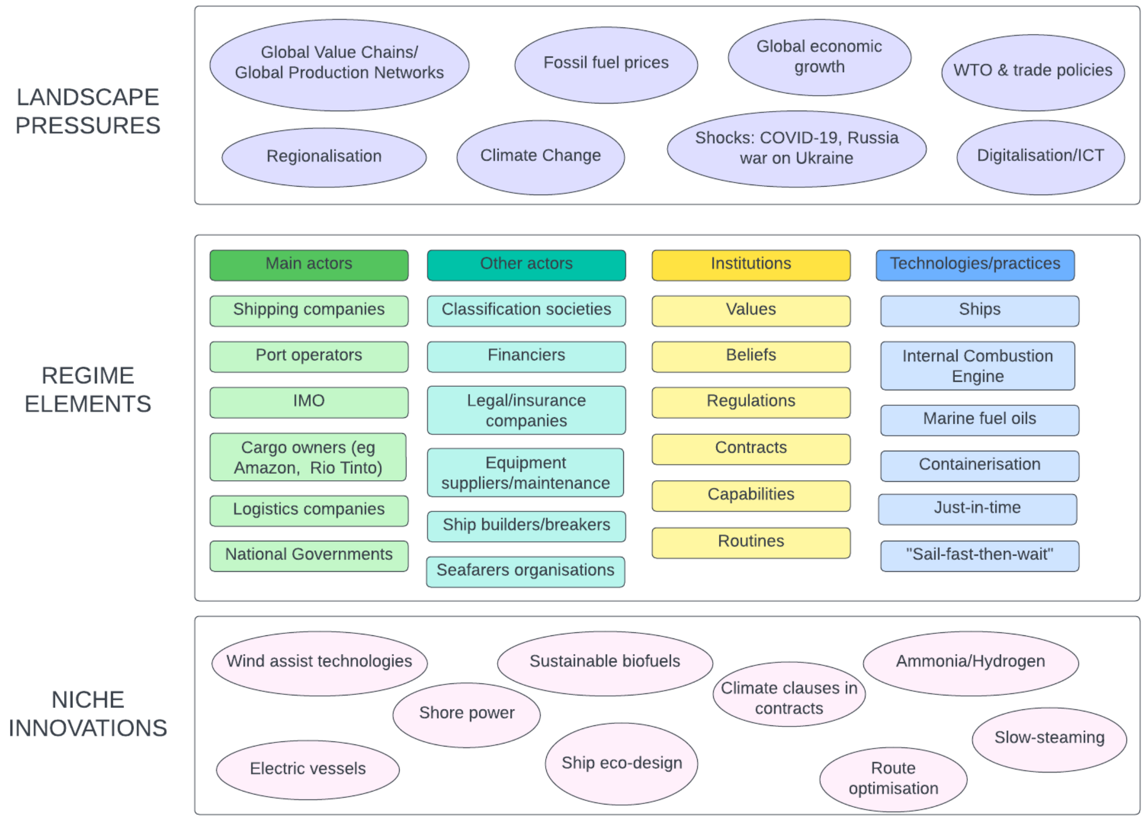

Figure 2-2: Landscape, regime and niche elements in global shipping

This definition of regime is used while cognisant of differences of opinion in the literature. Karanikolas et al. (2015) make the point that some people define regime differently, stating that while Geels (2004) calls regimes rules, Raven (2007) describes the regime as the whole sector. Sorrell (2018) too makes the argument there should be no distinction between regime and system. Sorrell also points out that Geels (2011) makes a distinction between systems and regimes, with systems comprising tangible elements, and regime comprising intangible elements, but argues that there are ambiguities in these relative definitions of system and regime, with Geels placing "regulations" in both the tangible system and intangible regime categories. There are further complications, with for example Pettit et al. (2018) describing the shipping regime solely in terms of actors, and Fuenfschilling and Binz (2018) placing actors as one of their categories of institutional rationality, a term defined as representing the regime. The definition of regime used in this thesis reflects the point that the regime represents the dominant institutional rationality (or formal and informal rule sets), but within the wider system other rationalities around informal rule sets also exist (Fuenfschilling and Truffer, 2014).

In this formulation, the existing global shipping regime is a deeply entrenched set of institutions, actors, practices and technologies that have co-evolved over decades. Some elements of the shipping regime have endured for centuries. For example, many of the contracts used between ship charterers and owners today are little different in form to how they were hundreds of years ago. The first known example of a contract document for the shipment of goods was in Cádiz in 1544 (Murray, 1982) – such Bills of Lading are still used today.

In the shipping regime, complex global supply chains for goods are serviced by logistics companies, ports, ship owners and operators, underpinned by global, national and local regulation, a labyrinthine network of finance, legal and insurance companies, and a host of other integral elements – such as ship builders, seafarers-organisations, classification societies and ship-breakers (Stopford, 2009). Figure 2-2 shows the wide range of actors within the global shipping regime.

Two critical elements of the regime are briefly discussed next. First, the unique governance arrangements in the shipping sector, owing to its global nature. Second, the different forms of institutional rationality within the sector.

Shipping has a complex set of interlinked global, regional and national governance structures, which Stopford (2022) argues is characterised by a dynamic relationship between processes at four tiers. Tier 1 is international regulation. Shipping is unusual for a global economic sector in that it has a well-established regulatory body with global jurisdiction – the International Maritime Organisation (IMO)[2]. The IMO's policy instrument of choice is standard-setting and regulation (IMO, 2023c). It has decades of experience at this, stemming from the introduction of global regulations to reduce the risks of oil spills following public outcry after major ecological disasters such as the 1967 Torry Canyon and 1989 Exxon Valdez oil spills, with a more recent focus on setting regulations on emissions to air, including more stringent requirements in particular geographic areas (IMO, 2014b). The IMO therefore has an ongoing impact on the shipping system - as the regime adapts to new IMO policies, and in allowing conditions for new innovations to grow in protected niches. Tier 2 is nation states, who enact IMO regulations, but also control maritime activities in their waters, register vessels, and set broad strategy and policies, such as in the UK's Clean Maritime Plan (Department for Transport, 2019a). Tier 3 is the operations of the shipping companies in line with Tier 1 and 2 constraints, but also in line with their own organisational strategies and priorities. Tier 4 relates to the actions of individual ships' captain and crew in carrying cargo safely, and in accordance with Tier 1-3 rules and standards.

Various other components of governance can be added to this basic four-tier structure. Five examples are set out here. First, there are other examples of Tier 1 global governance. At the global level, oversight of technical standards on ship design and operation is provided by the classification societies such as Lloyd's Register and Bureau Veritas, and the newly-established Poseidon Principles framework (Poseidon Principles Association, 2019) are intended to guide the incorporation of climate considerations into financial institutions' shipping lending decisions. Second, governance can exist between global and national levels, such as the EU's inclusion of maritime emissions in the EU Emissions Trading System (European Council, 2022) and regulations can be set at sub-national level, for example the policies of the Californian Government to cut pollution from ships in ports (CARB, 2020). Third, Tier 3 level governance – sitting between nations and individual ships – does not

[2] Stopford also includes the International Labour Organisation (ILO) in this tier, with its role in global promoting workers' rights, including at sea.

merely include shipping companies' internal governance in line with Tier 1 and 2 processes, but includes the practices of other pivotal actors in global supply chains: the charterers, such as Amazon and BHP Billiton, and those of the world's 2,916 ports (Lloyd's List, 2023). Fourth, there are new bilateral approaches, such as the 2021 Clydebank declaration to develop “green shipping corridors” between nations (UK Government, 2021b). And finally fifth, there are regional variations in the application of IMO regulations, for example the higher regulatory requirements on emissions to air in areas such as the Baltic Sea (IMO, 2023d).

As a result of this multi-level governance, change within the sector is not merely dictated by the actions of the IMO. The pace and scale of development of new technologies and practices in shipping is heterogeneous between nations, depending on for example the scale and quality of any supplemental global Tier 1 and sub-global Tier 2 policies to promote particular mitigation options, the variability of Tier 3 governance of companies, and their differing geographical focus of operations.

The preceding analysis in this section has focussed on actors and formal governance. However, cultural and symbolic meanings, markets and user practice are also important elements of the shipping regime (Geels, 2002). The potential for change within a regime is linked to how deeply embedded dominant institutional logics are within it, and whether it might be challenged by or integrated with alternative emerging and potentially contested institutional logics.

The global shipping regime is characterised as having a deeply embedded institutional rationality around market-efficiency. This logic has a broad internal mission of growth, with an external mission to facilitate global trade, by delivering reliable, secure, timely and cost-effective transport services (Stopford, 2009). Its values include economic efficiency and competition, for example through the widely applied “No More Favourable Treatment” principle. But there is also a longstanding value concerning safety, stemming as far back as the Plimsoll line legislation of 1876.

This rationality is however increasingly under pressure from the landscape pressure to address climate change and other environmental impacts, requiring greater intervention in markets (Geels et al., 2017, Roberts and Geels, 2018), and also potentially greater collaboration between actors. Such collaborations have the potential to run into conflict with existing norms. For example, numerous examples of actions to drive shipping decarbonisation – such as port collaborations, joint buying, standard setting and joint financing schemes – have been flagged for having the potential to run afoul of existing anti-trust rules and competition laws which aim to maximise the efficiency of markets and prevent cartels (Garcia, 2022).

A second logic in global shipping is therefore emerging around climate change, mirroring similar pressures in other sectors. Here, although many of the aspects of the sectors' institutional logic remain the same (for example safety is a core value in both), there are major and potentially far-reaching differences. Because this logic is still emerging, its precise components are still taking shape. It will also develop at different paces in different parts of the world, depending on the extent to which there are varying national pressures to address climate change. A whole range of different technologies and practice changes come to the fore in this logic, and other policy actions may become more relevant– for example the potential for market-based mechanisms such as carbon pricing to provide funding.

2.2.5 Niche innovations in the shipping system

There is a broad and strong consensus binding the actors in the global shipping regime around a core set of accepted technologies and institutions (Stopford, 2009). There are also a wide range of potential niche innovations that could break into the shipping regime, and potentially drive broader transition within the shipping system. Such innovations are described in overview studies such as by Balcombe et al. (2019) and Bouman et al. (2017), and examples are given in Figure 2-2. Some of these innovations emerge from outside the shipping sector – for example the implementation of digitalization technologies. Some innovations are driven from within the shipping sector, but outside of the main regime – for example experimentation in wind-assist technologies. But, following the findings of Geels and Penna (2015) in the car industry, innovations are also emerging from within the shipping regime – for example the drive for methanol vessels is coming from Maersk, one of the world's largest container companies, and the overarching climate regulations that are necessary to accelerate deployment of a range of currently niche innovations are being driven by a range of actors within IMO processes. The potential processes of uptake of niche innovations by the shipping regime are discussed in the next section.

Overall, Section 2.2 has shown that shipping has a complex set of actors, networks and institutions operating at different geographic scales, and an evolving polycentric governance structure. Despite the strong role of the IMO, there are both contested rationalities and also an incoherence between different levels of governance. This thesis aims to inform how accelerated decarbonisation of the sector could materialise, first through adding clarity on this contested rationality, and second through the focus on deployment of one technology at one level to draw conclusions for governance for the wider shipping transition.

The next section looks at previous transitions in shipping (section 2.3.1) and how a climate-related shipping transition might affect different parts of the sector in different ways (section 2.3.2). It then discusses whether landscape, regime or niche level effects would be likely to drive transition (section 2.3.3). There follows an overview of the relatively new and burgeoning shipping transitions literature, and an assessment of gaps in this literature (section 2.3.4). This leads into 4 areas of focus for the thesis (sections 2.4 to 2.7).

2.3 Transitions in shipping

2.3.1 Historic shipping transitions

Transitions can be driven from landscape, regime or niche levels, or combinations. Pettit et al. (2018) describe 5 historic "waves" of transitions in shipping, set out in Figure 2-3.
The drivers for these waves of historic transitions within the maritime sector have been very different and are set out in three main publications (Stopford, 2009, Pettit et al., 2018, Geels, 2002). The first wave saw a long transition from sail to steam. This primarily involved niche innovations in vessel design being gradually introduced into the main shipping regime, as steam technologies began to complement sails on vessels. In the second wave, landscape effects (the dramatic increase in availability of cheap coal) drove improvements in steam

technology and its rapid deployment in vessels. In the third wave, technology from other systems (the internal combustion engine) was adopted by the shipping sector. The 4th wave saw niche technical innovation in the shipping sector (containers) and major landscape shifts (trade globalisation via the General Agreement on Tariffs and Trade and the World Trade Organisation) combine synergistically, leading to exponential growth in global trade and sea trade specifically, and a radical overhaul of shipping logistics practice. The fifth wave, still ongoing, has seen technical innovation in Information and Communications Technology and digitalisation from other sectors – described by Mander (2017) as "pathway technologies" – combine with the landscape impacts of a further geographic distancing of production and consumption in global value chains. This has led to deeply embedded[3] just-in-time global supply chains, supplied by ever larger vessels.

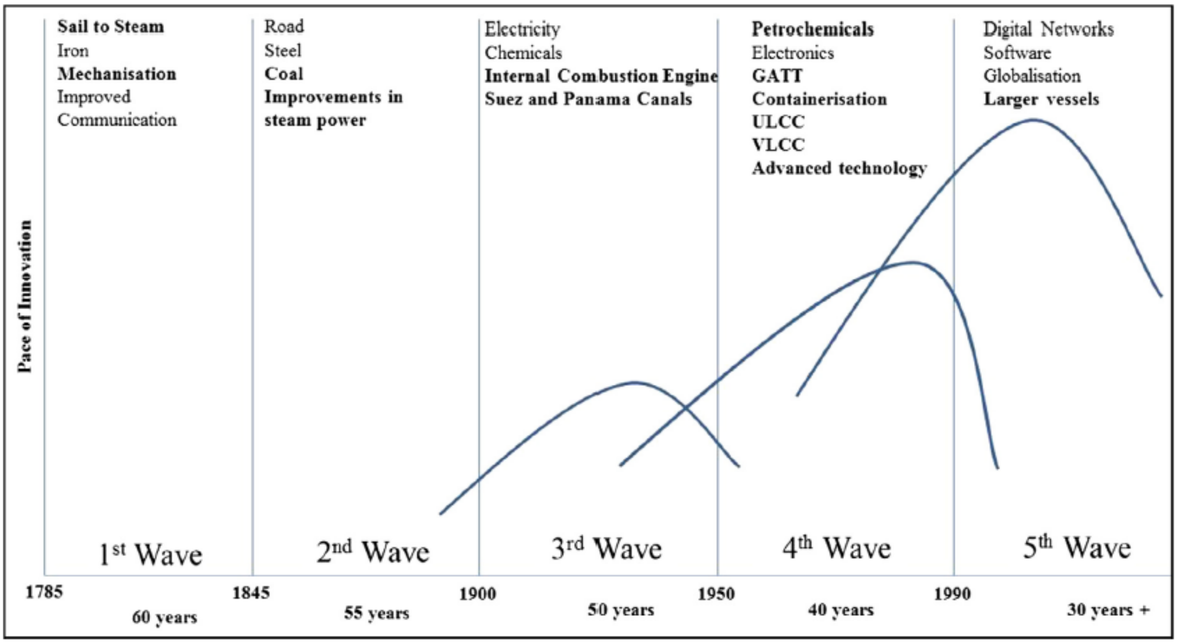

Figure 2-3: Five waves of transitions in shipping.

Source: Pettit et al. (2018)

2.3.2 A climate-related shipping transition

The shipping sector is at the cusp of a sixth wave, in which shipping makes a transition to be compatible with climate change goals. As set out in Section 1.3, this would constitute a very

[3] Yet curiously fragile: for example the deep global impacts of localised events, such as the Evergiven Suez Canal blockage of 2021, and the impact of Thailand flooding on the global electronics supply chain in 2020.

different transition to historic examples: it is being driven by political and social imperatives, not new technology, it will need to occur more rapidly and in a sector of greater complexity, and there is no single technological solution. Moreover, how this transition might occur is deeply contested: its scale and speed, the required technology and practice change, and the necessary governance structures and supporting policies. It is also likely that there will be multiple landscape, niche and regime drivers.

The impacts of these drivers will not be heterogeneous across the shipping system. For example, a purposive transition to address climate change risks will be occurring in other sectors as well as shipping, because meeting the Paris goals require all sectors and nations to act, and the overall impacts from this wider transition will vary within the shipping sector. For example, within the shipping sector the necessity of switching to a low or zero carbon fuel for propulsion would affect all ship classes. However, a successful transition in the wider energy system requires rapidly decreasing consumption of fossil fuels (IEA, 2021), and reduced requirements for sea-transport of fossil fuels (Faber et al., 2020, Jones et al., 2022) – which currently represent around 40% of sea trade by volume (Clarksons, 2021). This is particularly an issue in the oil sector, where a larger percentage of production is transported by sea compared with coal (where a greater proportion of consumption is near production) and gas (where use of pipelines predominates) (Jones et al., 2022). This means that a wider climate transition is likely to see rapidly diminishing need for oil tankers, whereas the impact on demand for vessels in the container segment is less clear-cut. The fall in sea transport of oil products could be compensated by a rise in demand for alternative fuels – hydrogen, ammonia and bioenergy – in both the shipping sector and the wider economy. Proportions of these fuels would require transportation by sea. However, given that decreases in oil consumption in most 1.5°C pathways are achieved predominantly by a combination of demand reduction, energy efficiency and widespread electrification using renewable power, it is likely that new demand for sea-transport of new zero-carbon fuels will not be of the scale of current sea-transport of oil (Jones et al., 2022).

Within the shipping sector, transition effects also vary across ship classes. Just within the sub-category of fuel-choice, there is a widespread belief in the industry that there is not likely to be a one-fuel solution (Franz et al., 2021, DNV, 2022b). Battery and hybrid-electric will be an increasingly attractive option as battery costs fall and range improves (Kersey et al., 2022), but different options will be needed for deep-ocean transport. Methanol is an attractive option as it requires fewer vessel adaptations than, say ammonia, and is already being rolled-out by major industry players such as Maersk (Maersk, 2022). However, the supply of methanol is limited by sustainability and affordability requirements (Gielen, 2021). Zero-carbon ammonia supply is less problematic (IRENA, 2022), however it is at a lower Technology Readiness Level for use in ship engines (DNV, 2022b). Ammonia also comes with major safety risks, as it is highly toxic to humans (Michaels, 1999) and ecosystems (Constable et al., 2003). There are major projects underway to address the risks from using ammonia as a fuel on ships, and from additional port bunkering (Stott, 2022, Ship and Bunker, 2022) however perception of risk may endure as a barrier to uptake (Royal Society, 2021), particularly in consumer-facing shipping segments such as ferries and cruise.

Overall, the speed and direction of transition in shipping to address climate change risks are uncertain and contested, and the required changes to technology and practices and how they would affect different sub-sectors in the shipping regime are similarly unclear. The next sub section explores the factors that might affect this transition.

2.3.3 Factors affecting future shipping transitions

Pettit et al. (2018) argue that the current shipping global regime is so entrenched that it would be difficult for any niche innovation to substantially alter its trajectory, therefore landscape pressures are pivotal to shaping shipping transitions. The likely greater importance of landscape effects here is also underscored by the recognition that this transition is a type of “sustainability transition” (Markard et al., 2012). These are a sub-set of broader transitions, with their own comprehensive literature (see previous section 2.1). Sustainability transitions are not treated differently to broader transitions here, as the mechanisms involved in transition are similar (Cherp et al., 2018), however it is noted that sustainability transitions are in large part responses to situations where entrenched regime practices and technologies enjoy major competitive advantages due to their appropriation of public commons, making it very difficult for niche innovations to succeed without greater purposive direction from Governments (Roberts and Geels, 2018). The continuing failure of the IMO to adopt any measure that puts any carbon price on marine fuel oils (Shaw, 2022) is an example of one such extreme competitive distortion in favour of entrenched carbon-intensive technologies and practices in the shipping sector, as the damage costs from these fuels' use are not internalised into market prices. Because of this, in shipping landscape changes are likely to be even more pivotal for challenging regime dominance.

Section 2.2.4's discussion of institutional rationalities in shipping suggests that the landscape pressure of climate change is creating a new rationality within the sector, but that this rationality is uncertain and contested. A clearer articulation of the shipping sector's climate change goal, and the implications for the sector in meeting it, would help to clarify the emerging institutional climate change logic in the shipping sector, which could help accelerate transition. Following from this, Hargreaves et al. (2013)'s discussion of institutional theory approaches to transition studies describes that when landscape pressures on the incumbent regime increase, transition may occur in two processes: direct change in the regime, or from opening up windows of opportunity for novel or radical innovations to occur in niches. First, reconfiguring existing regimes can be driven from within the regime itself, using the pressure from existing landscape processes, for example through the adoption of new standards or regulations (Smith, 2012), and in ongoing efforts to set an overarching climate framework within which the shipping regime must operate, for example the imminent revision of the IMO's initial greenhouse gas strategy, due in summer 2023. Second, pressure from landscape processes can be used to justify or nurture new innovations in niches. Niche-innovations in shipping can occur in a variety of protected spaces – either protected by specific Governments (such as Norwegian efforts to promote electric-shipping), or in particular sub-segments of shipping (such as ferries), or for particular technologies and practices (such as ammonia-fuels, slow steaming or shore power). The success of niche innovations depends critically upon the extent to which they are congruent with existing institutional logics, or can be made so, or fit with an emerging competing institutional logic.

There is a growing shipping transitions literature which has started to look at these potentialities for change. The following section gives an overview of how this has developed, and the main methodological approaches, and then sets out gaps.

2.3.4 Gaps in the shipping transitions literature

In 2019, when this PhD began, there were relatively few papers in the transitions literature that considered shipping, compared to other areas such as transition in the power sector and agriculture. Three papers from 2018-2020 illustrate this. First, the Technological Innovation System (TIS) paper on Norwegian shipping by Bach et al. (2020b) cites just two shipping transitions studies – the global-shipping Multi-Level Perspective (MLP) paper by Pettit et al. (2018) and a Norwegian consultancy report by Steen et al. (2019). Second, the Dynamic Capabilities shipping transitions paper by Stalmokaite and Hassler (2020) states that "*the shipping sector has so far received limited attention from sustainable transition scholars*", citing just four shipping transitions papers (Mander, 2017, Bergek et al., 2018, Karslen et al., 2019, Köhler, 2020). Third, a literature review by Shi et al. (2018) on shipping research methods did not include any of the above papers nor any mention of transitions methods: indicating that transitions methodologies were not considered as a core method for analysing the shipping sector.

There are however some other pre-2020 shipping transition papers. Some are explicitly about sustainability transitions, and use well established transitions methodologies, for example the seminal global shipping MLP paper by Geels (2002), a further MLP paper by Stalmokaitė and Yliskylä-Peuralahti (2019), the Transitions Management paper on Rotterdam by Bosman et al. (2018), and the TIS studies on scrubbers by Makkonen and Inkinen (2018) and on wind propulsion by Rojon and Dieperink (2014). Some papers also cover issues surrounding shipping transition, but without explicitly calling themselves transitions studies, or using transition methods. These include the Global Value Chain study by Poulsen et al. (2018), Governance studies by Lister (2015) and Gritsenko and Roe (2019) and the agency theory study by Rehmatulla and Smith (2015).

Since 2020 there has been however a rapid growth in shipping transitions papers – the above 18 "core" shipping transitions papers from 2002-2020 have been bolstered by a further 19 articles since[4]. In total, these 37 articles' coverage varies widely, from global to local scales, on all aspects of shipping, or very specific aspects of it, and using a wide range of methodological approaches, as set out in Table 2-4.

Table 2-4: Shipping transitions literature by geographic scale, subject area and methodological approach.

	All shipping		Sub-sector of shipping		
	Methodological approach	Geographic area	Methodological approach	Geographic area	Sub-sector
Global	MLP (1)	-	Governance theory (13)	-	Governance
	MLP (2)	-	Agent based modelling + MLP (14)	-	Wind-propulsion
	MLP (3)	-	Agent based modelling + MLP (15)	-	H2 + wind-propulsion
	Modelling (4)	-	Governance theory (16)	-	Governance
			TIS (17)	-	Scrubbers
			MLP (18)	-	Slow steaming + wind propulsion
			Global Value Chain (19)	-	Cargo-owners
			Agency Theory (20)	-	Energy efficiency
			TIS (21)	-	wind-propulsion
			Lit Review (22)	-	Energy efficiency
Regional /National	Actor roles (5)	Norway	TIS (23)	Norway	H2 + battery electric vessels
	Actor networks (6)	Norway	TIS + MLP (24)	Norway	Battery electric vessels
	Dynamic Capabilities (DC) (7)	Baltic Sea	Network Theory (25)	Norway	Offshore
	MLP (8)	Baltic Sea	TIS (26)	Norway	Biofuels
	MLP (9)	Netherlands	MLP task/institutional environments (27)	Norway	Battery electric vessels (BEVs)
	Lit Review (10)	EU	System Dynamics modelling (28)	Asia	LNG
			Innovation studies (29)	Norway	Battery electric vessels
			Mission-oriented TIS (30)	Norway	Battery electric vessels
			Survey + statistical analysis (31)	Norway	Shipowners + alternative fuels
			TIS (32)	Norway	H2, biofuels, BEVs
			Actor Network Theory (33)	Norway	LNG
Local/ port/ company	Transitions Management (11)	Rotterdam	MSA (34)	Oslo	Shore power
	MLP (12)	3 Norwegian ports	Practice theory (35)	Sweden	Ship's crew, energy efficiency
			Practice theory (36)	SW Norway	Engineers
			DC + MLP (37)	Sweden	Wind-propulsion

Refs: (1) (Geels, 2002); (2) (Pettit et al., 2018); (3) (Wells et al., 2018); (4) (Köhler et al., 2022); (5) (Bjerkan et al., 2021); (6) (Hessevik, 2021); (7) (Stalmokaite and Hassler, 2020); (8) (Stalmokaitė and Yliskylä-Peuralahti, 2019); (9) (Stolper et al., 2022); (10) (Bergsma et al., 2021); (11) (Bosman et al., 2018); (12) (Damman and Steen, 2021); (13) (Gritsenko and Roe, 2019); (14) (Karslen et al., 2019); (15) (Köhler, 2020); (16) (Lister, 2015); (17) (Makkonen and Inkinen, 2018); (18) (Mander, 2017); (19) (Poulsen et al., 2016); (20) (Rehmatulla and Smith, 2015); (21) (Rojon and Dieperink, 2014); (22) (Viktorelius et al., 2022); (23) (Bach et al., 2020b); (24) (Bergek et al., 2018); (25) (Hessevik, 2022); (26) (Bach et al., 2021); (27) (Bergek et al., 2021); (28) (Yin and Lam, 2022); (29) (Saether and Moe, 2021); (30) (Bugge et al., 2021); (31) (Mäkitie et al., 2022); (32) (Steen et al., 2019); (33) (Tvedten and Bauer, 2022) ;(34) (Bjerkan and Seter, 2021); (35) (Sjøtun, 2020); (36) (Viktorelius, 2020); (37) (Stalmokaitė et al., 2022).

There are some clear gaps within this literature. Some geographic areas are covered in great depth – 19 of the 23 sub-global papers focus on Baltic countries – with other countries and

[4] Because many shipping transitions studies do not label themselves as such, standard systematic literature review methods struggle to fully capture the range of literature on this subject. Here, "snowballing" was used instead– using the 18 core papers as a base, further post 2020 papers were found from manual review of every article which cited the original core 18 articles – any article which covers shipping transition is added to the core list, and used in an annual update to search for further new shipping transition articles.

regions far less studied. Global level studies of the whole sector tend to use the MLP, but do not focus on what the goal of transition should be. Similarly, studies of particular technologies and practices at the global level (papers 13-22 in Table 2-4) tend not to place themselves in the context of how they might interact with other technology and practice change to deliver overall transition goals.

One branch of inquiry is the use of modelling – as in the work of Köhler et al. (2022), which combines a structured scenario approach with transitions theory to plot plausible futures. This modelling work could be usefully complemented with a temporal assessment of required combinations of practice and technology change, for Paris-Agreement compatibility.

The largest subset of shipping transitions papers is of studies of one technology change at a specific (usually Norwegian) geographic scale. These analyses tend to use one analytical framework (usually based around TIS), or use one framework in combination with a broad MLP overview. There is a dearth of studies looking explicitly at political factors involved in transition – with the exception being the MSA paper on shore power in Oslo (Bjerkan and Seter, 2021). This suggests two useful complements to the literature. First, studies combining two in-depth analytical approaches, in order to combine insights from technological innovation approaches with those with a focus on political factors. Second, studies that go beyond analysis of the pioneering work in Baltic countries, to geographies where there are less supportive environments for shipping transitions.

To conclude section 2.3, the range of factors potentially affecting the rate of transition discussed in section 2.3.3 informs the design of the methodology employed in the thesis, in terms of suggesting a two-pronged focus – first on how landscape issues could affect institutional logics, and second on how niche innovation deployment can be accelerated. The discussion of gaps in shipping transitions literature in section 2.3.4 suggests areas of focus for this latter analysis of niche innovation deployment: on political factors and on geographies where shipping transition is slow.

The next four sections 2.4 to 2.7 set out a rationale and methodological approach for the four papers that capture the areas of research in this thesis.

2.4 The required scale and pace of global shipping transition

As discussed in section 2.2.4, emergent competing institutional logics such as a climate change imperative can struggle through lack of internal consistency, or clear articulation of values and goals or appropriate technologies and practices. This thesis, through Research Questions 1 and 2, aims to inform the emerging debate in shipping of what in practice an emergent climate logic means for the sector – its mission, values, practices and appropriate technologies.

A critical aspect of section 2.2.4 is that as of the start of this thesis, the "mission" aspect of the sustainability rationality was uncertain and contested. One aim of the thesis has therefore been to delineate what an appropriate mission is for global shipping, in light of broader agreed societal goals (i.e. landscape issues) for climate – Research Question 1. The research over a period from 2019 to the end 2022 has taken an explicit position that its intention is to try to inform global debates with the effect of influencing landscape processes.

The International Maritime Organisation (IMO) is a United Nations agency with responsibility for regulating the actions of the international shipping sector. Its environmental focus has traditionally covered the regulation of oil spills, and on measures to reduce air pollution (Chircop and Shan, 2020). In the last decade in particular, climate change has risen in prominence at the IMO, mirroring greater political and societal concern at a global and national level, and in other sectors. Following Greenhouse Gas (GHG) study reports in 2009 (IMO, 2009) and 2014 (IMO, 2014c), the IMO introduced its first GHG Strategy in 2018 (IMO, 2018d). However, this strategy's goals appear to be at odds with its stated aim to represent "*a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals*". The IPCC's 6th Assessment report states that to meet the 1.5^{o}C Paris target, global CO_2 emissions should reach net-zero by the early 2050s (IPCC, 2022a), however by contrast the IMO strategy states that the GHG emissions from international shipping should only be reduced by "*at least 50%*" by 2050 compared to 2008 levels. (CO_2 emissions represents 98% of the sector's overall GHG emissions (IMO, 2020)). Similarly, the IMO's 2030 target implies that shipping emissions would be constant throughout the 2020s (DNV.GL, 2018), whereas the IMO's sister-agency, UNEP, reports that global emissions should be halved by this point (UNEP, 2022).

This disconnect between international agencies reflects four main sets of complexities. First, overall climate change goals can vary. Some climate change targets are expressed in terms of all greenhouse gases, others just as CO_2. Some are set against a 1990 baseline, others use 2008, 2010 or 2020. In addition, it is not simple to translate a temperature target to an emissions target. The IPCC's work on carbon budgets expresses different cumulative budgets for a range of percentage likelihoods of exceeding given temperature goals – but what percentage likelihood of exceeding such a temperature goal is acceptable? Table 2-5 sets out carbon budget values from the IPCC's 6^{th} Assessment report (Masson-Delmotte et al., 2021a). The size of the available global carbon budget is critically dependent on the percentage likelihood of staying below a given temperature goal.

Table 2-5 Carbon budgets for different likelihoods of limiting warming to given temperature increases

	Remaining carbon budget from the beginning of 2020, for given likelihood of limiting global temperature rise ($GtCO_2$)				
Temperature increase relative to 1850-1900	17%	33%	50%	67%	83%
1.5°C	900	650	500	400	300
2°C	2,300	1,700	1,350	1,150	900
Notes:	• Cumulative emissions 1850-2019 = 2,390 ± 240 $GtCO_2$ • Global warming 1850-1900 to 2010-2019 = 1.07°C • Annual emissions in 2020 = 35 $GtCO_2$ • Different assumptions on non-CO_2 emissions reductions change carbon budget values ±220 $GtCO_2$				

Source: Based on Masson-Delmotte et al. (2021a), Table SPM.2

Second, it is not straight-forward to translate global budgets or targets to nations or to sectors. The difficulties in doing this for nations are reflected in the move from “top-down” attempts to impose targets on nations under the Kyoto Protocol (UNFCCC, 1997) to “bottom-up” approaches in the Paris Agreement (United Nations, 2015), where nations make Nationally Determined Contributions they believe are appropriate to meeting the overall goals of the Agreement. For sectors, there is no process for deciding, for example, what contribution the agricultural sector should make, relative to those by steel, aviation, road transport, buildings or shipping. Third, there are considerable challenges in data gathering in shipping, around how emissions are measured and accounted for, with the initial IMO strategy in 2018 being set before a major update to the IMO’s 4th Greenhouse Gas study (IMO, 2020), published in 2020, with this latter study proposing a major change in the delineation between international and domestic shipping emissions. Finally, the process by which targets are set by the IMO are informed by the climate science, but the consensus-based approach to decision-making in the IMO means that in practice it is difficult to agree on global targets that are believed to have very different implications, for example between those for developed and developing countries (Psaraftis, 2019). One manifestation of these tensions in the perceived conflict in the IMO between two principles (Chen, 2021) – the principle within Article 3 of the UNFCCC process of “*common but differentiated responsibilities*”(United Nations, 1992b), and the long-standing principle within the shipping sector of “*no more favourable treatment*” (ILO, 2006).

To an extent, these uncertainties and tensions are reflected in the IMO’s target – which specifies “*at least*” 50% reductions by 2050. But particularly in shipping it is essential to be clear early on what the end goal is, because ships’ average lifetimes are 28 years (Bullock et al., 2020), so a vessel designed and built now will still be operating in 2050. Decisions now affect emissions in three decades time, and consequently it is a matter of urgency that the sector has a clear view on the pathway required.

This analysis informs the framing of the first research question in this PhD: “*What contribution should shipping make towards meeting the goals of the Paris Agreement on climate change?*” Previous research has suggested that stronger targets than the IMO’s current targets would be required (Smith et al., 2015, Traut et al., 2018, Gilbert and Bows, 2012). **The first paper (Chapter 3) updates and builds upon this previous work to take into account three factors. First, it uses advances in data gathering and emissions accounting within the shipping sector, to allow a clearer and more accurate assessment of international shipping emissions within the global shipping sector. Second, it uses updated climate science data from the IPCC on permissible cumulative carbon dioxide emissions to stay within given probabilities of exceeding the Paris Agreement goals. Third, it assesses appropriate apportionment methodologies to enumerate appropriate contributions and pathways for the international shipping sector to the broader global climate goal.**

This research is directly policy-relevant because the IMO has a timetable to revise its initial 2018 Greenhouse Gas Strategy by the IMOs Marine Environment Protection Committee (MEPC) meeting in July 2023 (MEPC 80), with the December 2021 MEPC 76 meeting "*recognizing the need to strengthen the ambition of the Initial IMO GHG Strategy*" (IMO, 2021c) during this 2023 strategy revision process.

2.5 Changes in shipping technologies and practices

Another contested set of issues within in the shipping sector's nascent climate change transition is which technologies and practice changes should predominate, and the speed at which they would need to be adopted. This is addressed in Research Question 2. Two overview papers, by Bouman et al. (2017) and Balcombe et al. (2019), set out comprehensive lists of potential climate mitigation technologies and practice change, with quantified ranges for potential mitigation contributions from each option. Some complexities are also discussed, such as whether options in combination are synergistic, additive, or can cancel each other out – an issue returned to recently by Mason et al. (2023) in their discussion of the combined effect of voyage optimisation software used with flettnor rotors. However, there is a gap in the literature about the required timing of implementation of different mitigation measures in shipping.

The first paper sets out in Chapter 3 a clear CO_2 reduction pathway for the international shipping sector. The critical second question is *what change to technologies and practices, deployed at what time scales, could enable shipping to meet Paris-compatible pathways*?

Multiple factors affect the level of a given pollutant, at either the level of the global economy, nations or in specific sectors. The Kaya identity is a tool used to separate and link these factors – describing the level of carbon dioxide (CO_2) emissions as a function of human population, GDP per capita, energy intensity (per unit of GDP) and carbon intensity (CO_2 per unit of energy) (Kaya, 1989). Variants on the Kaya identity have been used – such as by Peters et al. (2017) who do not include the population factor. For shipping, Sharmina et al. (2021) modify the Kaya identity in line with Peters et al. (2017), expressing CO_2 as a function of GDP, energy intensity of GDP, and carbon intensity of energy. Carbon intensity is an indicator used widely in a policy and operational context within the shipping sector, however energy intensity tends to be expressed more commonly relative to "transport-work" (e.g. the energy used to transport one tonne of product for one mile), rather than per unit of GDP. Consequently, in this thesis the components of shipping emissions are considered in the form of a further modified Kaya identity, based on four functions – demand, distance, energy efficiency and carbon intensity, as set out in Figure 2-4.

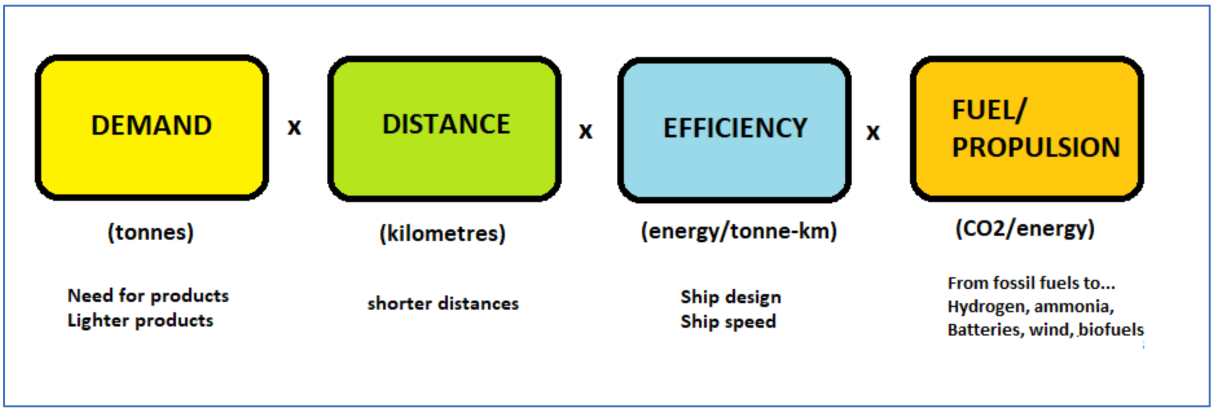

Figure 2-4: Revised Kaya identity for shipping, showing measures affecting each variable

Of these four variables, in shipping debates there is a strong assumption that transport-work (demand x distance) will increase in the coming decades. There is potential to reduce both tonnage and distance, for example by product light-weighting, 3D printing and regionalisation of trade, although the likely trade impacts of these processes in future are as yet very uncertain (Altman, 2022, Freund et al., 2022). Also, in scenarios involving strong global climate mitigation, sea-transport of products such as coal and oil will also decrease

(Jones et al., 2022). However, overall global sea-transport work in 2050 in the IMO's 4th Greenhouse Gas report is assumed to increase by 74 to 126% on 2018 levels (IMO, 2020), depending on scenario, predominantly because of the strong correlation between global economic growth and levels of trade and hence quantities of shipped product. Consequently, although measures to affect demand for shipping services are under-represented and under-researched in models and in the literature (Sharmina et al., 2021), and almost taboo in shipping policy debates, it is assumed in this thesis that even if stronger measures on transport-work were introduced, they would at best keep transport-work constant at today's levels. This means that irrespective of the critical issue of the future quantity of transport-work, measures on efficiency and carbon intensity are pivotal to reduce absolute emissions of CO_2 from shipping.

These two latter types of measure dominate current shipping decarbonisation policy deliberations. First, there are a range of new energy efficiency measures to meet the IMO's current "emissions intensity" target for 2030. These affect the design and operational efficiency of new and old ships, via a variety of regulations and guidance (EEXI, EEDI, CII, SEEMP[5]) over the next decade. Second, on carbon intensity there is an expectation that the heavy lifting for shipping decarbonisation will be done in the 2030s and 2040s through the widespread adoption of a new generation of low or zero carbon fuels, such as hydrogen and ammonia, among others (DNV, 2022b, Department for Transport, 2019a). There is however a danger with this latter expectation. Global temperature rise is strongly correlated with cumulative emissions of carbon dioxide (Matthews et al., 2018). Consequently, it is not solely achieving a zero emissions goal that determines whether a particular temperature goal is met, but also the shape of the emissions reduction pathway over time towards the zero-emissions end goal. In linear pathways towards zero emissions, the majority of the cumulative emissions are in the early years. And pathways with delays to emissions reductions will have higher cumulative emissions than those with more immediate reductions, unless there is a steeper later mitigation pathway. As a result, if shipping

[5] The Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ships Index (EEXI) are one-off ship-design indicators, measuring new and existing ships' CO_2 emissions per tonne mile. The Carbon Intensity Indicator (CII) is a measure of ships' emissions in practice, in CO_2 per cargo capacity-tonne mile. The SEEMP is a mandatory Ship Energy Efficiency Management Plan aimed at improving operational energy efficiency.

emissions do not start to decline until 2030, and rapid decarbonisation is left to the 2030s and beyond, then there is the potential that high cumulative emissions during the 2020s may mean that Paris-compatible carbon budgets for the shipping sector may already be exceeded, before the at-scale deployment of alternative fuels has begun. This is problematic when coupled with the IMO's explicit decision to tie its energy efficiency policies to its 2030 target, which with projected sectoral growth are predicted to see emissions overall merely staying constant to 2030 (DNV.GL, 2018).

The second paper (Chapter 4) therefore investigates a critical aspect of the broad research question around technologies and practices, by assessing whether it is possible to meet Paris-compatible pathways through reliance on ships being deployed with zero carbon fuels in the 2030s and 2040s. It does this by applying the concept of "committed emissions" in the academic literature (Davis et al., 2010, Tong et al., 2019) to the shipping sector for the first time. New data sets allowed this to be possible – the paper interrogates data from 2018, the first year of availability for the EU's Monitoring, Reporting and Verification (EUMRV) shipping emissions database (EMSA, 2019). It assesses the likely future emissions from existing ships, and from new ships, and compares these with a Paris-compatible carbon budget. The study then sets out the extent to which further measures are needed to reduce emissions from existing ships in this decade, for Paris-compatibility. Such measures include technology options such as wind-assist, shore power and fuel-blending, and operational practices such as slower speed.

The research conclusion from this paper is directly policy-relevant as an implication that stronger operational measures for the existing fleet are needed in the 2020s would require urgent revision and tightening of relevant IMO regulatory measures, particularly the Carbon Intensity Indicator.

2.6 National transitions in shore power

There are dozens of niche innovations in shipping from a carbon dioxide mitigation perspective (Balcombe et al., 2019, Bouman et al., 2017). This thesis – in line with its positioning that it is intended to inform live policy debates – focusses on one of these myriad options: shore-power, and its deployment in the UK.

Shore power connects ships to land-side electricity grids, allowing at-berth vessel energy use to be provided by shore-side electricity, rather than from burning oil in the vessel's auxiliary engines. This cuts local air pollution and noise (Kumar et al., 2019), and will reduce CO_2 emissions if electricity is low-carbon (Hall, 2010). Shore power solely for replacing auxiliary engine use in port is projected to be able to reduce overall sector GHG emissions by 3-10% (Bouman et al., 2017).

Shore power deployment is highly compatible with the existing regime. The required new infrastructure and the changes in practice are minimal, in comparison with the wholesale changes to ship engine design and bunkering infrastructure required by a transition to using ammonia-fuels, or in comparison with the implications for current "sail-fast-then-wait" contracts (Blue Visby, 2023) and just-in-time supply chain practices implied by slow-steaming. Shore power is also likely to be compatible and synergistic with other decarbonisation options, for example the provision of future alternative low-carbon fuels. There is a strong expectation that ammonia, hydrogen and methanol fuels will be a large part of the fuel solution for shipping and climate change, and that for these to be low-carbon, in the long-term their production would predominantly be via renewable electricity – for example electrolysis of water to make hydrogen. In such a case it would be more efficient and cost-effective for ship operators to use shore power rather than electro-fuels while at berth, as it would be using electricity directly, rather than conversion of electricity to make fuel to turn back into electricity.

Shore power is also an essential enabling technology for the greater use of hybrid-electric and fully-electric vessels, through the provision of battery recharge facilities. It is likely that the role for electric-vessels will grow, given the dramatic and continuing improvements in battery efficiency and reductions in battery cost, which are already making electric container vessels economically viable up to 1500 km (Kersey et al., 2022). This increases the future importance of shore power infrastructure in the wider shipping decarbonisation transition.

However, despite these benefits, shore power is not widely deployed globally. Ten years ago, this was due to technical issues that applied globally; these included a lack of common standards and uncertainties about equipment effectiveness. These issues have been overcome (Kumar et al., 2019), but its uptake remains slow and is also highly asymmetric, both within and between global regions. Shore-power deployment is concentrated in Europe, Asia and North America, but within this there is a high degree of variation. Within Europe, Norway has many facilities, countries such as Italy and Greece have none. In the USA, shore power is prevalent in California, but absent on the East Coast (DNV, 2022a). The UK has one military naval base with shore-power, but commercial projects to date are limited to Southampton and Orkney. This national and international asymmetry is due to the variation in political, economic, policy and cultural barriers to deployment in different locations (Williamsson et al., 2022).

The UK published the world's first national shipping climate change strategy in July 2019, at the start of this thesis (UK Government, 2019b). This strategy was strong on rhetorical ambition and highlighted a number of lead options for reducing the UK's greenhouse gas emissions released by ships, including the greater use of ammonia fuels and shore-power, with these options also highlighted in a follow-up study of potential UK "clean maritime clusters" (E4tech and UMAS, 2020). However, the strategy was vague on specific short- and long-term targets, and was light on specific policies to accelerate uptake of these options, with options such as the use of economic instruments being flagged as an area for "*further investigation*" in the UK Government's 2021 Decarbonising Transport strategy (Department for Transport, 2021b).

UK shore power was therefore a policy highlighted as important within the world's first national shipping climate strategy, but was also a technology that was not being deployed in the UK. This is in contrast to other locations such as cruise ports Bergen and Vancouver, where local air emission policies have driven uptake, or nations such as Norway, Germany, the USA and China, that have had specific national policies to improve take-up. These national policies have varied in both their type, coverage and effectiveness. In California (but not elsewhere in the States) a combination of regulation and state funding has driven rapid growth in shore-power infrastructure in ports and on container vessels (CARB, 2020). In the EU, a regulation to mandate port-installation of shore power facilities in ports failed because of a loophole allowing non-compliance: the regulation included the clause "*unless there is no demand and the costs are disproportionate to the benefits, including environmental benefits*" (European Parliament, 2014), which meant that in practice ports could avoid installing shore power if no state support or other funding is available. By contrast, in Norway, a major shore power funding package (Prevljak, 2022) linked to a wider ship-electrification strategy has seen the most comprehensive network of port and ship shore-power facilities in the world (DNV, 2022a).

The third paper (Chapter 5) therefore takes a case-study approach to assess the causes of slow shore power deployment in the UK, policies which might be most successful in accelerating its deployment, barriers to the adoption and implementation of such policies, and how these barriers might be overcome (research question 3). The results of this research have been disseminated to inform ongoing UK policy debates on shore power and wider UK maritime decarbonisation during 2019-2023. The case-study reflects the general polycentric nature of policy making in shipping (Gritsenko, 2017) – UK deployment is shown to be dependent on national policies, but also on specific local and sub-sectoral conditions, and global landscape issues, such as policies on pricing of marine fuel oils.

The case study involves interviews with 40 industry stakeholders, interrogating whether shore power is a necessary or viable option, and what could be done to accelerate its deployment. This qualitative data was analysed using two frameworks in the socio-technical transitions literature – Technological Innovation Systems (TIS) (Hekkert et al., 2007, Bergek et al., 2010) and the Multiple Streams Approach (MSA) (Kingdon, 1984a). The broad sustainability transitions literature, within the wider transitions literature, is clear that there are multiple interacting complexities in assessing what might drive the greater uptake of particular practices and technologies (Köhler et al., 2019). The most relevant factors – whether these are cultural, economic, political or social – vary greatly between sectors, technologies, practices, locations and time. Initial assessment of the interview data suggested that there are elements of the technical innovation system that were not functioning well for shore power in the UK. Use of the TIS framework was therefore chosen as one mode of analysis, given its utility in studies in other sectors in assessing which functions of a given technical system are strong, or weak and in need of improvement. Interviewees also strongly suggested that specific national policies, and the politics around them, were a key barrier to UK deployment. This led to research design complementing the TIS analysis with the use of the MSA approach, which explicitly assesses uptake of technologies and practices through a political and policy lens, in order to prescribe potential solutions. Using this dual-methodology approach – highlighted at the end of Section 2.3 as a novel methodological contribution to the shipping transitions literature – has led to a specific set of recommendations for accelerating shore power in the UK.

2.7 Overcoming barriers to shore power: local case study

Chapter 5 highlights that there are generic cultural, political and economic barriers to UK shore power deployment. However, interviewees were clear that circumstances can vary greatly at different ports. Some locations will have ample spare grid capacity, while others would require expensive network upgrades. Some ports have strong working relationships with ship operators, others less so. Some ports and ship operators have stronger pressures to address environmental issues than others, whether that is because of closer proximity to affected populations, or due to the attitudes of parent companies. It is therefore unlikely that there is a one-size-fits-all set of solutions at a national level, and even with stronger national policies, shore power deployment still may not be viable in some if not many locations. A further question therefore is how might the national solutions advocated apply in practice to a potential shore power project, and how can locality-specific factors be addressed?

The fourth paper (Chapter 6) therefore assesses in-depth the potential for shore-power at a specific UK port – Aberdeen – identifying whether it is a leading option to address environmental problems in the port, where shore power might best be deployed, what is the most appropriate technical option, and what is the economic case for this option, under a varying set of input assumptions. This is done via a mixed-method quantitative and qualitative study, involving interviews with ship and port operators, analysis of port power and ship movement data, multi-criteria analysis of appropriate technological

options, construction of a detailed techno-economic model to assess the lead option's financial viability, and analysis of how financial viability could be improved (research question 4). Shore power studies in the literature tend to focus on making the environmental and social case for it (Kose and Sekban, 2022, Innes and Monios, 2018), or on assessing how environmental benefits could be increased (Yigit and Acarkan, 2018, Prousalidis et al., 2017). There are gaps in the literature on how practically a project might be made economically viable, on how collaboration between stakeholders can be improved, and on how policy combinations can improve project economics, which this paper addresses.

The shore power research in Chapters 5 and 6 has been directly policy-relevant as the UK Government issued a call-for-evidence in 2022 on policy measures to accelerate shore power deployment (Department for Transport, 2022b). Moreover, in 2023 it will additionally be issuing a consultation on policies to accelerate UK shore power deployment, and refreshing its broader Clean Maritime Plan strategy, including its plans for shore power and wider shipping electrification (Department for Transport, 2022c).

2.8 Summary

This chapter set out a rationale for a mixed-method, multi-scalar approach to analysing shipping's nascent climate change transition. It used the Multi-Level Perspective to set out the current entrenched and stable shipping regime, how the landscape pressure of climate change might challenge this regime, and how this might lead to the nurturing of currently niche innovations. It then described a growing shipping transitions literature, and some core gaps within it that, this thesis aims to address. These research gaps include a lack of clarity on the goal and the speed of required transition, and the timing and types of technology and practice change necessary. They also include a lack of focus on the political aspects of transition, and on jurisdictions where progress is slow. This led to the delineation of four research questions, one each at global, EU, UK and local levels. Analysis of these questions aims to provide clarity on goals (Chapter 3), and the timing for deployment of different and technologies and practices (Chapter 4), and an assessment of how to overcome barriers to deployment (Chapters 5 and 6). Chapters 3-6 are the published or submitted journal papers for each of these 4 research questions.

Chapter 3 The urgent case for stronger climate targets for international shipping

This chapter is based upon the following published article: Bullock, S., Mason, J. and Larkin, A., 2022. The urgent case for stronger climate targets for international shipping. *Climate Policy*, *22*(3), pp.301-309. https://doi.org/10.1080/14693062.2021.1991876

Supplementary material for this chapter is presented at end of the thesis, as part of Chapter 8 Appendices, rather than at the end of this chapter. The above note on supplementary material also applies to Chapters 4, 5 and 6.

3.1 Abstract

International shipping is overwhelmingly reliant on fossil fuels, with annual carbon dioxide emissions equivalent to a country the size of Germany. Actions to reduce its emissions are therefore an important element of global efforts to combat climate change. This article re-assesses the international shipping sector's initial greenhouse gas emissions reduction targets against the Paris Agreement goals. The analysis is based upon the latest data from the Intergovernmental Panel on Climate Change (IPCC) and International Maritime Organisation (IMO) and uses the concept of carbon budgets to evaluate proportionate 1.5°C emissions pathways for the sector. The consequences of the resulting Paris-compliant pathways for shipping's existing mitigation targets and strategy are discussed. The article concludes that significantly stronger short- and longer-term targets need to be set for the sector to be compatible with the Paris Agreement's goals: 34% reductions on 2008 emissions levels by 2030, and zero emissions before 2050, compared with the sector's existing target of a 50% cut in CO_2 by 2050. Crucially, strengthening the target by the IMO's 2023 strategy revision date is imperative. The long asset lifetimes of ships and shipping infrastructure limit the speed of transition such that a delay of even a few years will dictate an untenable rate of decarbonisation and increased risk of pushing the already challenging Paris goals out of reach.

3.2 Key Policy Insights:

There is a gap between targets set out in the IMO's Initial Strategy and what is needed by the shipping sector to be Paris-compliant.

Paris-compliant targets require a 34% reduction in emissions by 2030, with zero emissions before 2050. Existing targets imply no absolute reduction in emissions to 2030, and only a 50% reduction by 2050.

The longer the delay in setting new targets, the steeper subsequent decarbonisation trajectories become. Delay beyond 2023 would necessitate an untenably rapid transition, given long shipping asset lifetimes and global requirements for new land-side infrastructures, increasing the mitigation burden on other sectors.

COP26 in November 2021 is an opportunity for the shipping sector to signal its intent to strengthen its targets, and to implement this in its 2023 strategy revision process, at the latest.

3.3 Introduction

The 2015 Paris Agreement sets out goals to prevent dangerous climate change, aiming to limit global temperatures rise to well below 2°C above pre-industrial levels, while pursuing efforts to keep below 1.5°C (United Nations, 2015). Under the Paris Agreement, nations submit "Nationally Determined Contributions" with the aim that their summed contributions meet the treaty's goals (United Nations, 2015). However, international shipping is excluded, with responsibility for emissions reductions previously being devolved to the International Maritime Organisation (IMO). International shipping has carbon dioxide emissions (CO_2) equivalent to Germany, the seventh highest emitting country globally (Global Carbon Project, 2020). Consequently, assessment of mitigation strategies for international shipping are of great importance for effective global climate governance.

For over a decade, policy makers and academics alike have noted slow progress in developing sufficiently strong policies and plans to mitigate shipping CO_2 (Bows-Larkin, 2015, European Parliament, 2020). It wasn't until 2018, in response to the 2015 Paris Agreement, that the IMO set out an initial draft emissions reduction strategy (IMO, 2018c). The strategy states that action should be based upon "*a pathway of CO_2 emissions reduction* *consistent with the Paris Agreement temperature goals".* However, as we go on to illustrate, the subsequent targets set by the IMO remain inconsistent with such a pathway.

The IMO strategy sets initial targets to reduce emissions by ***at least*** 50% by 2050 from 2008 levels, and an interim 2030 target to reduce emissions intensity by ***at least*** 40% from 2008 levels (IMO, 2018c). With projections of increased shipping demand over the coming decade, the interim intensity target is in practice widely considered to be equivalent to CO_2 emissions staying constant in absolute terms to 2030 (DNV GL, 2018, Faber et al., 2020). Submissions to the IMO in 2017 from member states argued that targets without absolute reductions this decade would be incompatible with the Paris goals (IMO, 2017) and analysis by (Bullock et al., 2020) used the concept of carbon budgets to highlight this point.

Future global temperature change is strongly correlated with total cumulative global emissions of CO_2 (Matthews et al., 2018, Millar et al., 2016). A carbon budget is the quantity of cumulative CO_2 emitted over time for a given probability of staying below a prescribed temperature target. This carbon budget metric has been used in national and global mitigation studies (Anderson et al., 2008, Allen et al., 2009, Anderson and Bows, 2011, Rockström et al., 2017) and incorporated as a core concept in IPCC reports (IPCC, 2018a, IPCC, 2013). Carbon budgets are also discussed at sectoral level as components of national carbon budgets, for example, for buildings (Habert et al., 2020, Steininger et al., 2020) and road transport (Marsden and Anable, 2021). While shipping is also a sector, most of its emissions are released in international waters. Couple this with its international governance arrangements and it becomes evident that there are practical and political challenges with international shipping emissions apportionment to nations (Gilbert and Bows, 2012). Analysing shipping emissions mitigation using a global carbon budgeting method, as is done here, thus allows for a quantitative interpretation of the Paris Agreement in a way that overcomes these challenges.

Using IPCC carbon budgets, (Bullock et al., 2020) concluded that the cumulative international shipping emissions of the existing IMO targets were more than double those of a Paris-compatible carbon budget, and that for a 50% chance of meeting the Paris 1.5°C goal, the shipping sector's fair share of mitigation effort requires a pathway equivalent to a linear reduction to zero CO_2 emissions from international shipping by 2040; similarly, analysis by (Smith et al., 2015) concluded that a linear reduction pathway to a 2042 zero emissions date is compatible with 1.5°C

Such mitigation pathways are considerably more challenging than those laid out in the IMO's initial strategy, however, the complexities of determining proportionate actions for the international shipping sector in meeting the Paris goals is under-researched in the academic literature. This and recently updated IMO emissions data and methodologies necessitate a reassessment of international shipping's contribution to the Paris 1.5°C goal, the focus of this paper.

In particular, the IMO's 4th Greenhouse Gas (GHG) Study in 2020 set out a new methodology for more accurately reflecting the split between international and domestic shipping emissions, the latter being counted within individual nations' emissions inventories. The new approach uses a "voyage-based" calculation of GHG emissions, and is more accurately aligned with IPCC inventory guidelines (Faber et al., 2020). This change reduces the emissions contribution of international shipping relative to domestic shipping and is reflected in a 16% lower value for GHG emissions from international shipping in 2008, compared with the IMO's 3rd GHG Study.

Here we revisit the analysis in (Bullock et al., 2020) and (Smith et al., 2015) and use the carbon budget methodology in light of both the newly published IMO 4th GHG Study and the most recent available emissions data, to articulate what a Paris-consistent pathway for shipping is, so as to inform relevant debate at COP26 and at the upcoming IMO Marine Environment Protection Committee (MEPC) Meeting 77, and to promote urgent subsequent revision of the IMO strategy in 2023. The analysis presented provides a robust evaluation of the gap between existing ambition and one that is Paris-compliant, to assist policy makers in setting new and Paris-compliant targets for shipping.

3.4 Methods

The analysis sets international shipping GHG budgets and pathways in three steps. First, a global carbon budget is established based upon Chapter 2 of the IPCC 1.5 report (Rogelj et al., 2018), defining the goal as a 50% probability of keeping warming below 1.5°C. All global budgets are set against probability ranges for a given temperature rise. The wording of the Paris Agreement is that nations should "pursue efforts" to keep temperature rise below

1.5°C. Assigning probabilities to wording such as this cannot be exact, but here we assume that a 50:50 chance is the greatest risk compatible with a “pursue efforts” aim. It should be noted though, that Article 4’s requirement is that actions should represent “highest possible ambition”, and that it would be prudent to improve those odds, given the scale of impacts people are already experiencing at well below 1.5°C. In the results section, for illustrative purposes, we present budgets for 33%, 50% and 66% probabilities of exceeding 1.5°C.

Second, an international shipping share of the global carbon budget is established, based on a grandfathered allocation, using international shipping’s share of global CO_2 emissions in a chosen baseline year. This approach is used in Traut et al. (Traut et al., 2018) and by the International Chamber of Shipping (International Chamber of Shipping, 2018), and follows the “fair and proportionate” wording of the IMO (IMO, 2011). A summary of other options by (IMO, 2017) suggested possible apportionment proportionate to the emissions reduction effort of comparable sectors, or to the effort of all or subsets of countries. However, these approaches are not included here as they explicitly lead to higher temperature outcomes (in the range 1.75 to 3.1°C) (IMO, 2017). There are also arguments that shipping should receive a larger budget than proportionate to shipping’s existing share, due its vital role in global trade (Morimoto, 2018), or that shipping will need to make deeper cuts because of the greater limitations to cutting emissions to zero in other sectors such as agriculture (Bows-Larkin, 2015, Gilbert et al., 2014). The summary paper to the IMO (IMO, 2017) concluded that there remains insufficient data on limitations to sectoral emissions reductions to determine different levels of ambition. Other approaches are possible, for example, a recent study advocated allocating international shipping emissions to nations (Selin et al., 2021), however, others highlight the complex political and technical difficulties in doing so (Gilbert and Bows, 2012); in practice, international shipping emissions remain under the remit of the IMO.

Assessments of contributions to global emissions reduction efforts often focus on the issue of equity or “differentiated responsibility”: where developed (“Annex 1”) nations have greater current and historical per capita emissions, and therefore a greater responsibility and requirement to act (Du Pont et al., 2017). For an international sector such as aviation, such arguments suggest greater-than-global-average contributions to mitigation, given flying is highly inequitable between nations. International shipping, on the other hand, underpins global trade, with equity issues far less clear-cut. Nevertheless, global trade is still significantly driven by wealthier countries, so assuming that the sector's share of the remaining budget is proportional to shipping's share in any given baseline year is arguably a generous and inequitable allocation. We also note that negative emissions technologies are likely to be necessary for sectors where CO_2 emissions cannot be reduced to zero, but the evidence indicates that shipping is a sector which can fully decarbonise (Lloyd's Register, 2019, Climate Change Committee, 2020).

The final major issue in allocating an international shipping budget is the choice of baseline year. This parallels discussion in the literature around issues of historical responsibility and fairness (Du Pont et al., 2017). For selecting a baseline year from which to calculate shipping's carbon budget, there are two principal options. The first is a baseline year of 2020, reflecting the most recent date from which to estimate an up-to-date global carbon budget; the second is to use 2008, which is the baseline year used in the IMO's existing strategy. In 2008, international shipping emissions contributed a higher percentage of the global total emissions (2.4%) than in all subsequent years, including 2020, when its global share is estimated to be 2.0%. This reduction occurred because, in the last decade, after cuts in 2009 and 2010, international shipping's emissions have been broadly constant, whereas global emissions have risen. Therefore, the IMO's use of a 2008 baseline allocates a larger share of the remaining global carbon budget to international shipping, compared with using a 2020 baseline. This paper provides analysis for both a 2008 baseline, as it is the year the IMO uses, as well as an analysis for 2020. Using 2008 lowers the required ambition from the international shipping sector, while using 2020 illustrates what a proportional response for the sector would be if Paris-compliant mitigation efforts were shared from the present day.

The analysis then sets out pathways for emissions compatible with these international shipping carbon budgets. To explore the implications for the sector in terms of the timing of policy implementation, the pathway analysis uses a linear function and a logistic function. The linear function presents the simplest mathematical outcome that is bound by the carbon budget, whereas the logistics function presents trajectories articulating mid-term rates of mitigation effort when varying the speed of short-term action. It is assumed that emissions will rebound from the 2020 COVID-19 pandemic during 2021 and 2022. See supplementary material for further methodological detail and sensitivity analysis.

Overall, the international shipping carbon budget is described by the formula:

$$ISCB_x^y = \frac{ISE_x}{GE_x} * GCB^y$$

Where $ISCB_x^y$ is the international shipping carbon budget for a y per cent chance of keeping temperature rise below 1.5°C, using a baseline year of x, ISE_x and GE_x are international shipping CO_2 emissions and global CO_2 emissions in year x, and GCB^y is the global carbon budget remaining from the start of 2021 for a y per cent chance of keeping temperature rise below 1.5°C.

3.5 Results

Chapter 2 of the IPCC 1.5 report (Rogelj et al., 2018) sets out a global carbon budget of 580 $GtCO_2$ from 2018 for a 50% chance of keeping warming below 1.5°C. 100 $GtCO_2$ are subtracted to account for earth-system feedbacks (Rogelj et al., 2019). 107 $GtCO_2$ are removed to account for emissions from 2018-2020, assuming a 7% COVID-related reduction in 2020 CO_2 emissions compared with 2019 (Le Quéré et al., 2020). This leaves a remaining global carbon budget of 373 $GtCO_2$ from the start of 2021.

Assuming that international shipping's carbon budget is proportionate to its share of global emissions in a given year, the sector's carbon budgets for different probabilities of achieving the Paris 1.5°C goal are set out in Table 3-1.

Table 3-1 International shipping carbon budgets for different probabilities of limiting temperature increase to 1.5°C, and different assumptions around historical responsibility

Probability of limiting temperature increase to 1.5°C	International shipping carbon budget (2008 baseline) $GtCO_2$	International shipping carbon budget (2020 baseline) $GtCO_2$
33%	17.0	12.5
50%	10.7	7.4
66%	6.8	4.2

In the following analysis, we take the 2008 and 2020 baselines for 50% probability of limiting warming to 1.5°C as our central pathways.

Cumulative international shipping emissions under the current IMO targets are twice as high as a Paris-compliant carbon budget (Table 3-2, and see appendix 8.1). Keeping within a Paris-compliant carbon budget will therefore require the IMO to move beyond the “at least 50% reduction by 2050” in its initial strategy, to significantly and explicitly strengthen its targets to be over twice as ambitious.

Table 3-2 Paris Agreement 1.5°C carbon budgets compared with existing IMO targets

	Cumulative emissions from 2021 onwards ($GtCO_2$)
50% 1.5°C carbon budget (2020 baseline)	7.4
50% 1.5°C carbon budget (2008 IMO baseline)	10.7
Emissions implied by current IMO targets to 2050, then assumes linear reduction to zero by 2060	20.2
Emissions implied by current IMO targets to 2050, then assumes linear reduction to zero by 2070	22.2

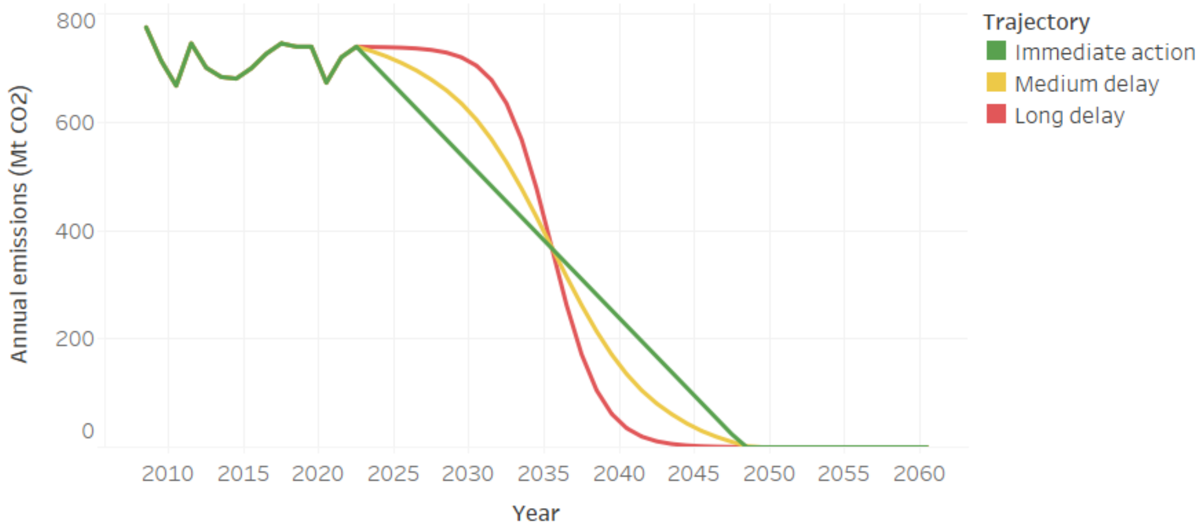

Figure 3-1 CO_2 pathways to zero emissions, using 2008 IMO baseline for calculating carbon budgets

Figure 3-1 shows pathways compatible with the larger 2008 baseline carbon budget. A linear trajectory is shown alongside two logistic function trajectories for two assumed growth rate factors: one representing a medium delay in action and the other representing a longer delay in action. The figure shows that any delay in action requires a steeper subsequent decarbonisation pathway. Table 3-3 shows the maximum annual carbon reduction rates for each pathway. For the scenario, using a 2008 baseline to calculate the sector's carbon budget if emissions reductions start in 2023 after a COVID bounce-back and then follow a linear downward trajectory, there is a 25-year decarbonisation pathway to zero emissions, with an annual reduction rate of 4% on 2023 levels. However, delaying emissions reductions increases the maximum annual reduction rate to as high as 15%. Further detail on annual reduction rates is set out in supplementary material.

It is important to note that using a 2008 baseline allows more leeway for the shipping sector. Using an arguably more appropriate 2020 baseline makes decarbonisation trajectories steeper (Figure 3-2). The implications of this are set out in Table *3-3*. Using a 2020 baseline to calculate the sector's carbon budgets, linear emissions reductions starting in 2023 imply a 16-year transition, with zero emissions by 2039 and an annual reduction rate of 6%. Delay in action requires a steeper transition and the long delay trajectory increases the maximum annual reduction rate to 22%. The graphs are a stark illustration of the degree of urgency. For the 2020 baseline method, even the pathway with the longest transition is just 16 years long – arguably infeasible in any practical sense, particularly given the long asset lifetimes of ships. Because of delays in reducing emissions in the last decade, the only feasible carbon budgets for shipping are the ones which choose generous baselines for the sector.

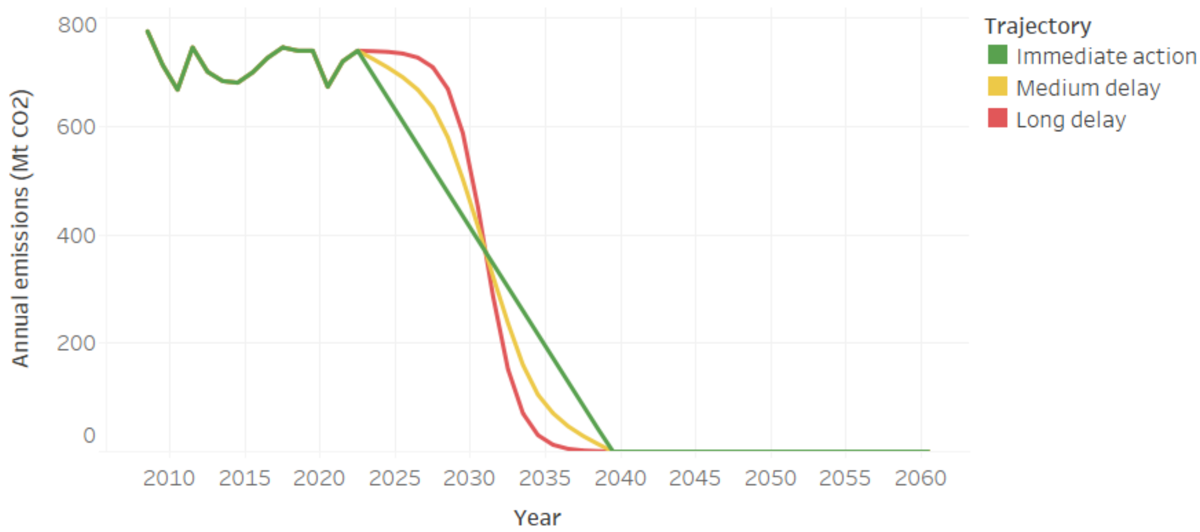

Figure 3-2 CO_2 pathways to zero emissions, using 2020 baseline for calculating carbon budgets

Table 3-3 Transition rates and dates for different carbon budget scenarios

	Carbon budget based on IMO's 2008 baseline year			Carbon budget based on a 2020 baseline		
	Major transition period	Years for transition	Max annual reduction (%)	Major transition period	Years for transition	Max annual reduction (%)
Cuts from 2023	2023-2047	25	4	2023-2038	16	6
Medium delay	2025-2045	21	7	2025-2037	13	12
Longer delay	2030-2040	11	15	2027-2034	8	22

As shown in Figure 3-1 and Figure 3-2, and widely discussed in the literature (Peters et al., 2015, Anderson et al., 2008), cumulative emissions on a linear downward trajectory are dominated by those released in the early years. It follows that if there are delays to implementing appropriate mitigation measures in the near-term, keeping within a given carbon budget requires far deeper reductions in later years. The outcome for shipping, at best, is that the sector would have around a decade to completely decarbonise if the IMO does not strengthen its current 2030 target, assuming ongoing trade growth. The IMO's targets are contrasted with the 2008 baseline 1.5°C pathways in Figure 3-3, which show the deep disconnect between the IMO's current targets and Paris-compatible mitigation efforts.

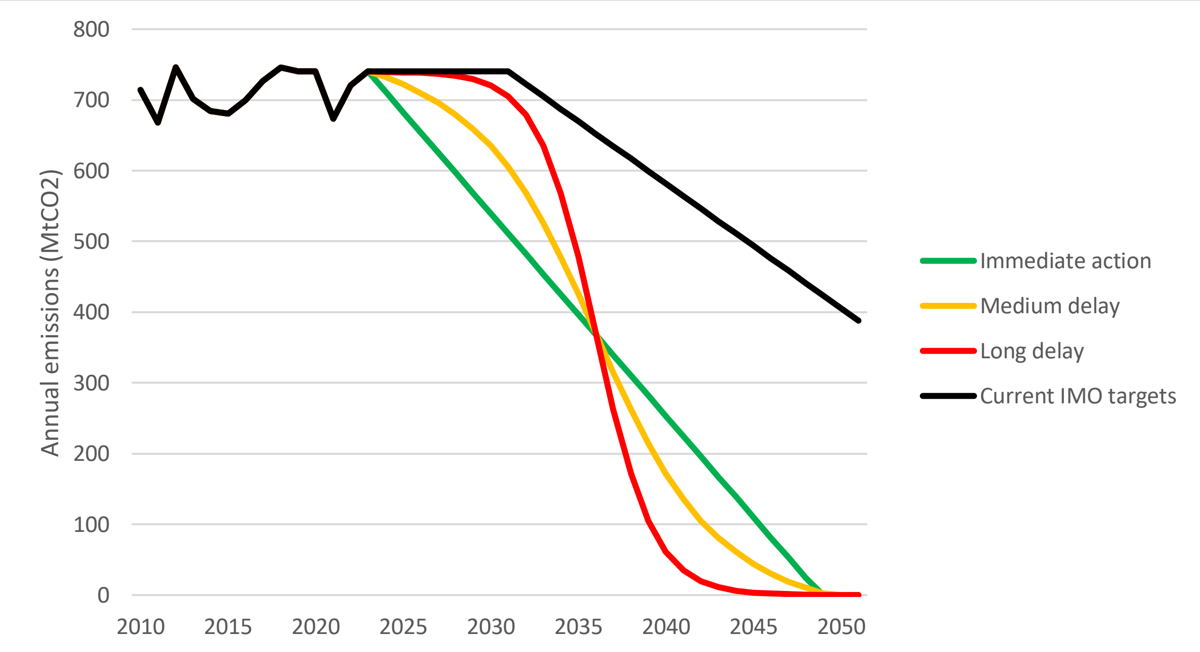

Figure 3-3 The IMO's targets and Paris-compatible 1.5°C pathways (2008 baseline)

3.6 Discussion

Figure 3-1 and Figure 3-2 show that the longer the delay in cutting emissions, the greater the required rate of transition. To remain within Paris-compatible carbon budgets, the length of any possible delay depends upon the feasibility of the subsequent increased rate of decarbonisation.

Shipping assets have average lifespans of over 25 years (Bullock et al., 2020). In addition, deployment of alternative fuels at scale will require trillions of dollars of investment in land-side infrastructure (Krantz et al., 2020). Consequently, attempting to decarbonise the entire sector across all nations in anything under 25 years would be exceptionally difficult and highly imprudent to be relied upon. We assume here that 90% of the full transition would require a minimum of 25 years.

With the larger 2008 baseline budget, the implied emissions in 2030, under the IMO's current 2030 carbon intensity target, would then require a transition to a completely decarbonised global sector in the following 11 years. This is not feasible, and so requires an urgent revision to the IMO's 2030 target.

All pathways using the 2020 baseline and the “long delay” pathway using the 2008 baseline require far fewer than 25 years. Even the “medium delay” pathway using the 2008 baseline requires 21 years, between 2025 and 2045. It would be prudent, therefore, to assume that only the “immediate action” pathway with a 2008 baseline is both feasible and compatible with the Paris targets. This involves emissions falling from 2023, the same year as the IMO's planned revision of its initial strategy. This pathway, in stark contrast to the IMO's initial strategy, has a 34% cut on 2008 levels by 2030, and zero emissions by 2048. Such targets are slightly less stringent than the earlier assessments (Bullock et al., 2020, Smith et al., 2015), as a consequence of the use of the IMO's baseline and the methodological adjustment used in the 4th GHG Study.

As major international strategies tend not to deliver immediate results, this implies that the IMO should be introducing stronger measures and setting the groundwork for stronger targets well before 2023. The ideal opportunity would be during the UNFCCC COP26 in November 2021, when countries are bringing forward revised Nationally Determined Contributions. This also coincides with the IMO's MEPC77 meeting, which provides a more focused forum for discussion. A delay in implementing new targets would mean that either shipping demand would need to fall, or that shipping could no longer play it fair and proportionate part in meeting Paris goals.

A final issue is whether even 25-year transitions are achievable. The literature is clear that multiple technical and operational options exist for decarbonising shipping, such as energy efficiency, shore power, wind-propulsion, slower speeds and low-carbon fuels (Bouman et al., 2017, Gilbert et al., 2014, Balcombe et al., 2019, Lloyd's Register, 2019). An analysis of the committed emissions from ships covered by the new EU Monitoring, Reporting and Verification (EUMRV) regulation illustrated how shipping could stay within 1.5°C carbon budgets. It required a dual-track approach. First, targeting the existing fleet in the 2020s with policies focused on speed, energy efficiency and other technical measures. Second, policies to incentivise the widespread deployment of zero-carbon fuels in the 2030s for both new and existing ships (Bullock et al., 2020). This implies that with a similar roll-out of policy and measures in other jurisdictions, international shipping can still make such a transition. It is fortunate also that slow-steaming is an operational change that is not only available now, but one that can deliver immediate and deep emissions reductions (Bouman et al., 2017). A better understanding of the maximum possible deployment rates for all shipping mitigation options is a critical area for future research.

3.7 Conclusion

If the shipping sector is to play its fair part in meeting the Paris Agreement goals, and avoid other sectors needing to increase their efforts, then it is imperative and urgent that the IMO strengthens its existing targets. Our results suggest that the IMO should grasp the imminent opportunity to bring a revised set of targets to COP26 and MEPC77, including a 34% cut on 2008 levels by 2030 and a zero emissions target before 2050, and to formalise these in the IMO's 2023 strategy revision. If it does not set such targets quickly, then the required rate of transition will rapidly become untenable, resulting in an increased risk of pushing the already challenging Paris goals out of reach. There is a considerable body of literature that illustrates a wide range of mitigation options that are available to the sector, unlike, for example, to aviation. Nevertheless, setting and meeting such targets requires the IMO and other stakeholders to take immediate action. Implementation requires working across their full range of mitigation levers, from those that influence energy demand and efficiency to others that accelerate the shipping sector's low-carbon technology transition. It is time for the IMO to grasp the nettle of what '***at least'*** means in its target setting and face head-on the stark gap between what it is currently proposing and what is needed to be Paris-compliant.

Chapter 4 Shipping and the Paris climate agreement: a focus on committed emissions

This chapter is based upon the following published article:

Bullock, S., Mason, J., Broderick, J. and Larkin, A., 2020. Shipping and the Paris climate agreement: a focus on committed emissions. *BMC Energy*, *2*(1), pp.1-16.
https://doi.org/10.1186/s42500-020-00015-2

4.1 Abstract

The concept of "committed emissions" allows us to understand what proportion of the Paris-constrained and rapidly diminishing global carbon dioxide (CO_2) budget is potentially taken up by existing infrastructure. Here, this concept is applied to international shipping, where long-lived assets increase the likelihood for high levels of committed emissions. To date, committed emissions studies have focussed predominantly on the power sector, or on global analyses in which shipping is a small element, with assumptions of asset lifetimes extrapolated from other transport modes. This study analyses new CO_2, ship age and scrappage datasets covering the 11,000 ships included in the European Union's new emissions monitoring scheme (EU MRV), to deliver original insights on the speed at which new and existing shipping infrastructure must be decarbonised. These results, using ship-specific assumptions on asset lifetimes, show higher committed emissions for shipping than previous estimates based on asset lifetimes similar to the road transport sector. The estimated baseline committed emissions value is equivalent to 85-212% of the carbon budget for 1.5°C that is available for these EU MRV ships, with the central case exceeding the available carbon budget. The sector does, however, have significant potential to reduce this committed emissions figure without premature scrappage through a combination of slow speeds, operational and technical efficiency measures, and the timely retrofitting of ships to use zero-carbon fuels. Here, it is shown that if mitigation measures are applied comprehensively through strong and rapid policy implementation in the 2020s, and if zero-carbon ships are deployed rapidly from 2030, it is still possible for the ships in the EU MRV

system to stay within 1.5°C carbon budgets. Alongside this, as there are wide variations between and within ship types, this new analysis sheds light on opportunities for decision-makers to tailor policy interventions to deliver more effective CO_2 mitigation. Delays to appropriately stringent policy implementation would mean additional measures, such as premature scrappage or curbing the growth in shipping tonne-km, become necessary to meet the Paris climate goals.

4.2 Introduction

4.2.1 Climate change and committed emissions

The UNFCCC Paris Agreement sets out globally agreed goals for action on climate change, aiming to keep the global surface temperature rise well below 2°C above pre-industrial levels, while pursuing efforts to keep below 1.5°C (United Nations, 2015).

The global climate responds approximately linearly to cumulative carbon dioxide (CO_2) emissions, and over the timeframes of relevance to the Paris Agreement goals, the rise in global mean surface temperature is strongly dependent on cumulative emissions of CO_2 (Matthews et al., 2018). As such, cumulative CO_2 emissions to 2100 are a better predictor of climate stabilisation than rates of change in emissions, concentration targets and emission levels in a given year (Millar et al., 2016). A carbon budget is the quantity of cumulative CO_2 that can be emitted over time to deliver a prescribed probability of staying below a given temperature target. This carbon budget metric has been used in national and global mitigation studies (Anderson et al., 2008, Allen et al., 2009, Anderson and Bows, 2011, Rockström et al., 2017) and incorporated as a core concept in IPCC reports (IPCC, 2018a, IPCC, 2013). Measures to reduce other greenhouse gas emissions such as methane are also required to achieve the Paris Agreement goals. Different gases have different lifetimes and warming effects so the climate's response to non-CO_2 emissions are modelled independently of cumulative CO_2 (IPCC, 2018a).

Long-lived fossil-fuel infrastructure assets are prone to "carbon lock-in" (Unruh, 2000), committing sectors and economies to CO_2 emissions years and often decades into the future (Seto et al., 2016). The concept of committed emissions from existing infrastructure has been used to examine what proportion of carbon budgets might be taken-up by the future operation of existing high-carbon assets (Davis et al., 2010, Tong et al., 2019). At a global level, Tong et al. (Tong et al., 2019)'s study of committed emissions concludes that "*little or no additional CO_2-emitting infrastructure can be commissioned*" and also that early retirement of existing high-carbon infrastructure might be required to meet the limits laid out in the Paris Agreement.

4.2.2 Committed emissions and shipping

The shipping sector is vital to the world's economy – it transports over 80% of the world's trade by volume (UNCTAD, 2019). However, it is also a major contributor of greenhouse gas emissions, with international shipping emitting around 800 $MtCO_2$ a year (Olmer et al., 2017, IMO, 2014a). If the sector were a country, it would be the 6th highest emitter in the world, ranked between Germany and Japan. As such, the shipping sector needs to make substantial cuts in emissions to play its part in meeting the Paris Climate Agreement goals.

In addition to measures implemented in 2013 to improve efficiency through the design of new ships (IMO, 2019b), the international maritime sector has set climate change targets, of an at least 50% reduction in greenhouse gas emissions by 2050 versus 2008 levels (IMO, 2018d). Ships have a long-lifespan, the average age of a ship scrapped in 2018 was 28 years (Clarksons, 2019c), and so these targets may be harder to achieve than in sectors with a more rapid turn-over of assets. There is also the potential for committed emissions from existing ships to take up a high percentage of any carbon budget ascribed to the shipping sector. Analysis of committed emissions from existing shipping assets can therefore inform the rate, extent and types of response required from the shipping sector, for both existing and future ships, towards meeting the Paris climate goals.

To date, studies of committed emissions have been in-depth analysis of the power sector (Edenhofer et al., 2018, Pfeiffer et al., 2018, Cui et al., 2019) or high-level global analyses where shipping is one of many sectors considered (Davis et al., 2010, Tong et al., 2019, Smith et al., 2019). To estimate shipping emissions, global-coverage papers have taken assumptions from elsewhere in transportation. Smith et al. (Smith et al., 2019) assume asset lifetimes for ships to be similar to those for aviation, and Tong et al. (Tong et al., 2019) employ the assumptions used in Davis et al. (Davis et al., 2010), that shipping and aviation assets would have similar lifetimes as those in the road transport sector at 17-28 years.

However, there are three reasons, explored in detail in this paper, why a more in-depth analysis for the shipping sector would significantly augment these global analyses:

i. Assuming lifetimes similar to the road transport sector under-estimates committed emissions in shipping, as typically ships have an average scrappage age of 28 years, higher than road transport averages.
ii. The size distribution, age distribution and average age at scrappage of existing assets in the shipping sector varies considerably, both between different ship types and by size within type. A more granular analysis better accounts for such differences than use of sector-wide averages. An example of a within-type difference is set out in Figure 4-1 using data for container vessels in the EU MRV system, with many newer ships being over four times larger than those 20 years or older.
iii. Unlike for example in aviation, many of the proposed solutions for lowering emissions in the shipping sector can be applied to the existing fleet (Bows-Larkin, 2015), not just to new assets. A committed emissions figure in the shipping sector should take into the account the potential for existing assets to produce less CO_2 in future.

This then points to a need to evaluate the committed emissions of the shipping sector in greater detail, to reflect the specific nature of the sector. This paper is the first to analyse committed emissions at the level of individual ships, using new datasets published for the first time in mid-2019. This paper presents an evaluation of a large subset of global shipping's committed emissions under various assumptions, and sets out implications for efforts to mitigate shipping CO_2 in line with global climate change goals.

The methods section presents the datasets used, issues concerning data quality, and details for how committed emissions is calculated, under different assumptions. The results and discussion sections identify the committed emissions across ship types for existing ships and for new ships, and compare the range of total committed emissions with a range of different carbon budgets for the shipping sector. They assess which measures might be more important in delivering rapid mitigation in each ship type, given the different age and committed emissions profiles of these sub-fleets, and whether such mitigation measures could bring emissions within carbon budgets. The conclusions section sets out implications for the challenges facing shipping in tackling climate change. Further detail on methodology can be found in supplementary information and the accompanying spreadsheet.

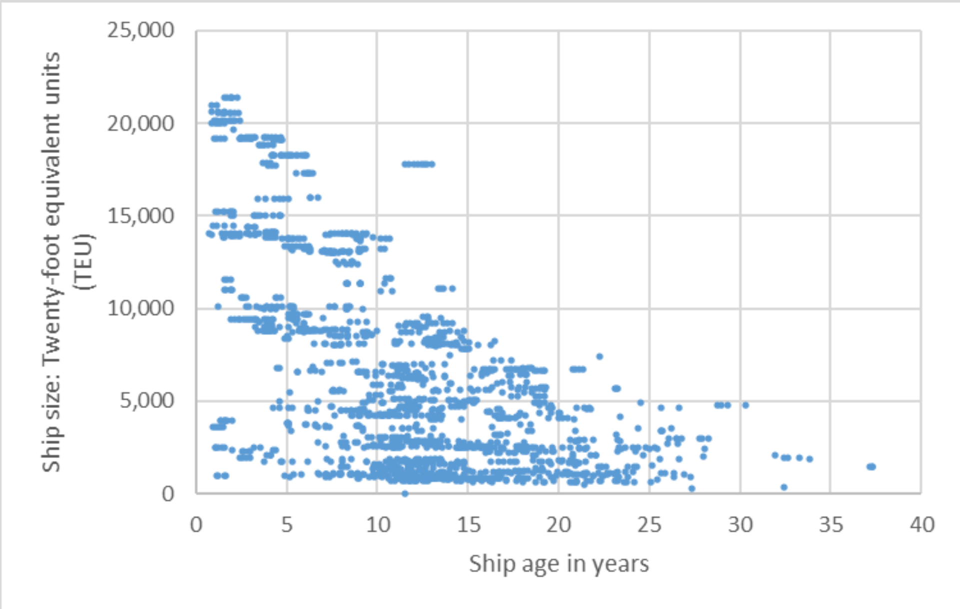

Figure 4-1 Comparison of ship size versus age for container ships in the EU MRV.

Ship size given in TEUs, "twenty-foot equivalent units", a standard shipping container. Source: authors' analysis of 2019 fleet data from Clarksons (Clarksons, 2019b).

4.3 Methods

This section is split into five parts. First, a description of the datasets related to shipping CO_2 emissions; second, a methodology for calculating the baseline committed emissions figure for existing ships in a segment of the global fleet; third, methods for assessing how this baseline value might change under different assumptions; fourth, a comparison of this range of committed emissions with a range of possible carbon budgets for this shipping segment, and; fifth, an assessment of factors affecting potential emissions from ships which will be built in the next decade. This section is abridged; further details can be found in supplementary information.

4.3.1 Data

The shipping sector's global greenhouse gas emissions have been analysed at an aggregate level by the IMO (IMO, 2014a), and in other studies (Olmer et al., 2017). However, until recently data has not been freely available to assess ship-level greenhouse gas emissions.

Data released in July 2019 from the European Union's new Monitoring, Reporting and Verification (EU MRV) system for CO_2 emissions allows this granularity (EU Parliament, 2015). The International Maritime Organisation's Data Collection System (IMO DCS) commenced in 2019 with global coverage but individual ship data will be kept confidential (IMO, 2019a).

The EU MRV system's initial reporting period was for 2018, with publicly available ship-level data for fuel consumption, energy efficiency and CO_2 emissions for approximately 11,000 ships. Data is updated regularly; this paper is based on data published during September 2019. To date, one published article has assessed this new EU database – analysing energy efficiency data for a subset of the bulk carrier fleet (Panagakos et al., 2019). We present the first analysis of the CO_2 data across the whole of the EU MRV dataset, and combine this data with other datasets to provide a new analysis of how these CO_2 data vary by ship age across all ship types. This first evaluation of data on CO_2 emissions versus age allows the most detailed estimation to date on committed emissions from a large sub-section of global shipping.

Two other data sets are also used; Clarksons World Fleet Register (Clarksons, 2019b) datasets by ship type for IMO number, size (e.g. deadweight tonnage (DWT)) and age, and Clarksons World Shipyard Monitor (Clarksons, 2019c) for average scrapping age of each type and size of ship worldwide. The individual ship data from Clarksons is provided on a commercial basis and cannot be disclosed, however aggregate results are presented in this paper. Combined, these datasets give a value for expected years of remaining service-life for each of the 11,000 ships.

The EU MRV regulation covers all ships over 5,000 gross tonnes, with some limited exemptions (e.g. warships), with coverage of over 90% of CO_2 emissions from ships calling at EU ports, in 15 ship categories (EU Parliament, 2015). It requires reporting of the annual CO_2 emissions from all ships' journeys that include an EU member state port as destination or departure point, and also emissions at berth in EU ports. It includes emissions from journeys involving non-EU ports: so long as at least one of the destination or departure ports is in the EU. The coverage is therefore not of ships registered in the EU, but ships' journeys involving an EU port. The ship-owner must also report on fuel types, emissions factors, ship energy efficiency, transport work, total distance travelled and time at sea. The EU's reporting system uses recorded fuel consumption as the main basis for its calculations. Data quality is good, with minor issues discussed in supplementary information.

4.3.2 Baseline committed emissions

A baseline committed emissions value for each ship is calculated, by multiplying each ship's remaining service life by its current annual emissions. A ship's remaining service life is calculated by subtracting its likely scrappage age from its current age. For each ship its scrappage age is estimated by taking the values of average scrappage age for ships of its type and size, for each year in the last ten years' publications of Clarkson's World Shipyard Monitor, and taking an average value across these ten years. It is assumed that in future years until scrappage, a ship's annual emissions are the same as in 2018. See Supplementary information for details and sensitivity analyses on these assumptions.

The total baseline emissions from each ship class, $E(i)^{class}_{baseline}$, is calculated by summing across the total number of ships in each class, N_T, where i represents each individual ship. The total baseline emissions from the full fleet, $E^{\,fleet}_{\,baseline}$, is then calculated by summing across the total number of classes, N_{class}.

$$E(i)^{ship}_{baseline} = [t(i)_{ship\ age} - t_{scrappage}] * E(i)^{ship}_{annual} \tag{1}$$

$$E(i)^{class}_{baseline} = \sum_{i=1}^{N_T} E(i)^{ship}_{baseline} \tag{2}$$

$$E(i)^{fleet}_{baseline} = \sum_{class=1}^{N_{class}} E(i)^{class}_{baseline} \tag{3}$$

4.3.3 Mitigation measures that may alter baseline committed emissions

There are a wide range of options for cutting CO_2 emissions from shipping (Gilbert et al., 2014). A literature review by Bouman et al. (Bouman et al., 2017) summarises some of these options, in five categories, such as new fuels and retrofitting technical improvements, see Table 4-1.

This list is not exhaustive, for example ammonia, hydrogen and batteries could be added to the alternative fuels category. Implementing any or all of these various options would lower the total value for committed emissions. Similarly, external changes in demand or the organisation of production-consumption networks that use the shipping sector, either due to ongoing economic development or deliberate policy intervention, also have substantial potential to reduce emissions (Mander et al., 2012).

Table 4-1 Measures to cut shipping CO_2 emissions

Category	Measure
Hull Design	Vessel size, hull shape, light-weight materials, air lubrication, resistance-reduction devices, ballast water reduction, hull coating
Power and propulsion system	Hybrid power, power system machinery, propulsion efficiency devices, waste heat recovery, on-board power demand
Alternative fuels	Biofuels, Liquefied Natural Gas (LNG)
Alternative energy sources	Wind-power, fuel cells, cold ironing, solar power
Operation	Speed optimisation, capacity utilization, voyage optimisation, other operational measures

Source: Based on Bouman et al. (2017).

It is also uncertain to what extent the identified improvements would be applied in future, both at total fleet level, or in ship types, and in different regions, given multiple uncertainties around cost, demand, regulation, and technological deployment rates. To explore how these interventions might alter the committed emissions, a model is constructed to allow user inputs to vary the start times, diffusion rate and deployment levels for different classes of improvement for all ships in each ship class. Four inputs are applied sequentially to the baseline:

- Lower speeds: reducing overall energy required;
- Technical and operational efficiency measures: reducing the fuel required for ships' propulsion, use of shore-power for ships in port ("cold-ironing"), retrofitting of wind-propulsion devices, etc;
- Blending-in quantities of zero-carbon fuels: reducing the carbon intensity of fuel used;
- Zero-carbon retrofits: full-conversion to zero-carbon fuels.

There are challenges associated with combining the various values for CO_2 reduction potential published in the literature for use in a simple model. These include: large ranges of uncertainty; the extent to which individual measures are additive; varying impact between ships of different type, age and size; and uncertain impacts of economic and political factors on the extent of technological uptake. In this study, given the large uncertainties in future deployment of the various options, “low”, “mid” and “high” ranges for each type of measure are used, as set out in Table 4-2. The details of the assumptions and literature sources used as the basis for Table 4-2 are set out in supplementary information 8.2.3.

Table 4-2 Model input assumptions for calculating reductions to baseline committed emissions

Measure	Input value	Low	Mid	High
Speed	Slow speed improvement factor	0.85	0.75	0.65
	Year slow speed improvement starts	2030	2024	2022
	Years until total speed improvement achieved	10	5	3
Technical and operational	Non-speed: improvement factor	0.95	0.80	0.65
	Non-speed: years until improvements achieved	15	10	8
Blending	Blending: year starts	2030	2025	2022
	Additional annual % of ships using blended fuel	1	2	4
	Additional annual rise in % blended fuel = zero C	1	2	4
Zero-carbon fuel	Year zero-carbon fuel available for retrofit	2035	2030	2025
	Years till all ships retrofitted to use zero C fuel	15	10	10

This paper focusses on reducing on-ship CO_2 emissions, however meeting the Paris climate goals requires consideration of full life-cycle emissions, of CO_2 and other greenhouse gases. Whilst LNG is conspicuous for its high life-cycle methane emissions (Lindstad and Rialland, 2020, Pavlenko et al., 2020), the potential benefits of other alternative fuels are also highly dependent on the balance of CO_2 upstream and non-CO2 emissions in production, distribution and use (Gilbert et al., 2018, Kobayashi et al., 2019). This paper assumes that LNG is not a sufficiently low carbon solution for shipping. We accept that in practice it will be difficult to achieve genuinely zero carbon fuels, and use the term “zero-carbon fuel” to mean fuels which have close to net-zero whole life-cycle greenhouse gas emissions, for example liquid hydrogen produced by hydrolysis of water using wind power.

Whilst our analysis has focussed on technological and operational measures to cut emissions; a further set of policy options would be measures to reduce the volume of goods and the distances they are transported. It may be the case that in future these options are raised up the political agenda, as decarbonisation imperatives grow with increasing climate impacts, or if technological and operational measures are slow in delivery. The potential impact of stronger decarbonisation policy on shipped trade is discussed in depth by Walsh et al. 2019 (Walsh et al., 2019). For this analysis, our starting assumption is that global climate mitigation effects on volumes of shipped trade would be to lower trade growth, rather than lead to absolute reductions, following the Low Energy Demand scenario included in IPCC SR1.5 (Grubler et al., 2018). Further detail on measures to reduce committed emissions is set out in supplementary section 8.2.3.

4.3.4 Shipping carbon budgets

The concept of carbon budgets is prominent in IPCC reports (IPCC, 2013, IPCC, 2018a), given the near linear relationship between cumulative carbon dioxide emissions and temperature rise. For ships covered by the EU MRV system, we calculate carbon budgets for meeting the Paris Agreement's goal to "pursue efforts" to keep warming to below 1.5°C in two stages. First, we set out a range of global carbon budgets to indicate equivalence with this goal, then we ascribe a proportion of that global carbon budget to ships in the EU MRV system.

This paper takes as its starting point the carbon budgets set out in IPCC SR 1.5 (Rogelj et al., 2018). Work since then is summarised in Rogelj et al. (Rogelj et al., 2019) who propose a framework for consolidating the various carbon budget methodologies and uncertainties, and sets out the remaining (2019 onwards) global carbon budget for 33%, 50% and 66% probabilities of staying under 1.5°C warming, at 700, 440 and 280 $GtCO_2$ respectively. Rogelj et al. also ascribe a variation to these budgets of $\pm$250 $GtCO_2$ to account for uncertainty in the success of policies to mitigate non-CO_2 emissions such as methane. The complex outlook for non-CO_2 mitigation is summarised in depth by Roe et al. Roe et al. (2019).

In applying a budgeting approach to shipping specifically, we acknowledge that there is no established or agreed mechanism for ascribing a share of global carbon budgets to this sector. Typically, the literature on apportionment methodologies in shipping has focused on the issue of dividing effort between nations (Gilbert and Bows, 2012, Anderson and Bows, 2012, Committee on Climate Change, 2011, ben Brahim et al., 2019), given the complexities of ownership, operation and use, rather than determining a share of emissions for the shipping sector as a whole. Traut et al. (Traut et al., 2018) propose that the share of a future global carbon budget for international shipping should be "proportionate to the sector's current share of global emissions", an approach which has also been articulated by the International Chamber of Shipping (Morooka, 2012). There are, however, arguments that shipping should receive a larger share, given its vital role in facilitating global trade (Morimoto, 2018), and likewise arguments the sector should receive less, for example given its greater capability to make emissions reductions than sectors such as aviation or agriculture (Bows-Larkin, 2015, Gilbert et al., 2014).

We adopt the "proportionate to current share" approach for EU MRV shipping, assuming that the ratio of EU MRV carbon budget to global carbon budget is the same as the ratio of 2018 EU MRV CO_2 emissions to 2018 Global CO_2 emissions. We note that taking this approach might overestimate EU MRV budgets, as equity methodologies in the mitigation literature tend to focus on capability and responsibility, and by most metrics the EU has more capability and responsibility than the global average (Du Pont et al., 2017). Nevertheless, sensitivity tests on 10% higher and lower budgets for both international shipping and EU MRV shipping produced marginal difference in implications for the sector (see results section).

Overall, the EU shipping carbon budget is described by the formula:

$$EUCB_x = \frac{EUE_{2018}}{GE_{2018}} * GCB_x$$

Where $EUCB_x$ is the EU shipping carbon budget for a x per cent chance of keeping temperature rise below 1.5°C; EUE_{2018} and GE_{2018} are the EU shipping CO_2 emissions and global CO_2 emissions in 2018, and GCB_x is the global carbon budget remaining from the start of 2019 for a x per cent chance of keeping temperature rise below 1.5°C.

4.3.5 Committed emissions from future ships

Finally, in addition to committed emissions from existing ships, there are also committed emissions from ships to be built in coming years. For example, there are roughly 3,000 ships on global orderbooks for delivery over the next 3 years, which will use high-carbon fuels, and be used on average for over two decades. Beyond this, as existing ships are scrapped and replaced, and if the global ship fleet size continues to increase as per historic trends, then these new ships (replacement and additional) will also contribute further emissions, given that it is not likely that a large proportion of new ships will run on zero-carbon fuels until at least 2030 without significant policy changes (DNV GL, 2018). This paper briefly discusses the likely relative size of the emissions of existing versus new ships, and implications for climate change policy in the shipping sector.

Fleet growth is highly uncertain. DNV-GL assume that global fleet dead-weight tonnage will increase by 35% on 2016 levels by 2050 (DNV GL, 2018). However, this may not translate into shipping tonne mile growth; for example de Backer and Flaig (De Backer and Flaig, 2017) argue that digitalisation and use of robotics may increase intra-regional trade at the expense of inter-regional trade. Furthermore, growth in different fleet sub-categories will vary. DNV-GL's maritime outlook forecasts that global growth is strong for most sectors to 2030, but from 2030 oil tanker trade will fall. Falling demand for transportation of other fossil-fuels may also have implications for shipping (Sharmina et al., 2017, Mander et al., 2012). In this paper we analyse 1%, 2% and 3% annual growth rates in the total number of ships, applied uniformly across the whole fleet. We also tested this assumption against ship category variations, for example keeping the overall fleet growth rate at 2% per annum but reducing oil tanker growth to 1% reduces overall new ship committed emissions by 4%. We also note the extremely uncertain long-term impact of the ongoing COVID-19 pandemic, both on shipping generally and on specific sub-sectors such as cruise. In the short-term there will be major effects, although it is unknown what the long-term impacts will be. For instance, following the 2008 financial down-turn the shipping industry rebounded quickly, with tonne-miles transported ten years later aligning with prior trends (International Chamber of Shipping, 2018).

Ships are becoming more fuel-efficient every year driven by measures such as the Energy Efficiency Design Index (EEDI) (Transport and Environment, 2018). Analysis of IMO data by Transport and Environment (Transport and Environment, 2018, Transport and Environment, 2019) shows that current new ships are considerably more fuel-efficient than existing ships. The top 10% performing new ships are between 40 and 60% more fuel efficient than comparable ships of the same type and size. In this analysis we assume as an initial baseline that new ships are 40% more energy-efficient than existing ships of the same type and size, with a further annual 3% improvement in EEDI values.

4.4 Results

4.4.1 Existing ships' emissions in 2018

The EU MRV database splits ships into 15 categories. Table 4-3 sets out the total CO_2 emissions and average emission per ship, in each ship type.

2018 EU MRV CO_2 emissions total 138 $MtCO_2$, around 17% of international shipping CO_2 (Olmer et al., 2017). 67% of these emissions comes from 4 ship types – container vessels, bulk carriers, oil tankers, and roll-on roll-off passenger ships ("ro pax").

Table 4-3 2018 CO_2 emissions by ship type; EU MRV data.

Ship type	Number of ships with fuel and CO_2 data	Total fuel/year (Mt)	Total CO_2/year ($MtCO_2$)	Average CO_2 /ship/year (tCO_2)
Bulk Carriers	3,311	5.57	17.46	5,272
Chemical Tankers	1,268	2.91	9.13	7,199
Combination Carriers	7	0.03	0.08	12,013
Container Ships	1,665	14.04	44.07	26,467
Container Ro-Ro Cargo	72	0.46	1.43	19,890
Gas Carriers	294	0.79	2.45	8,340
General Cargo Ships	1,048	1.87	5.88	5,612
LNG Carriers	194	1.90	5.46	28,154
Oil Tankers	1,686	5.62	17.67	10,479
Other Ship Types	104	0.33	1.03	9,933
Passenger Ships	146	2.03	6.39	43,776
Refrigerated Cargo	140	0.57	1.78	12,730
Ro Pax	344	4.30	13.78	40,060
Ro-Ro	257	1.89	5.91	23,009
Vehicle Carriers	433	1.62	5.07	11,702
TOTAL	10,966	43.94	137.65	12,553

Source: EU MRV database. NB: EU "passenger ship" definition equates to "cruise ships" in Clarksons. $MtCO_2$ = million tonnes of carbon dioxide.

4.4.2 Baseline committed emissions

There is a large variation in the average remaining life for ships of each type, shown in Figure 4-2. Values for remaining ship service life and CO_2 emissions per ship allows calculation of a baseline committed emissions figure for each ship, and for the full EU MRV fleet, as set out above in equations 1-3 (section 4.3.2).

These results from the model for individual ship baseline committed emissions are summed over ship type, and shown in Table 4-4 and Figure 4-3. The headline figure from Table 4-4, and the central result of this paper, is that the baseline committed emissions from all existing ships in the EU MRV fleet is 2260 $MtCO_2$.

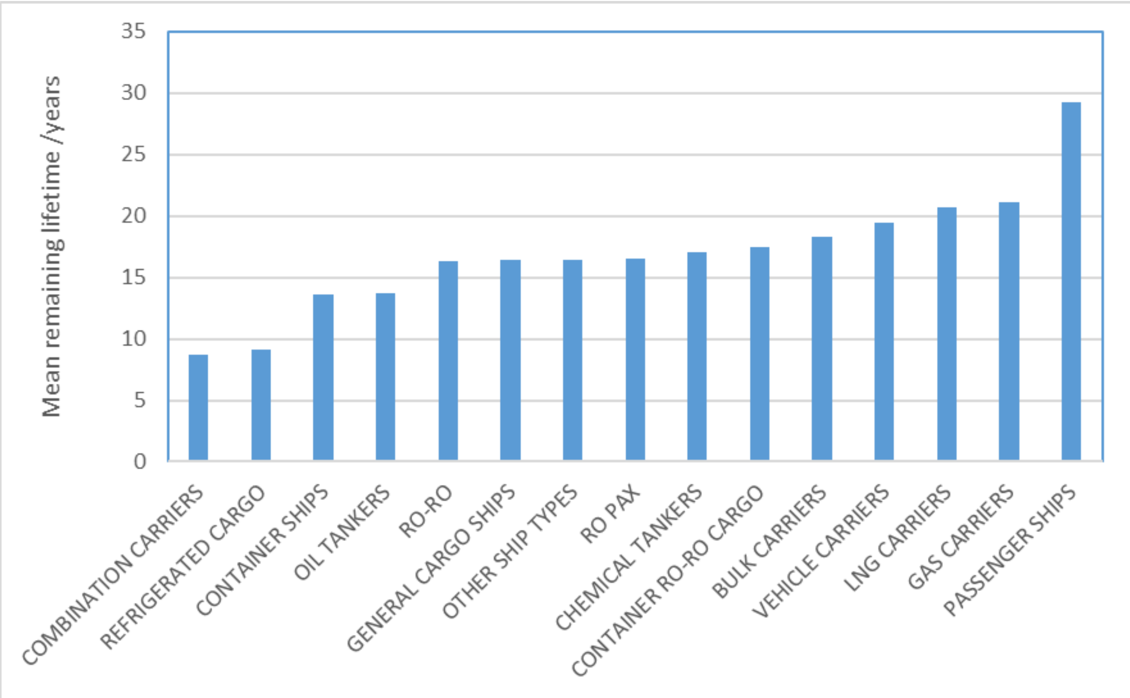

Figure 4-2 Mean remaining lifetime, by ship type.

Table 4-4 Baseline committed emissions for existing ships, by ship type

Ship type	Number of ships with fuel/CO_2 data	Total CO_2/yr (Mt CO_2)	Committed future CO_2 ($MtCO_2$)	Ratio of committed to current	Average age	Scrappage age + assumption
Bulk Carrier	3,311	17.5	307	17.6	8.7	Varies by size: 21.6-32.3
Chemical Tanker	1,268	9.1	150	16.5	9.8	26.8
Combination Carriers	7	0.1	1	9.3	15.6	24.3
Container Ships	1,665	44.1	658	14.9	11.7	Varies by size: 19.7-28.2
Container Ro-Ro Cargo	72	1.4	24	16.5	12.1	28.2
Gas Carriers	294	2.5	51	20.9	8.5	29.4
General Cargo Ships	1,048	5.9	91	15.4	12.5	28.2
LNG Carriers	194	5.5	107	19.5	8.7	29.4
Oil Tankers	1,686	17.7	227	12.8	9.7	Varies by type/size: 20.0-30.8
Other Ship Types	104	1.0	13.0	12.6	17.6	28.7
Passenger Ships	146	6.4	191	30	17.2	44.5
Refrigerated Cargo	140	1.8	19	10.6	22.3	30.8
Ro Pax	344	13.8	228	16.5	22.5	Varies by type: 30.8-44.5
Ro-Ro	257	5.9	97	16.5	15.8	30.8
Vehicle Carriers	433	5.1	96	19	11.6	30.8
TOTAL	10,966	137.7	2260	16.4	10.8	

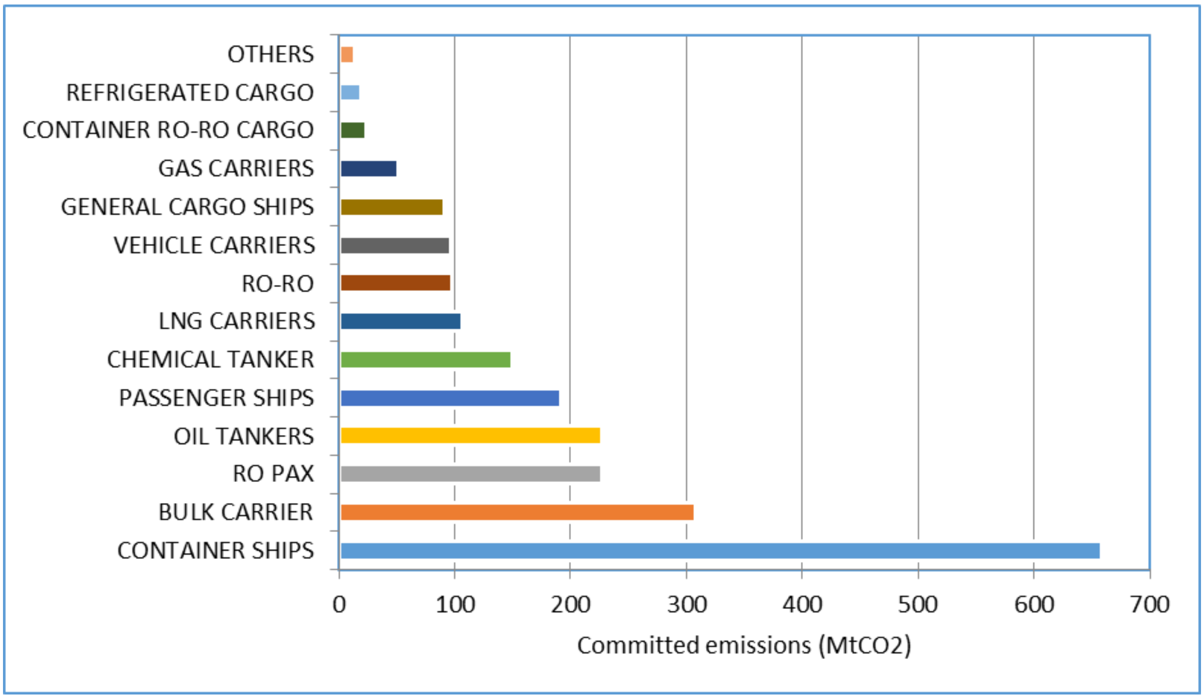

Figure 4-3 Baseline committed emissions 2019-2050, by ship type, in $MtCO_2$.

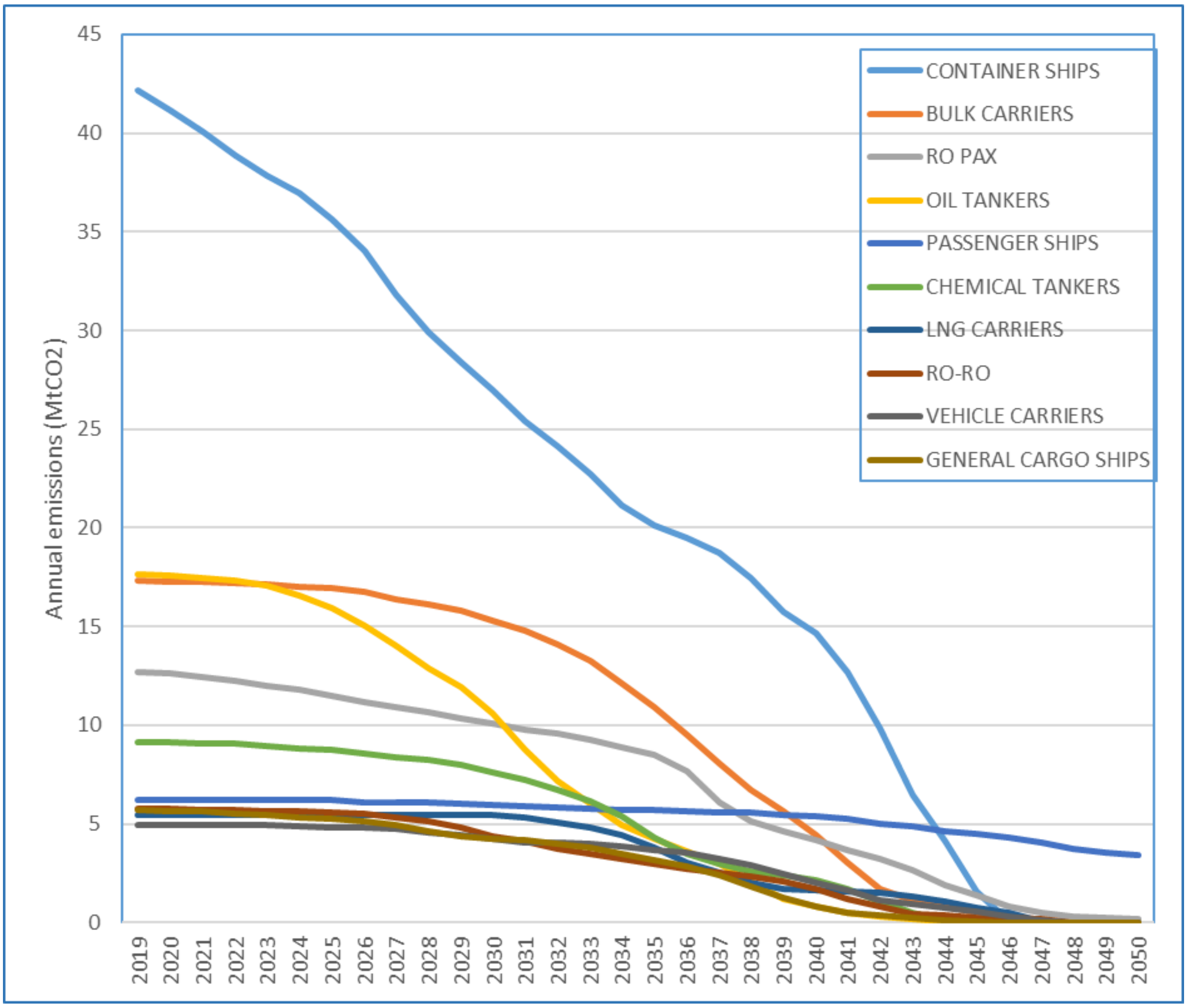

Figure 4-4 Committed emissions for existing ships

[from the 10 largest ship types (by emissions total) through time. Total committed emissions for a ship type are represented by the area under its curve.]

Five ship types account for 71% of baseline committed emissions: container, bulk carriers, ro pax, oil tankers and passenger ships. The split of cumulative committed emissions in $MtCO_2$ for the ten largest ship types is shown in Figure 4-4.

The baseline committed emissions data show distinct differences between comparable ship types:

- **Passenger ships and ro pax**

The average ro pax ship is 5 years older than the average passenger (cruise) ship. Also, passenger ships are on average older when they are scrapped. Both factors act to give passenger ships a greater average remaining life. Consequently, the total committed emissions from passenger ships is only 16% lower than for ro pax ships, despite there being 58% fewer passenger ships.

- **Gas carriers and refrigerated cargo ships**

Gas carriers and refrigerated cargo ships ("reefers") have similar average lifetimes, but the gas carrier fleet is much younger on average (8.5 vs 22.3 years) with far longer expected remaining life. This, plus the greater numbers of gas carriers, counterbalances gas carrier ships having lower average annual emissions than reefers. Overall, the gas carrier ship type has higher baseline committed emissions (51 $MtCO_2$ vs 19 $MtCO_2$).

Matching the age data with ship size data also highlights variations within ship types. For example, within the container ship type it is newer container ships that are responsible for the highest committed emissions. Despite newer container ships being much more efficient, the recent trend for container ships to become much larger has a greater impact. Graphs showing these trends are available in supplementary information (Figures 8.5-8.7).

4.4.3 Comparison with shipping carbon budgets

The total CO_2 emitted in 2018 from the 10,966 ships submitting 2018 CO_2 data to the EU MRV system is 137.7 MtCO2. Global CO_2 emissions in 2018 were 36.6 $GtCO_2$ (Friedlingstein et al., 2019). Using the Traut et al. (Traut et al., 2018) assumptions, the carbon budget for the ships in the EU MRV system is proportionate to their share of total global emissions at 0.38%.

As set out in the methods section, this paper uses a range of carbon budgets expressing different probabilities of meeting the Paris Agreement's 1.5°C goal. The share of the remaining global carbon budget for ships in the EU MRV system for these probabilities of keeping below 1.5°C warming is set out in Table 4-5, and compared with the baseline committed emissions from existing ships in the EU MRV of 2,260 $MtCO_2$.

Table 4-5 EU and Global Carbon budgets for different probabilities of meeting 1.5°C goal

GOAL	Global Carbon Budget ($MtCO_2$)	1.5°C Carbon Budget For ships in EU MRV ($MtCO_2$)	EU MRV baseline committed emissions ($MtCO_2$)	EU MRV baseline committed emissions as a % of Global Carbon Budget
< 1.5°C 33% probability	700,000	2650	2,260	85%
< 1.5°C 50% probability	440,000	1670	2,260	135%
< 1.5°C 66% probability	280,000	1070	2,260	212%

4.4.4 Carbon budgets implied by IMO targets

The IMO currently has a strategy and target to reduce greenhouse gas emissions by "at least" 50% by 2050, compared with 2008 levels. This strategy is due to be revised by 2023 (IMO, 2018f).

The EU MRV cumulative emissions implied by the IMO's current global target are however far higher than a Paris compatible 1.5°C budget. The IMO does not set out the rate at which emissions would fall by 2050 under its target, but it does have an interim 2030 target of an "at least" 40% cut in CO_2 emissions per transport work by 2030. This implies flat emissions from now to 2030, given IMO expectations of growth in transport work, counteracting transport work efficiency savings (DNV GL, 2018). With these assumptions, if emissions continued to fall post 2050 to zero by 2060 then the cumulative EU MRV emissions from 2019 would be 4150 $MtCO_2$; if the zero-date was 2075, this value would be 4750. Both are considerably higher than the Paris-compatible range in Table 4-5 of 1070 to 2650 $MtCO_2$

The current IMO target gives much higher carbon budgets than Paris 1.5°C carbon budgets for two reasons. First, the IPCC conclude that net zero emissions would be required by 2050 (IPCC, 2018b), not a reduction of 50%. Second, the lack of an absolute 2030 target means emissions reduction is delayed to later decades.

Overall this implies that the IMO's "at least 50%" target requires substantial tightening to be Paris-compatible. Using a proportionate-to-current-share approach, and the global carbon budgets set out in Table 4-5, linear reductions for international shipping to be Paris 1.5°C compatible are set out in Figure 4-5 below, with a central result of a required zero emission date of 2041, and a 47% cut in 2020 emissions by 2030. A sensitivity test of giving international shipping a 10% higher or lower share of the global carbon budget moves the zero emissions date only marginally, from 2041 to 2043 or 2039 respectively.

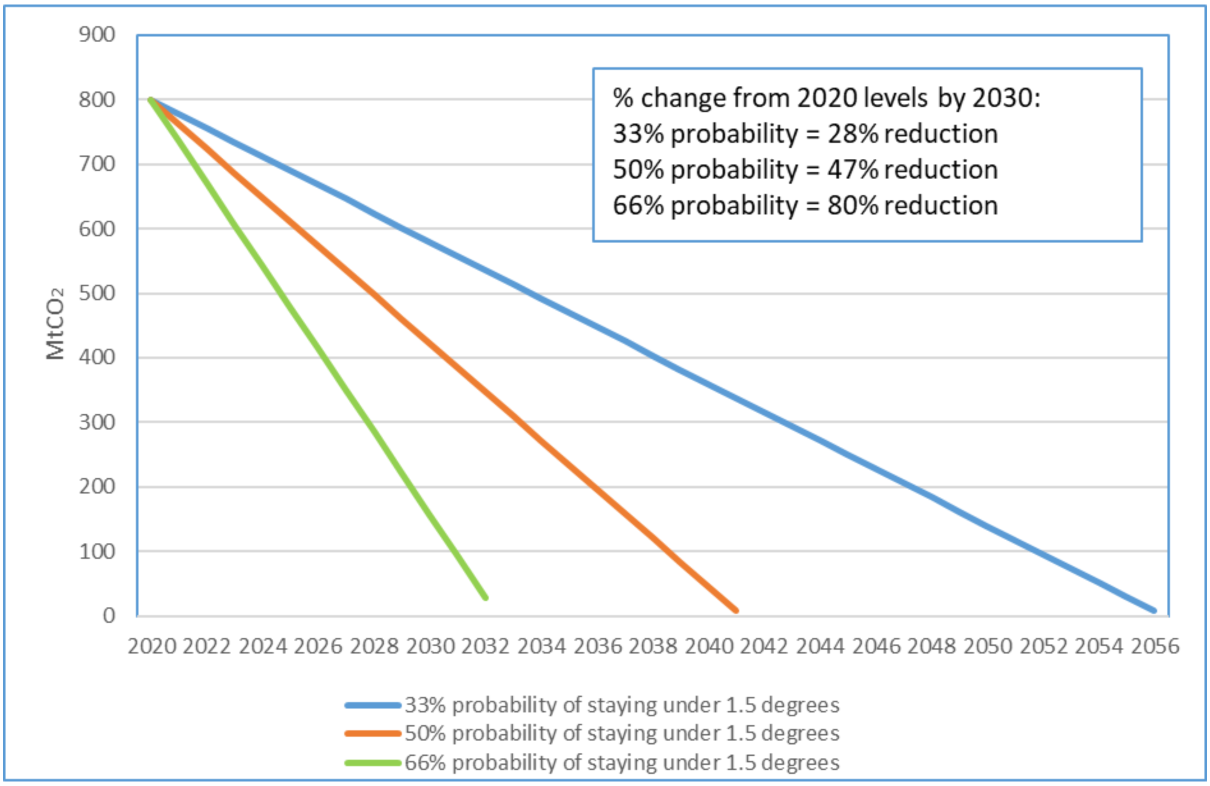

Figure 4-5 International shipping CO2 trajectories compatible with Paris 1.5°C target

4.4.5 Measures to reduce baseline committed emissions

Slower speeds, operational efficiencies and blended and zero-carbon fuels can lower baseline committed emissions without premature scrappage of existing ships. The values in Table 4-2 were input into the model (see supplementary information and accompanying spreadsheet), with results shown in Table 4-6.

Table 4-6 Effect of different measures on reducing committed emissions

	Inputs (Low-mid-high):			Committed emissions $MtCO_2$ under different measures			% reduction on baseline committed emissions		
Individual measure:	Improvement	Start date	Years until fully deployed	Low	Mid	High	Low	Mid	High
Slow-speed	15%-25%-35%	2030-2024-2022	10-5-3	2179	1919	1652	4	15	27
Technical and operational	5%-20%-35%	2030-2025-2022	8-10-15	2190	1924	1629	3	15	28
Fuel blending	1% pa – 2% pa- 4% pa	2030-2025-2022	n/a	2256	2226	2048	0	2	9
Zero-carbon fuel	n/a	2035-2030-2025	15-10-10	2092	1722	1270	7	24	44
All 4 measures				1976	1320	793	13	42	65

These results show that there is potential for measures to reduce baseline committed emissions by 65%, to 793 $MtCO_2$, assuming coverage of all four measures, with strong policies implemented rapidly. However, if these measures are implemented slowly, and to a lesser extent, then the reduction falls to just 13%, resulting in emissions of 1976 $MtCO_2$. Applying any measure on its own also reduces potential emissions savings. Under the model's mid-range assumptions, full retrofit of zero-carbon vessels within a decade from 2030 has the largest impact, but there are also large savings from speed reductions and from operational efficiencies in the 2020s.

A further analysis examined the effects of applying stronger policies, at mid-range timescales, versus mid-range policies, at faster timescales. It shows that implementing policies faster delivers greater savings than delivering stronger policies, although clearly doing both results in the highest reductions (Table 4-7).

Table 4-7 Effect on emissions reduction of varying the pace and strength of policy implementation

Policy strength	Policy implementation date	Committed emissions	% reduction on baseline committed emissions (2260 $MtCO_2$)
Mid	Mid	1320	41
High	Mid	1115	51
Mid	High	949	58
High	High	793	65

[Definitions for “mid” and “high” are as set out in Table 4-2]

4.4.6 New and replacement ships

Although there are measures which can reduce baseline committed emissions from existing ships, there are also committed emissions from future new ships. This section sets indicative values for the size of these additional committed emissions. New ships are split into two types: replacement ships for existing ships when they are scrapped, and “additional” ships reflecting the growth of shipping trade in total.

Figure 4-6 shows these three components of total fleet size under different assumptions for overall fleet growth.

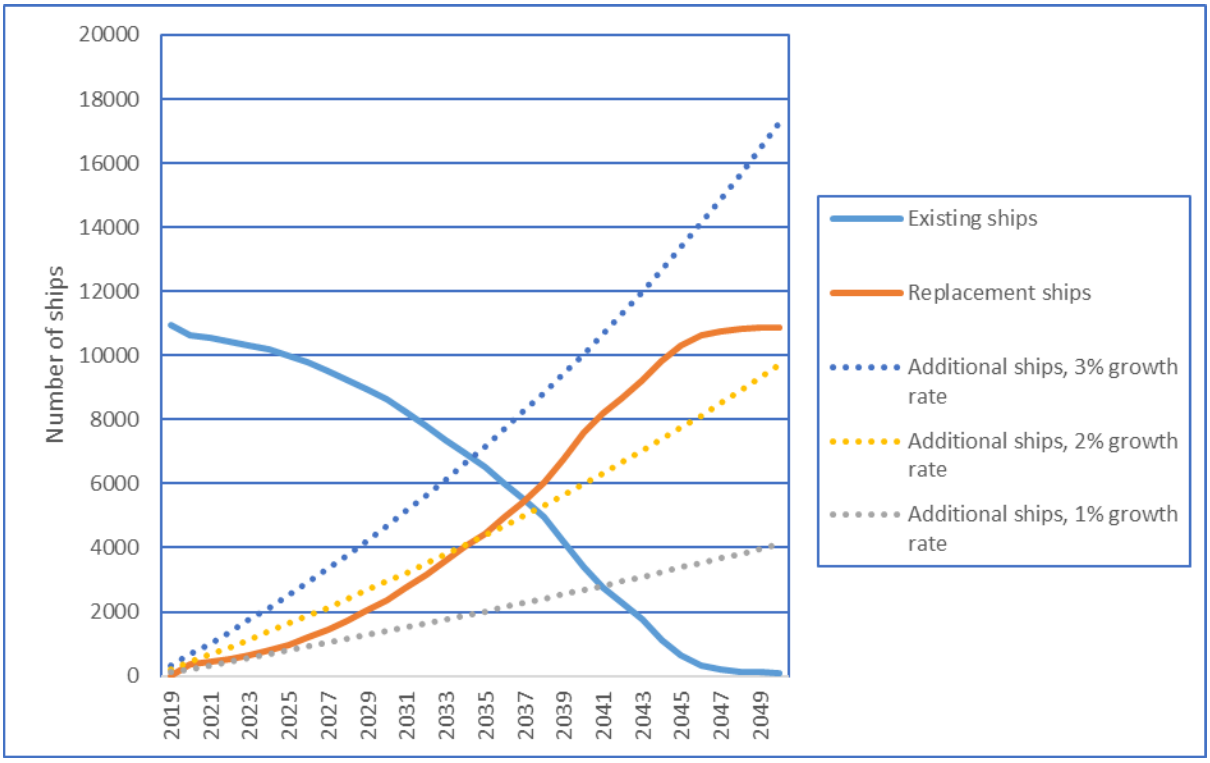

Figure 4-6 Number of ships in EU MRV under different assumptions of fleet growth rate

Although in a high growth scenario the number of new additional ships dominates the total figure by 2050, in 2030 the majority of the shipping fleet is still existing ships for all assumptions on growth rate.

The replacement and additional new ships would contribute additional committed emissions. Assuming that these new ships have efficiencies 40% better than existing ships, and that there are further 3% annual EEDI improvements, then the new ship committed emissions before any additional operational efficiencies, fuel blending or slow steaming are set out in Table 4-8, for different assumptions on fleet growth and starting date for introduction of zero-carbon fuels.

Table 4-8 Effect of varying growth rate and year new ships start to use zero-carbon fuels on new ship committed emissions

	Annual growth rate of fleet:		
	1%	2%	3%
	Committed emissions ($MtCO_2$):		
New ships start to use zero-carbon fuels from 2030, full deployment within 10 years	320	430	560
New ships start to use zero-carbon fuels from 2035, full deployment within 10 years	560	740	960

These results show the large difference in new ship committed emissions between a starting date of 2030 and 2035 for the adoption of zero-carbon ships and zero-carbon retrofits. A faster fleet growth rate also puts greater pressure on adoption of an early zero-carbon ship date to keep within carbon budgets. The combination of existing ships' committed emissions (Table 4-6) and new ships' committed emissions (Table 4-8) is shown in Table 4-9, compared with carbon budgets.

Table 4-9 Effect of varying zero-carbon ship date on committed emissions, versus carbon budgets

	Emissions in $MtCO_2$				
	Existing ships	Replacement and additional ships	Total	Carbon budget for 50% 1.5°C	Total as a % of a 50% 1.5°C budget
Zero-carbon fuel ships available from 2030, fully deployed in 10 years, no operational/speed measures	1,722	430	2,152	1,670	129%
Zero-carbon fuel ships available from 2035, fully deployed in 10 years, no operational/speed measures	2,027	740	2,767	1,670	166%

Table 4-9 shows that zero-carbon fuels for all new ships from 2030, plus retrofitting of all existing ships over 2030-2040, still leaves shipping emissions over budget, at 2152 $MtCO_2$ compared with a budget of 1,670 $MtCO_2$ for a 50% chance of exceeding 1.5°C warming. However, other measures can also be applied. Using the mid-range input values for slow-speeds, technical and operational efficiencies and blended fuels in Table 4-2 would reduce existing ships' committed emissions to 1,320 $MtCO_2$, a 400 $MtCO_2$ saving. A similar percentage reduction for new ships would save a further 100 $MtCO_2$, bring emissions in total down from 2,152 to 1,652 $MtCO_2$.

4.5 Discussion

There are three main contributions to the literature from this analysis, discussed in turn in this section. First, because ships have long lifetimes, the baseline committed emissions from existing ships are large: at 2,260 $MtCO_2$ this is 135% of the carbon budget for a 50% probability of exceeding 1.5 °C. New ships built in the 2020s will also add to this. Second, this committed emissions value could be considerably lower: if measures are introduced to lower ship speeds, improve operational efficiencies and use zero-carbon fuels it is possible for shipping to stay within a 1.5 carbon budget, the date of deployment being important. Third, there are significant differences in the age profile of different ship types, which has implications for decision-makers wanting to implement policies to cut shipping emissions. All three contributions highlight the importance of policies focussed on the existing fleet rather than solely on performance standards for new build such as the IMO's EEDI.

4.5.1 Shipping's committed emissions

There are three previous papers that have considered shipping's committed emissions, all of them treating shipping as a sub-set of transportation emissions as part of a global analysis, and all using extrapolations for shipping based on asset lifetimes elsewhere in the transport sector (Davis et al., 2010, Tong et al., 2019, Smith et al., 2019). This paper adds significant value to the existing literature on committed emissions by calculating an in-depth committed emissions value in a large segment of the shipping sector, using for the first time shipping-sector-specific assumptions about asset lifetimes. The 2,260 $MtCO_2$ baseline committed emissions value in this paper is around twice what might be expected if following the Tong et al. (Tong et al., 2019) methodology, which is in turn based on Davis et al (Davis et al., 2010). The main cause of this difference is due to the different values used for the lifetimes of existing ships. This study uses an average of 28.3 years, whereas Tong et al. use assumptions for mean lives of motor vehicles, of 16.9- 28.0 years. This paper's value is similar to that derived by Smith et al (Smith et al., 2019), who assume that ship lifetimes are similar to those of planes at 26 years. However, our use here of non-uniform age and lifetime profiles of different ship types and sub-types of ship is a further contribution.

The baseline committed emissions value for existing ships of 2,260 $MtCO_2$ is 135% of an EU MRV ships' carbon budget for a 50% chance of staying below a 1.5°C global temperature target (85 to 212% for 33% to 66% probability respectively). Global carbon budget values are subject to ongoing research, but the results of this analysis reinforce the finding of Tong et al. that committed emissions from existing high-carbon infrastructure leave very little room for new future high-carbon infrastructure. In addition, replacement and additional ships built in the 2020s will also run predominantly on fossil fuels, adding to committed emissions.

However, our larger committed emissions value could be lowered, if policies or practices are adopted that mean these long-lived assets use less or zero-carbon fuel in future.

4.5.2 Lowering committed emissions below carbon budgets

Applying the findings of Bouman et al.'s 2017 review (Bouman et al., 2017) of measures for reducing greenhouse gas emissions in shipping to latest individual ship level emissions data allows us to assess the sector's compatibility with global climate targets and the balance between CO_2 mitigation measures targeting the existing fleet and new builds.

The results show that even with rapid deployment of zero-carbon fuel in new ships from 2030 and if all the existing ships at that date were retrofitted to use zero-carbon fuels over the following ten years, then the emissions from this fleet would be 2,152 $MtCO_2$, which is 129% of a carbon budget with 50% probability of 1.5°C (See Table 4-9). If this date were delayed to 2035, committed emissions would total 2,767 $MtCO_2$, 166% of a 1.5 budget, highlighting the considerable additional emissions due to just a 5 year delay.

Assuming a 2030 zero carbon-fuel date, introducing additional measures such as lower speeds, fuel blending, and operational and technical efficiencies, based on mid-range assumptions from the literature, could lower emissions to 1652 $MtCO_2$, just under a 50% 1.5°C carbon budget.

Two points follow from this. First, it is imperative that zero-carbon fuels and associated infrastructure are developed and deployed at scale such that new ships running on such fuels are rapidly deployed from 2030 at the latest, and that existing ships are retrofitted from that date. Second, this is not sufficient for a 1.5°C target, and slow-speed and efficiency measures also need to be deployed in the 2020s.

With an assumption of zero-carbon new ships by 2030, the vast majority of the total committed emissions comes from existing ships (80%), rather than ships built between now and 2030. This is because the turnover of the shipping fleet is slow: even with an assumption of annual fleet growth at 2%, older, less fuel-efficient ships dominate the fleet. With 80% of committed emissions coming from existing ships, this means that measures to cut emissions need to focus predominantly on these ships, rather than just measures such as the IMO's EEDI policy (IMO, 2019b), which focuses on new ships. A revised IMO Greenhouse Gas strategy should aim to reduce emissions in-line with carbon budgets for the Paris Agreement 1.5°C goal. This paper suggests that for international shipping, a zero emission date around 2040 would be an appropriate goal, with an interim target of 47% cuts from 2020 emissions by 2030.

The analysis here shows that the individual measure with the greatest potential to deliver these emissions reductions is slower speeds, with major reductions from early implementation (Table 4-7). This adds further weight to the argument for adopting measures that incentivise or mandate slower ship speeds, as these could implemented far faster than the majority of the operational measures requiring retrofit in shipyards.

4.5.3 Policy interventions and ship type

Analysis of emissions data by ship type can aid policy-makers by enabling a focus on areas with greatest potential. Container ships have the highest baseline committed emissions, at 29% of the total. The EU MRV data show that even though new container ships are among the most energy efficient vessels (in gCO_2/t nm), the fact that they are so large, so new and so long-lived means they have a disproportionately large impact on total committed emissions. Paradoxically perhaps, this suggests a mitigation policy focus on the ships that are already some of the most efficient. Slow steaming and operational measures are well suited to bringing committed emissions down in the container ship type, reducing their committed emissions by 27% in this analysis. This is further reinforced by evidence that container ships on average travel at faster speeds than other ship types (DNV GL, 2018) meaning there is potentially great scope to reduce container emissions via this parameter.

Some types of ships are very long-lived, notably cruise, passenger and ro pax vessels. Slow steaming may be harder in these cases, which means that retrofit and operational efficiency measures are likely to bring the largest gains. Figure 4-2 shows a large range for average remaining life by ship type: for example refrigerated cargo ships have on average 9 years remaining life, whereas passenger ships have 29 years. All other things being equal, a ship owner will be less willing to invest in retrofitting measures to a ship with less remaining life. This means that for ships and ship types with shorter remaining life, the successful uptake of emissions reduction measures requires action from policy-makers, such as regulating on speed, retro-fitting to improve efficiency, or market-based mechanisms that impact on fuel price.

A further issue is the interplay between EU and non-EU markets. Refrigerated cargo vessels in the EU MRV are old, at 22 years on average, but outside the EU they are on average 9 years older. If retrofitting is not an economic option for old refrigerated cargo vessels, and they are sold on into non-EU markets, then the emissions would merely be transferred into other geographical areas. EU policy makers might therefore consider incentives for early scrappage for very inefficient older ships. The types where it appears that this might be more applicable are refrigerated cargo, container ships and oil tankers. Within ship types opportunities have also been identified. For example, compared to other ship types, container ships' remaining lifespan is low, but within the container ship type, ships with shorter remaining life are smaller and less efficient. A differential approach might then be appropriate within the container fleet; speed reduction measures being appropriate for all ships, but with an additional emphasis on further operational measures for the larger, newer, more efficient ships, and early retirement for the older, smaller, less efficient ships.

Finally, a stated aim for the EU MRV system is that it helps to bring emissions down (EU Parliament, 2015). This initial analysis of the EU MRV suggests that its data is useful in highlighting to EU and global policy-makers which areas and policy interventions might deliver the largest emissions reductions benefits. The EU has also stated that it will take unilateral action on shipping's CO_2 emissions if there is insufficient progress at IMO level (EU Parliament and Council, 2018). In such a situation the EU MRV dataset will be useful for policy makers and analysts in determining priority areas for climate mitigation measures in the shipping sector. It is intended that the EU MRV programme should be integrated with the global IMO Data Collection System (DCS) over time. To aid policy-makers, industry and others in determining effective interventions, we suggest that the IMO should similarly make individual ship data from their forthcoming DCS monitoring programme publicly available, as is the case with EU MRV.

4.6 Conclusions

This study provides a new assessment of the scale of the mitigation agenda for the shipping sector, and the imperative for significantly accelerating efforts to target CO_2 policies within the existing global fleet. Building on Tong et al. (Tong et al., 2019), we analyse recently published EU ship CO_2 data, with shipping sector-specific data for ship lifetimes and find committed emissions for this EU dataset to be twice that presented in their study. We find that existing ships are expected to contribute 85% to 212% of the sector's 1.5 °C-compatible carbon budget. Emissions from replacement and additional ships in the 2020s would add to this, further exhausting carbon budgets.

The ships that were in operation at the time of writing in early 2020 will still make up the majority of the fleet in 2030. To keep within carbon budgets, the shipping sector will need not only to adopt new very low-carbon fuels and new very low-carbon ships by 2030 at the latest, but in addition rapidly deploy measures such as operational efficiency and impose slower speeds *within* the 2020s to mitigate the committed emissions from the existing fleet. Combining these measures could cut the baseline committed cumulative CO_2 emissions from existing ships by up to 65%. Comprehensive adoption of the mid-range assumptions (Table 4-2) for existing and new ships would be sufficient to stay within Paris compatible carbon budgets.

The shipping sector has a broad suite of options to decarbonise but needs major policy interventions to incentivise change to the existing fleet. By distinguishing between types of ship, this analysis illustrates the huge value of retrofit solutions that help shipping align with Paris goals. Specifically, container ships are shown to be the greatest contributor to committed emissions, and perhaps counter-intuitively, newer ships are the biggest contributors within the container category, despite being more efficient because they tend to be larger in size. Passenger ships have disproportionately high committed emissions, given their small numbers, because they tend to be very long-lived: regulation that improves operational efficiencies should therefore be a priority in this type of ship. Across ship types, slow steaming stands out as the most promising measure that could be applied quickly to deliver large reductions in emissions in line with Paris goals.

The committed emissions from ships are significant, yet a combination of policies on very low--carbon ships from 2030, combined with speed and operational measures from the early 2020s, could keep shipping within a Paris-compatible carbon budget. However, any delay to appropriate policy implementation would mean additional measures, including demand-side or early scrappage interventions, to meet the Paris climate goals. In summary, the time left to deliver on what is dictated by the global Paris Agreement is too short to rely on measures that predominantly focus on improving the efficiency of new ships. Instead we conclude that policy makers should urgently change their current focus towards measures targeting the existing fleet.

Chapter 5 Accelerating shipping decarbonisation: a case study on UK shore power

5.1 Abstract

Shore power connects ships to land-side electricity grids, cutting fuel use in port to reduce carbon dioxide emissions and air pollution. It also enables the transition towards greater use of electric vessels. Despite these benefits, the global deployment of shore power is slow, particularly in countries such as the UK. This paper presents findings from a qualitative case study using two theoretical frameworks from the transitions literature to assess barriers to UK shore power deployment. The findings identify a need for capital funding and taxation policies, and illustrate that shipping's low status in the political hierarchy impedes their implementation. Measures to strengthen interactions between shipping actors would help increase the political pressure required to implement policies supporting shore power and shipping more broadly. These changes in the governance and organisation of shipping are essential to deliver the near-term emission cuts necessary for aligning UK shipping emissions with the Paris Agreement.

5.2 Introduction

Shipping is overwhelmingly reliant on fossil fuels for propulsion (Faber et al., 2020) and a major contributor to climate change. Carbon dioxide (CO_2) emissions from international shipping are equivalent to those of a large industrial country such as Germany (Global Carbon Project, 2021). The Paris Climate Agreement has established a goal to pursue efforts to limit global temperature rises to 1.5^{o}C (UNFCCC, 2022), and if international shipping is to make a fair contribution towards this goal, its carbon dioxide emissions need to be cut by at least a third by 2030 (Bullock et al., 2022c).

The literature cites myriad options for shipping decarbonisation, including shore power, demand reduction, ship efficiency improvements, wind-assist technologies and slower-speeds, as well as alternative fuels (Bouman et al., 2017, Cullinane and Cullinane, 2019, Mander et al., 2012, Gilbert et al., 2014). Ultimately, shipping will require zero-carbon fuels, however the slow turn-over of the fleet and the scale of investment needed for alternative fuel infrastructure (Krantz et al., 2020) means that it is likely to be the 2030s before alternative fuels are deployed at scale. Given the need for substantial emissions reductions before 2030, other short-term measures to reduce emissions are essential (Bullock et al., 2020).

Shore power[6] is one decarbonisation option that can deliver short-term cuts to CO_2 emissions. Shore power enables ships to connect to land-side electricity grids, cutting their use of fuel while berthed in ports. A review of studies of shipping mitigation measures found fleet-wide potential for 3-10% reductions in CO_2 emissions from shore power (Bouman et al., 2017), a substantial reduction in a sector where mitigation is characterised by many small-gain options rather than one silver-bullet. Shore power also offers benefits to local air quality and noise pollution (Zis, 2019), and paves the way for wider uptake of hybrid and electric vessels (Kumar et al., 2019). Yet, in spite of these benefits, shore power deployment is limited, largely concentrated in Norway and California, with some deployment in Northern Europe and China (DNV, 2021), and cruise ports with acute air pollution problems such as Seattle and Vancouver. In the United Kingdom (UK), shore-power projects are scarce, with only three large projects operational or near-completion. The barriers to shore power in general are well researched (see Section 5.3), but how they manifest within specific nations like the UK, why they persist and how they may be overcome is much less well understood.

This paper presents a new case study of shore power in the UK, and a novel application of transitions theories to elaborate on why socio-technical barriers to shore power persist and how they could be overcome. Forty interviews with stakeholders across the maritime sector in the UK and EU are analysed using an analytical framework that combines theories from the transition literature: the Technological Innovation Systems (TIS) framework, and the Multiple Streams Approach (MSA) (see Section 5.4). The paper combines insights from these theories to set out strengths and weaknesses of the UK shore power system, and barriers to improved functionality. It proposes policy solutions to overcome these barriers, and assesses the political challenges to adopting them (Section 5.5). Section 5.6 discusses these results, and the potential for a window of opportunity for stronger shipping decarbonisation

[6] Shore power is also referred to in the literature as cold ironing, onshore power supply (OPS), shore-side electricity, shore-side power, alternative maritime power (AMP) and shore-to-ship power supply.

policy on shipping in the UK. It outlines interventions which could both keep this window open for longer, and increase the likelihood of successful policy implementation for shore power and in the broader shipping sector.

5.3 Literature Review: barriers to shore power, and lessons from transitions literature

Shore power enables ships to reduce fuel consumption while at berth in ports, cutting local air and noise pollution (Kumar et al., 2019, Winkel et al., 2016), as well as CO_2 emissions in countries where electricity supply is lower-carbon than combusting marine fuel oil (Hall, 2010, Yun et al., 2018). In the UK, this would cut ships' CO_2 emissions at berth by over 70%, as ship's fuel oil emits around 700gCO_2/kWh (Faber et al., 2020), compared with under 200gCO_2/kWh for UK shore power (BEIS, 2021a). This benefit will increase in the coming decade as the UK's electricity supply system is further decarbonised (BEIS, 2021b). From a port perspective, emissions from ships tend to be the largest contributors to air pollution and greenhouse gas emissions, compared with port equipment or buildings. Shore power is therefore a key technology for ports to reduce their environmental impacts (Misra et al., 2017, Oslo Kommune, 2018), helping them to meet the United Nations Sustainable Development Goals that many ports emphasise in their strategic plans (Alamoush et al., 2021).

Much research on shore power focusses on how the environmental benefits of shore power can be improved, for example by increasing the CO_2 benefit by using land-side micro-grids and renewable energy generation to reduce the carbon-intensity of electricity (Yigit and Acarkan, 2018, Wang et al., 2019, Kumar et al., 2019). However, these benefits will not be realised if shore power deployment remains low, underscoring the necessity of understanding how barriers to the deployment of shore power can be overcome, which is the principal contribution of this paper.

5.3.1 Assessing barriers to shore power

Multiple barriers to shore power are well documented in the literature, through individual case studies such as of Kaohsiung Port, Taiwan (Tseng and Pilcher, 2015) or comprehensive global review articles (Radwan et al., 2019, Williamsson et al., 2022).

These barriers can be categorised in various ways, such as into economic, technical, stakeholder and institutional elements (Williamsson et al., 2022). These elements vary in their relative importance. For example shore power is a mature technology and various technical issues that previously impeded deployment have been overcome, with international standards to ensure compatibility between electricity grids and ships that use different power frequencies (Kumar et al., 2019). In contrast, the literature points to serious and persistent economic problems. Shore power projects have high capital costs, particularly for ports (Wan et al., 2021). It is difficult to recoup these costs because shore power is expensive compared with untaxed marine fuel oils (Tang et al., 2020, Yin et al., 2020). If the external benefits from reduced CO_2 and air pollution were costed into project evaluations, investment in shore-power would provide a net positive return on investment (Innes and Monios, 2018, Ballini and Bozzo, 2015). However, these benefits tend not to be internalised into project appraisal, so projects struggle to be competitive, particularly from a port operator perspective.

Project complexity is also a widespread and persistent barrier. Shore power projects require investments from multiple entities: from ports and ship owners/operators, and often on land-side electricity grid infrastructure (Kumar et al., 2019). Collaboration is needed between these entities, but there is often a “chicken-and-egg” situation where port operators will not deploy shore power because there is no demand from ship-owners, and ship-owners/operators will not invest in ship-upgrades until they see ports where their vessels could plug-in (Raucci et al., 2019, Zis, 2019).

There is a critical gap in the literature around why these well-documented barriers have not been overcome. Research has identified solutions – for example studies of shore power in China propose various policy or governance changes including emission control policy (Tan et al., 2021), electricity service charges (Tang et al., 2020) and government subsidies (Wu and Wang, 2020). But while these studies give insight into what and how policies might be used to address barriers to shore power deployment, they do not examine what factors are preventing or might accelerate such policies’ introduction.

As pointed out by Williamsson et al. (2022), shore power’s institutional, economic and stakeholder barriers are highly contextual, and these political, regulatory and cultural variations are strongest between nations. A national-level assessment of why shore power barriers have not been overcome would therefore be an addition to the shore power literature. A particular focus on the UK has merit because it has very slow shore power deployment to date (BPA, 2020) compared with more successful countries such as Norway or the USA, despite being a country where the technology's deployment is deemed to be a positive intervention (UK Government, 2019b). This focus also has merit because there is an absence of academic literature exploring the causes of this low UK deployment. Although barriers to shore-power deployment are well known in their generic sense, they vary depending on national-scale political, cultural and regulatory conditions. Thus, an assessment of the most important specific barriers at the UK level is an important prerequisite to understanding what is preventing solutions being introduced. This study therefore assesses both UK-specific barriers and the factors preventing them from being overcome.

5.3.2 Transitions theories' utility for analysing shore power

The absence of research on how shore power barriers can be overcome is one that methods and concepts from the transitions literature are well-placed to address. Transition theories enable understanding of the policy and political contexts that surround system innovations, as they are adept at examining issues such as the lock-in and inertia that hinder progress towards sustainability (Bergek et al., 2021). Transition studies take an interdisciplinary approach, combining methods and ideas from economics, political studies and sociology to analyse how and why change occurs in complex systems (Köhler et al., 2019, Zolfagharian et al., 2019).

Positioning shipping as a socio-technical system shows it to be comprised of a complex set of interactions between people, institutions and technologies at many scales to deliver societal needs (Geels, 2002, Pettit et al., 2018). Socio-technical transition analysis has been used to uncover the complex processes affecting progress towards decarbonisation in the shipping sector, in a growing shipping transitions literature. Three examples illustrate this point. First, determining the optimal conditions for new market formation in shipping is shown to be highly situation-specific (Bergek et al., 2021), with heterogeneous actor motivations and fragmented governance (Stalmokaite and Hassler, 2020, Damman and Steen, 2021). Second, in the face of long-standing subsidy of polluting shipping fuels, mixes of innovation policy, market-based mechanisms and regulatory reform are needed to overcome economic barriers to new technologies (Makkonen and Inkinen, 2018, Bach et al., 2020a). Third, analysis of power dynamics and politics is essential for understanding the different roles played by key actors (Bjerkan et al., 2021), and unpicking why some policies are adopted while others flounder (Bjerkan and Seter, 2021, Hessevik, 2021).

Section 5.3.1 highlighted the importance of unravelling national-scale political, cultural and regulatory conditions, however the gap in national-scale empirical research persists. Overall, the majority of shipping transitions analyses are at either a global scale (e.g. (Geels, 2002, Pettit et al., 2018), multi-country studies (Stalmokaitė and Yliskylä-Peuralahti, 2019) or port scale (Bjerkan et al., 2021, Bosman et al., 2018, Damman and Steen, 2021). Global studies have proven the value of transitions literature in understanding how change occurs in shipping, for example by exploring the transition from sail to steam (circa 1780–1900) (Geels, 2002, Pettit et al., 2018) or the particularities of developments such as wind-propulsion (Köhler, 2020) and slow-steaming (Mander, 2017). Other global studies have focussed on governance (Gritsenko, 2017), firms (Stalmokaite and Hassler, 2020), or shipping segments (Poulsen et al., 2016), revealing how the interactions between established and emergent systems affect the uptake of new technologies and practices. Established systems contain multiple sources of inertia – including infrastructure, knowledge, sunk costs and vested interest – as they are designed to endure. Subsequently, emergent innovations meet resistance unless they align with established configurations (Bach et al., 2021).

At the other end of the geographical scale, studies focus on experiences of shipping transitions at sub-national and port scale to elaborate more fully on the interactions between established and emergent innovations. For example, Bjerkan and Seter (2021) show that successful shore power deployment in the Port of Oslo was contingent on multiple interacting factors: cross-party political consensus, lack of controversy, a clear policy goal, integrated policies, generous funding, technological maturity and collaboration between actors. Understanding the intricacies and interactions that surround systems innovations is important to understand how blocked transitions can be accelerated.

However, between these global and local studies, analyses of specific technologies within national or sub-national contexts are relatively uncommon and concentrated on Norway (Bach et al., 2020a, Bergek et al., 2018, Sjøtun, 2020, Bjerkan and Seter, 2021, Hessevik, 2021). There are also few transitions studies that focus on shore power, barring Bjerkan and Seter (2021), who conclude that overcoming economic and regulatory barriers are pivotal for shore power deployment. In many countries the economic and regulatory measures that would affect shore power deployment are implemented primarily at a national level[7]. This implies that a national focus for transitions analysis of shore power is a gap which can usefully be addressed.

5.3.3 Literature review summary

There is a gap in the literature concerning how long-standing barriers to shore power can be overcome, particularly at a national level and for countries such as the UK, where shore power deployment has been slow. Transitions theories' focus on examining the conditions for change in a technological sector means that they are well placed to address this gap. However, despite there being a vibrant body of research on shipping transitions, there are few studies that directly examine shore-power, particularly at a national scale. This leaves research questions regarding why the various barriers that impede shore power have not been overcome, and what could be done to accelerate deployment.

5.4 Methods

This research uses an inductive design method with three key steps: data collection via interviews and desk research, preliminary analysis to identify theories and frameworks that would help elaborate on limits to progress in shore power deployment, and more in-depth analysis of the data using the chosen theoretical frameworks.

Forty semi-structured interviews were undertaken online between May and October 2020. Interviewees included a range of actors, networks and institutions that reflect the variety of actors involved in shore power deployment in the UK (See Table 5-1).

15 interviews were conducted with ports, as they are a heterogeneous group and critical parties in shore power provision. Collaboration with two port trade associations – the UK Major Ports Group and the British Ports Association – produced a sample of ports that represented diversity in terms of their geography, predominant user, ownership structure, and attitude to shore-power. Similarly, the UK Chamber of Shipping provided introductions

[7] Although in some countries, such as Australia and Germany, regional Government has a strong role to play in decision-making. In the UK regional bodies have lower influence.

to ship operators representing the main UK shipping segments. Additional, broader perspectives were also sought, such as that of ports in the EU with prior experience of shore power deployment. Interviews were with senior personnel and granted on condition of anonymity – for individuals and companies - allowing interviewees to reflect candidly on their experiences. Recruitment ceased when saturation occurred, which was after approximately 35 interviews. No new topics were identified in the last five interviews.

Table 5-1 Number of interviews by interviewee type

Interviewee grouping	Number of interviews	Types
UK ports (P)	15	Geography: Northern Ireland, Scotland, England Main cargo type: dry bulk, offshore, container, ferry, cruise Attitudes: going ahead, actively considering, uncertain, opposed, not considered Ownership: local authority owned, Trust port, privately owned
European ports (E)	4	Mix of ports with successful and less successful shore power projects
Shipping companies (S)	12	Types: cruise, container, ferry, cargo, offshore
Others (O)	9	Including 4 trade associations, 2 equipment providers, 1 electricity network company, 1 Government, 1 ship classification society

Note: P, E, S, O codes are used to identify the grouping for quotes used in section 5.5.2.

The interviews followed an interview guide (Appendix 8.3.4), with questions designed to gather the interviewees' perspectives on i) the merits of shore power relative to challenges facing the sector and other options to address those challenges ii) the barriers to shore power and iii) the ways that these barriers might be overcome. Interviews were recorded and transcribed verbatim with accompanying desk research used to investigate different projects, developments and policies identified by participants.

Shipping transitions literature tends to deploy one theory or tool for analysis (see Appendix 8.3.5), however Cherp et al. (2018) propose that because transitions are complex, they benefit from being analysed with more than one theory or framework, allowing different approaches to uncover and illuminate different aspects affecting transitions. Informed by the themes emerging from the interview data, two such frameworks were selected: from the socio-technical perspective, the Technological Innovation Systems (TIS) theory (Hekkert et al., 2007, Bergek et al., 2008) and from the political perspective, the Multiple-Streams Approach (MSA) (Kingdon, 1984b, Kingdon, 2011).

The TIS and MSA are complementary theories, highlighting different aspects of transitions. TIS approaches have been used in the past to diagnose the slow deployment of technologies (Wieczorek and Hekkert, 2012), which resonates with our research questions. The TIS outlines the structure of the system surrounding a technological innovation in terms of actors and their interactions; institutions, which includes formalised rules as well as norms and customs; and infrastructures, which includes the knowledge ecologies, physical and financial structures that surround shore power. It then aims to understand how innovation systems evolve over time by focussing on system 'functions' that include knowledge development and diffusion, market formation and resource mobilisation (see Table 5-2). Functions are defined as processes that have an impact on the goal of the system, which is to deploy and utilise a new technology (Bergek et al., 2008).

Table 5-2 Definition of TIS functions

	Function	Summary Description
F1	Entrepreneurial Experimentation	Entrepreneurs combine new knowledge, technologies, markets and networks in experiments to reduce uncertainties and improve system performance
F2	Knowledge Development	Improvements in the breadth and depth of knowledge in a system, can be measured by R&D spending, patents, learning curves
F3	Knowledge Dissemination	Diffusion of knowledge within the system via networks, within and between core actor groupings
F4	Guidance of the Search	Mechanisms which steer the deployment of resources and capabilities in particular directions, via Governments or markets, by for example "hard" policy targets, or "soft" processes such as iterative changes to how solutions to problems are framed.
F5	Market Formation	The use of policies (such as tax breaks) and other measures to create effective spaces where new markets can thrive
F6	Resources Mobilisation	Mobilization of physical, human and financial resources for the greater diffusion and use of technologies and processes
F7	Creation of legitimacy	Regulatory and cultural processes which lead to the technology being perceived to be acceptable, e.g. regarding safety, cost, value.

(based on Bergek et al., (2018) and Hekkert et al., (2007).

While initial coding (see Appendix 8.3.6) highlighted the importance of socio-technical and political barriers, issues of power and policy making were particularly foregrounded. Political dimensions can be under-regarded in socio-technical studies (Meadowcroft, 2009), so the MSA framework was selected as an additional theoretical lens to use. MSA is widely-used in political science to understand how policy change occurs, characterising change by analysing the interactions between three “streams” that must converge for a policy to change. The ‘problem stream’ refers to how a problem is framed and how it gains attention over others, the ‘policy stream’ to how policies to overcome problems are identified and gain acceptance, and a ‘politics stream’ to how policymakers choose which policies to implement. Policy entrepreneurs are identified as the binding agent between these three streams, promoting solutions to problems to decision-makers at critical “windows of opportunity” when policy change occurs. Such windows tend to be brief, given the multiple competing and changing demands for policy-maker attention at any given time.

The MSA complements the TIS by investigating when and how windows of opportunity develop around a given problem that could allow for more rapid change.

The analytical framework for how MSA and TIS are combined to analyse the UK shore power system is set out in Figure 5-1 .

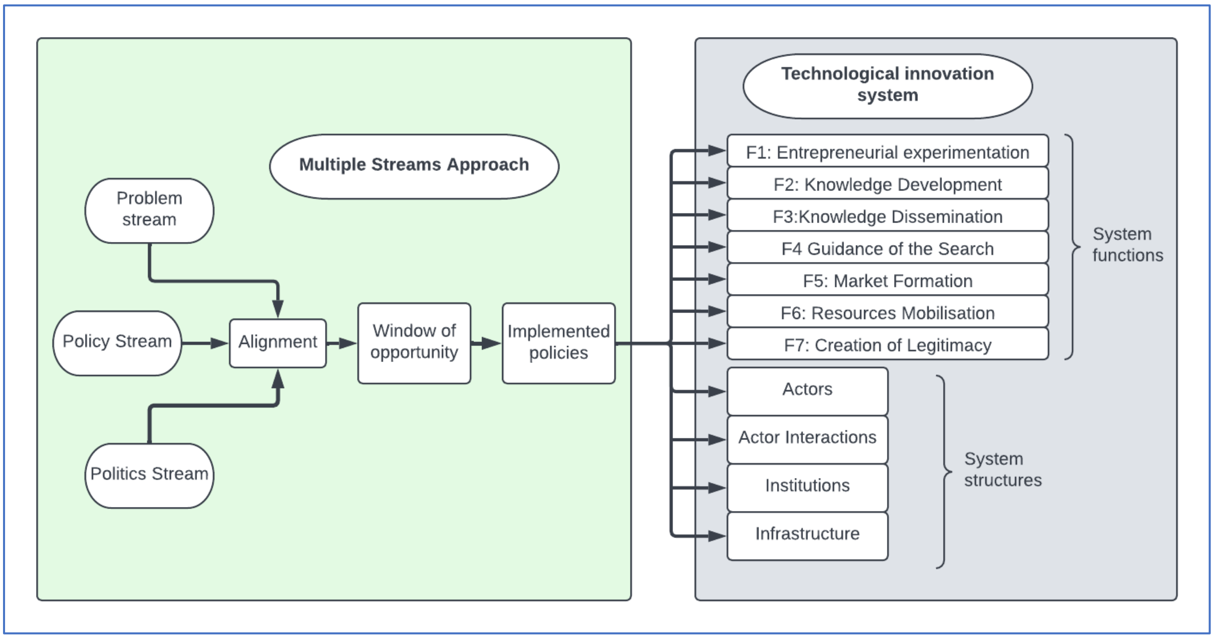

Figure 5-1 Analytical framework for integration Multiple-Streams Approach (MSA) and Technological Innovation System (TIS) frameworks.

Policies impact upon (black arrows) system structures and functions. Source: the author.

Once selected from the initial analysis, the TIS and MSA frameworks were used to analyse the interview data more deeply. The interview transcripts were returned to, using these analytical frameworks to deductively code the data to identify and elaborate on processes for change. For both TIS and MSA, analysis of the interview data was complemented by desk research and document analysis of technical and economic studies of shore-power projects, government policy documents, academic papers and industry reports.

Following the method proposed by Wieczorek and Hekkert (2012) and adopted by Sawulski et al., (2019), the TIS analysis involved i) identifying the structural dimensions of the UK shore power TIS, ii) analysing the effectiveness of critical TIS functions; iii) assessing the main barriers to improved system functionality, and iv) identifying solutions to increase the system's effectiveness. The MSA is then used to assess what impedes delivery of such solutions: to what extent the problems, policies and politics of shore-power are linked, who the policy entrepreneurs are, and whether there is currently a window of opportunity to accelerate or increase deployment of shore-power in the UK.

5.5 Results: UK Shore power: system problems, goals and solutions

Sections 5.5.1.1 to 5.5.1.4 present the results of the TIS analysis, in terms of structure, functions, barriers and policy solutions. For brevity, the majority of the analysis of the UK shore power system's functionality, and on the structural elements of institutions and infrastructures, is set out in Supplementary Information, sections 8.3.1-8.3.3.

5.5.1 TIS analysis

5.5.1.1 UK Shore power system structure

The UK shore power structure has three components, actors, institutions and infrastructures. First, the main actors and their interactions are set out in Figure 5-2 .

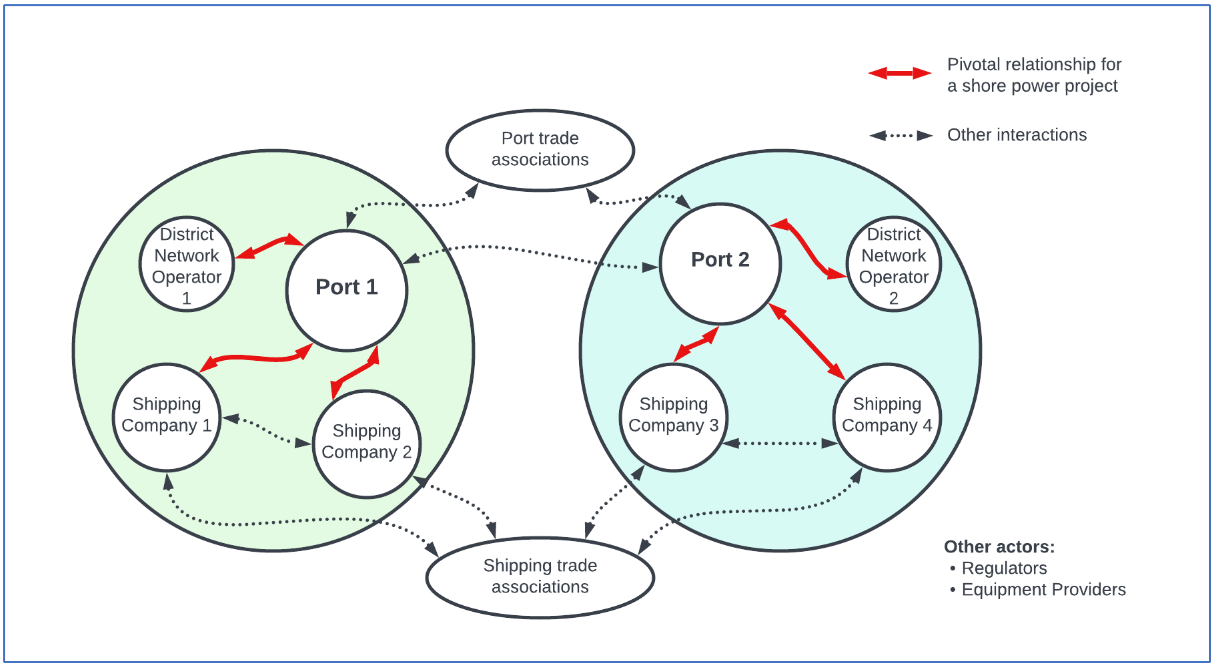

Figure 5-2 core actors and interactions in shore power projects

Source: the author.

Three core actors for a shore power project are:

(i) the port, providing the shore-side infrastructure for vessels to connect to the grid;

(ii) ship owners/operators, to ensure installation of the on-board equipment for ships to be able to connect to shore power;

(iii) the District Network Operator (DNO) responsible for electricity grid upgrades and connections from port to grid.

There are other external actors – shore power equipment providers, national and local Government policy makers and regulators. Port and shipping trade associations also play a pivotal role in the knowledge ecology of shore power, enabling knowledge dissemination within their sectors, and between their sector and regulators and other actors such as the DNOs. There are also intermediaries involved in shore power projects; consultants and other businesses with expertise in shore power project planning or energy management, and knowledge institutes such as shipping innovation networks and universities.

Unlike many energy-related systems in the UK, there is not a strong civil society presence in shipping. No national environmental non-government organisation focusses on shipping or ports, though there are local groups focussed on improving air quality near some ports.

5.5.1.2 Shore power system functionality

The three structural components interact to affect seven highly inter-dependent and mutually reinforcing or destabilising system functions (Table 5-2).

Interview analysis and desk research revealed that the most advanced function is Guidance of the Search (F4) – there is an increasingly clear narrative and direction from Government and other stakeholders that decarbonisation is essential and inevitable, and that shore power has a role to play in delivering it.

Knowledge Development and Knowledge Dissemination (F2&F3) are both reasonably advanced, though with notable gaps, particularly around absence or weakness in a number of critical relationships, for example between ports and DNOs, and in a lack of centralised repositories for key data or ideas, such as around business cases or electricity network upgrades.

The weakest functions are Market Formation (F5) and Resource Mobilisation (F6) – with major problems around accessing grant funding, constructing compelling business cases and the lack of policy support around fuel and electricity pricing. Interviewees repeatedly stressed two main barriers. First, the lack of capital funding support from the UK Government, contrasted with Europe. Second, shore-power, and indeed all alternative fuel technologies, have to compete with untaxed marine diesel oil. This is a problem globally but compounded in the UK by high levels of electricity taxation: countries like Germany, France, Denmark and Sweden have all lowered the electricity taxes paid by shore power projects; the UK does not do this.

On resources (F6), ports are experiencing further difficulties mobilising financial resources to deploy shore power. The lack of capital grant funding from Government is compounded by its decision to remove the subsidy for red-diesel used by ports, with interviewees stating that this will introduce costs, reducing ports' ability to fund capital projects. A final difficulty with resource mobilisation is a number of absent or weak relationships between critical actors. In particular, lack of collaboration between port and shipping operators was a widely cited problem, with interviewees often laying the responsibility for lack of action on each other. Many stressed that port and shipping entities need to collaborate more. Another interaction tension is that ports tend to have very low levels of interaction with DNOs and the National Grid, despite uncertainty about grid capacity for shore-power projects repeatedly being cited as a problem.

These market and resource barriers feed into low levels of Entrepreneurial Experimentation (F1), and problems of Creating Legitimacy (F7). Although there are established global companies offering shore power equipment and installation packages, the complexity of projects, financial barriers and lack of policy support are preventing experimentation. Ports do not yet see energy as a core business, and shore power tended not to be seen by ship operators or ports as an entrepreneurial opportunity, but rather something that might be required by them in future in response to regulatory pressure.

5.5.1.3. Barriers to UK shore power

From the TIS analysis, the main barriers to shore power deployment are summarised in Table 5-3, listed against the functional and structural categories. The focus on barriers is complemented in Table 5-3 by the addition of "inducement mechanisms" – the Hekkert et al. (2007) methodology focusses primarily on overcoming "blocking" mechanisms (i.e. barriers), whereas as Bergek et al. (2010) point out, the encouragement and nurturing of any "inducement mechanisms" can also be useful. Solutions to address these barriers are discussed in section 5.6.

Table 5-3 Barriers to UK shore power TIS functionality

No.	Structural area	Barrier to shore power deployment	Main functions this affects
1	Institution	Globally, marine fuel oil is untaxed	F1,F5,F6
2		High level of electricity taxation in UK	F1,F5,F6
3		Lack of guidance for ports on decarbonisation	F2, F3
4		Lack of grant funding for ports/ships for SP projects	F1,F5,F6
5		Shipping advocates have low political power compared with those in other transport modes	F4,F7
6		Lack of policy to back up broad maritime decarbonisation goals	F1,F5,F6,F7
7	Interaction	Absence of relationships between ports and DNOs	F1,F2
8		Weak and sometimes mistrustful relationships between ports and ship operators	F2,F5
9		Absence of relationships between ports and entities providing business models for energy management	F1
10		Complexity and multi-stakeholder nature of SP projects	F5,F6
11		Competitive relationships between ports preventing information sharing	F3
12	Actor	Energy not seen as a core business for ports, so some expertise and capacity is often missing	F1,F5
13		Urgent issues of Covid-19 and Brexit are reducing capacity for ports and shipping operators to focus on decarbonisation/shore power	F7
14	Physical infrastructure	Electricity assets (cables, substations etc) on port property are often old, making investments difficult, complex and costly	F1
		Inducement mechanisms	
15	Institution	Presence of a nascent overall shipping decarbonisation strategy	F4
16	Interaction	Some examples of specific ports and shipping operators increasing collaborative work	F3, F6
17	Actor	Commitment of trade associations to promote policy solutions	F4,F5, F6,F7

Source: the author.

5.5.1.4 Policies for shore power

The work of Wieczorek and Hekkert (2012) sets out goals for systemic policy instruments that either overcome system problems, or amplify system strengths, by focussing on actors and their interactions, institutions and infrastructure. Using this categorisation to reflect on the data collected, we identify eight interventions that address weaknesses or amplify strengths identified in Section 5.5.1.3 to improve the functioning of shore power in the UK, based on suggestions made by interviewees. These interventions are summarised in Table 5-4.

Table 5-4 Interventions for accelerating shore power deployment

	Type	Measure	Barrier (Table 5-3)	Detail
1	Institutional: global	Carbon pricing via the IMO	1	This might also be addressed at a regional level, for example in recent proposals by the EU Commission to include maritime emissions within the EU Emissions Trading Scheme.
2	Institutional: national	Capital funding for projects	4,14,15	Funding to the recent Clean Maritime Demonstration Competition could be expanded and made into a multi-year programme.
3	Institutional: national	Tax cuts for shore power	2, 15	Exempting shore power electricity from existing environmental taxation would help level the playing field with marine fuel oil, as other countries have done.
4	Institutional: national	Regulatory standard	6,15	Work with the port and shipping sectors on the design and implementation of a Zero-Emission berth standard or similar intervention aimed at cutting pollution in ports. This would increase demand for shore power in the shipping sector.
5	Institutional: national	Shore power information service	3,15	A one-stop-shop Government information service for ports and ship operators on technical and economic issues and business case development for shore power projects. This could be housed within the proposed new UK-SHORE office in DfT, flagged in the Transport Decarbonisation Plan.
6	Interaction	Working group for smart-grid development	5,7,17	To address network capacity issues, the trade associations, government, OFGEM, national grid and DNOs could convene a working group with the aim of developing a clear framework for enabling the development of port smart grids.
7	Interaction	Working group for data and best-practice sharing	5,8,10, 11,16	The port and shipping trade associations could lead a focussed working group aiming to increase collaboration and sharing of data and best practice on shore power deployment
8	Actor	Development of business models	9,12,17	The port associations and KT networks could work with the new UK-SHORE unit to investigate business models for energy management in ports.

Source: the author.

introduction of a global carbon price on marine fuel oils could address the competitive disadvantage faced by cleaner fuels, but there has been little progress at the IMO to introduce such market-based mechanisms since they were first proposed in 2008. There is increasing likelihood of fragmentation of global shipping policy if progress is not forthcoming, and this could be argued to be starting to happen, with the EU Parliament voting in June 2022 to include maritime emissions in the EU Emissions Trading Scheme (European Parliament, 2022).

Without a robust global carbon price, measures such as shore-power will struggle to compete against marine fuel oils. Consequently, other targeted national economic policies (2-4), are needed to improve business-cases. Research has consistently shown (see section 5.3.1) how a variety of economic barriers slow the uptake of shore power. Our results illustrate that in the UK, particularly important constraints are a relative lack of capital funding for shore-power, combined with taxation that favours conventional marine fuel oil. A strategy to overcome these is the introduction of countermeasures, e.g. capital funding and tax exemptions delivered at a national scale through the forthcoming revision of the UK's Clean Maritime Plan. Similarly, regulatory standards can complement economic instruments by mandating provision of ship and port shore power infrastructure, as in California and recently proposed by the EU. Payments for non-compliance with such standards could be ring-fenced to provide further shore-power capital funding.

The findings here also highlight the importance of improved knowledge dissemination and exchange between the multiple actors in the UK shore power system, helping address system barriers 7-12 (Table 5-3). For example, stronger networking on specific issues would enable sharing of best practice, helping overcome remaining technical and economic barriers (e.g. network capacity, smart grid deployment, business model development). Knowledge dissemination would be strengthened by a central body to coordinate information sharing on shore power and UK shipping decarbonisation more generally, either through the new UK-SHORE unit, or via another Government agency, such as the Maritime and Coastguard Agency. Increasing the strength of the network of actors involved in shore-power in the UK can contribute to building the capacity and connectedness of actors lobbying for stronger policy for shipping decarbonisation generally, and shore power specifically.

As an example of knowledge dissemination, measure 6 (Table 5-4) on a smart-grid working group would directly address the perceived lack of expertise and capacity on energy-management. But it would also help indirectly, through strengthening knowledge infrastructures and the interactions between actors, and by creating space for the development of actors' capabilities in new areas. The soft measures set out in Table 5-4 can therefore help to build a stronger and better connected set of actors, capitalising on the existing work of the trade associations and other entities such as Maritime UK.

5.5.2 Multiple Streams Approach (MSA): the political and policy landscape

This section uses the MSA framework to assess whether the policy or other interventions to improve the functioning of the current shore power TIS identified in Section 5.5.1.4 are likely to be implemented, by analysing how the three "streams" – problem, policy and politics – interact.

5.5.2.1 The problem stream

Interviewees were clear that they saw air quality and climate change as two major problems for shipping, and that there is increasing pressure locally and globally to tackle both. Historically, the global regulatory response to environmental harms from shipping has focussed on air pollution, where the IMO has successively tightened regulations on SOx and NOx from old and new vessels. More recently, climate change has risen up the global environmental agenda for shipping, with the IMO introducing a strategy for greenhouse gas emissions reduction in 2018, with the IMO's Marine Environmental Protection Committee (MEPC) stressing that increased ambition is needed in the IMO's forthcoming 2023 climate change strategy revision (IMO, 2021c).

A similar shift in focus towards climate change occurred at regional and national scales. The EU, frustrated with lack of progress on climate change at the IMO (European Commission, 2021c), is increasingly introducing policy to reduce greenhouse gas emissions from shipping. Similarly, the UK issued the Clean Maritime Plan (CMP) for shipping decarbonisation. This has established an expectation about the trajectory and pace of future emission reductions in the UK. Interviewees expressed a sense of inevitability around the need for action on maritime decarbonisation:

> "*The direction of travel has already been set. Through broader policy framework in things like the Clean Maritime Plan and obviously its decarb targets to 2050 and well-established carbon budgets and the CCC, so the trajectory is set. The implication for ports is that we will be under pressure on increasingly stringent emissions criteria or targets as we go forward*" [interviewee Port Operator 17].

However, despite climate change being widely recognised throughout the shipping sector, respondents felt that shipping emissions were often seen as a lower-order concern within broader environmental debates. Acknowledgement of the urgency of reducing emissions is high and increasing, but a difficulty for shipping remains that its emissions are seen as a small part of a much larger global problem. In addition, it is a sector less obviously connected to people's daily lives (Poulsen et al., 2018), so its emissions are not high in the public or politicians minds, compared with those from other sources, such as cars and planes.

5.5.2.2 The policy stream

Various policies have been developed around the world to promote shore power, particularly to address local air pollution. One successful example is shore-power regulation in California, first deployed in 2007 and strengthened over the years (CARB, 2020). Other attempts at shore power regulation have been less successful. For example, a 2014 EU directive (European Parliament, 2014) mandated shore power provision in ports, but included a clause on competitiveness which meant that in practice, lack of implementation was justifiable. Deployment has been accelerated instead through national policies: capital grant funding and reductions in electricity taxes. The 2021 EU Commission "Fit for 55" package sees proposals for strengthened regulations for shore power infrastructure for ports and ships, alongside more generic shipping policy such as inclusion of maritime emissions in the EU ETS.

In the UK, the Government's interest in shore power is likely shaped by consistent interventions in the last two years from multiple industry bodies on both the need for shore power and for policies to enable it (BPA, 2020, UK Chamber of Shipping, 2020). Shore power is a technology option for which the Government appears to be strongly considering. In 2019, the Clean Maritime Plan had an accompanying report on maritime electrification, with shore power prominent. In 2020, a technology report for the Government included shore power as one of five priority "clusters" for maritime decarbonisation (E4tech and UMAS, 2020). In 2021 Transport Decarbonisation Plan stated that shore power has: *"the potential to quickly reduce greenhouse gas and pollutant emissions from the ports and shipping sector, and is an option that is likely to be 'low/no regrets'",* and committed to *"consult this year on the appropriate steps to support and, if needed, mandate the uptake of shore power in the UK"* (Department for Transport, 2021b) and in February 2022 issued a call-for-evidence on possible shore power policies (Department for Transport, 2022b). However, as yet there are no specific policies to support shore power, and interviewees highlighted that the Government's strategy documents provide a weak mandate for action on shore power and other decarbonisation options:

> "*At the moment we have a vision of 2030, 2050 clean maritime industry, but in the short-term no legislation at the moment to drive change in the business"* [interviewee Other 5 (see table 5.1)]

> *"The Clean Maritime Plan [has] quite weak, long-term objectives, no detailed road maps or plans to get there…it's not concrete or clear what they want"* [interviewee Port Operator 8].

In order to be effective, interviewees describe a need for more specific interventions:

> "*The Clean Maritime Plan is more scaffolding than building. Putting the foundations down, the bricks up, let alone the electrical wiring, has been noticeably delayed, for good reason* [COVID]" [interviewee Port Operator 17]

> "*We've not had anything firm from Government. To me there's a lot of uncertainty out there still*" – [interviewee Port Operator 9].

5.5.2.3 The politics stream

At a political level, there are various pressures affecting the likelihood that shore power will be supported as a policy solution to the problems of air pollution and climate change. On air quality the signs are less positive. The Government does have an Air Quality Strategy, but although the UK legal system has found on three occasions that the Government is breaking the law on NOx levels (BBC, 2018), and ordered ministers to produce compliant plans to tackle air quality, the Government has still not done so. The political pressure on the Government has not yet been sufficient to persuade them to introduce a legally compliant strategy. This is mirrored in one aspect of air quality strategy – the UK Government has not followed up the Port Air Quality strategy since 2019. Although many ports have submitted draft plans, interviewees noted that there appears to be a policy hiatus:

> "*We've not heard back, it does kind of question the priority they give to this material.*" [interviewee Port Operator 8]

"*We're not getting any real pressure from regulators at the moment*" [interviewee Port Operator 9]

"*We're in the early days of developing our air quality strategy...but there's been no real driver*" [interviewee Port Operator 10].

On climate change, interviewees sensed more momentum with ramped-up rhetoric and ambition from the UK Government on climate change generally, and shipping decarbonisation specifically. However, there remained considerable scepticism that this would translate into policy. It was a repeated concern that there was low civil service policy capacity on shipping within the Department for Transport compared to other transport modes:

"*On shipping there's an astonishing lack of capacity in DfT"* [interviewee Shipping operator 4].

The Department was seen to be prioritising other transport modes:

"*Traditionally it's a Cinderella mode. We've spent less than £5m on greening maritime in last 2 years, buses £250m on a single project. Clearly buses have a more core role to people's day to day life, but Maritime is a major emissions source*" [interviewee Other 4].

In addition, it was expressed that the Department did not have much power over the pivotal decision-making body regarding shore power - the Treasury. This is critical given the need for capital funding and tax changes to accelerate shore power deployment, which are both under the Treasury's control.

In summary, from the MSA analysis, consensus is building that shipping's air and climate impacts are a problem, in the policy stream shore power is increasingly framed by industry and policy makers as part of the solution, and in the politics stream, political pressure is increasing, but it will need to strengthen further to overcome substantial inertia to ensure policies are adopted and sustained, given the lack of priority given to shipping policy.

5.6 Discussion

These findings suggest a new "window of opportunity" for shore power and ports more generally may be opening. This is because climate change has risen up UK and global agendas, as has recognition of the shipping sector's contribution to this problem. But this opportunity is considered by some to be much more extensive, as shore power will likely have a wider range of end-users in future, as hybrid or fully-electric vessels become more prevalent. The work of policy entrepreneurs, particularly trade associations, has helped raise the prominence of the necessity for greater policy on UK maritime decarbonisation, and shore power in particular. There is also greater political space for policy interventions to accelerate deployment of UK shore-power, with the UK Government's creation of a nascent Clean Maritime Plan decarbonisation strategy (due for revision in 2023), and the inclusion of international shipping emissions into the legal requirements of the UK Climate Change Act 2008.

However, in shipping, political pressure to decarbonise remains diffuse, compared with other more visible or apparently easier-to-decarbonise sectors. Consequently, despite some strong advocates for shipping decarbonisation within the UK Government and in wider industry, it is also clear that at present new policies are unlikely to proceed quickly. This is considered by stakeholders to be due to a general lack of political priority given to shipping within the Department for Transport, and also by key bodies such as the UK's Treasury, who are seen as a veto-institution whose power and relative lack of interest is a formidable obstacle. This view was most recently expressed in shipping trade press reports that the February 2022 consultation into shore-power policy does not include capital funding for shore power due to Treasury reluctance (Meade, 2022). This is problematic as MSA theory specifically suggests that windows of opportunity rarely remain open for long.

Overall, stronger policies for shore power can improve the weaker functions of the current UK shore power TIS, as shown in Figure 5-3, which would have knock-on positive effects on other system functions. To deliver these policies requires better alignment of the three streams, and in turn, a strengthening of the politics stream in particular. There is also the possibility of a positive feedback loop, where seemingly minor interventions to improve interactions between actors can lead to greater coordination of actors in the political stream. This can lead to better aligned streams, lengthening the window of opportunity, in turn strengthening policies, positively affecting system structure and functions, and so on. Similarly, improving guidance of the search can strengthen the problem and policy streams, creating another positive feedback.

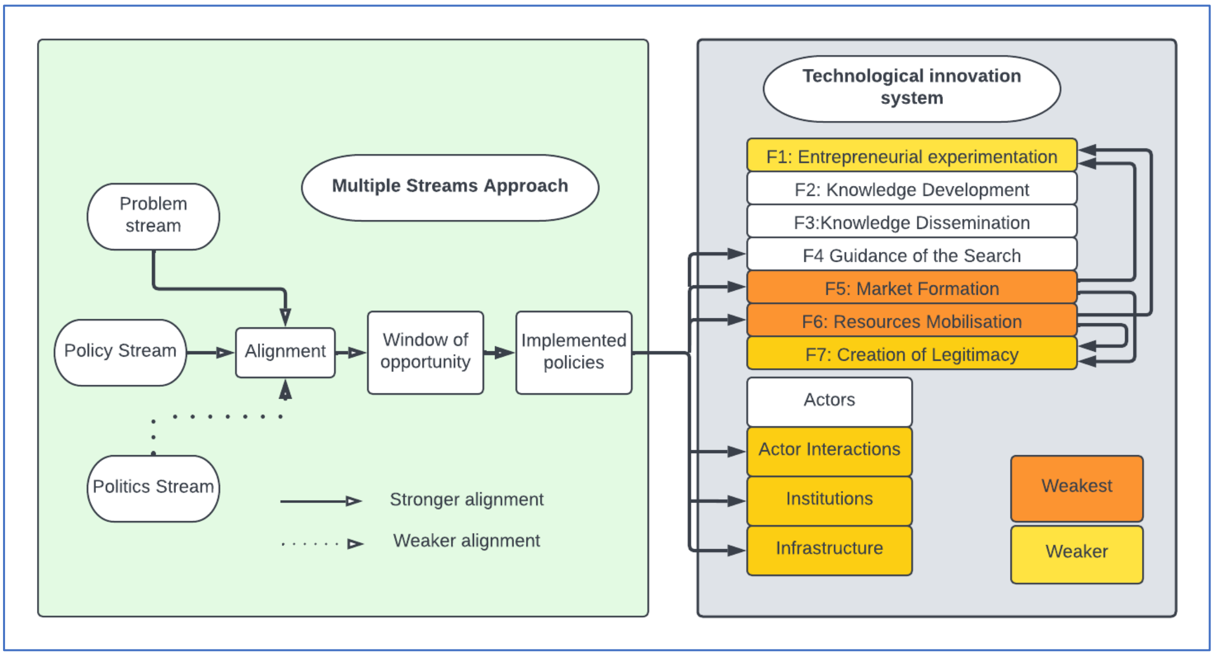

Figure 5-3 Analytical framework for the UK shore power system

Showing the weaker functions and structures in the Technological Innovation System (shaded yellow and orange), and how stronger alignment in the three MSA streams can lead to strengthening of system functions and structures, with further positive knock-on effects (black arrows). Source: the author.

5.6.1 Implementing policy

Although efforts to raise maritime decarbonisation and shore power up the UK policy agenda could be seen as a success, the hard work of securing necessary policies has only just begun. In line with the findings of Bjerkan and Seter (2021), who concluded that for Oslo, shore power "*policy implementation might require even more political work than policy adoption*", it seems likely that for national UK policy for shore power to be implemented, greater political pressure will be necessary.

Here we suggest three ways in which recent developments, linked with the capacity and knowledge measures 5-8 in Table 5-4, may help to promote progress in all three MSA streams – problem, policy and politics.

Jones and Baumgartner (2012) point out that accelerated change may occur through either reframing an issue, or through shifting the policy venues where decisions are taken:

"*punctuating the equilibrium*". On reframing, the twin environmental problems of air pollution and climate change are typically treated separately. So, first a reframing of shore power as a means to tackle both problems together, formalised through greater integration of the current Clean Air Strategy (air pollution) and Clean Maritime Plan (climate change), might help strengthen arguments in the problem stream, and incentivise stronger policy to support measures like shore power that deliver on both objectives. Given the Clean Maritime Plan is due for revision in 2023, and the Clean Air Strategies for ports also require updating, there is an imminent opportunity for integration.

Second, on shifting policy venues, the trailing in the July 2021 Transport Decarbonisation Plan of a new "UK Shipping Office for Reducing Emissions – UK-SHORE", building on the perceived success of similar models in other transport sectors, for example the UK Office for Zero Emission Vehicles, might help in the policy stream through opening new venues for policy deliberation. Similarly, the recent inclusion of international shipping emissions into the UK's carbon budgets indicates that as Government now has a stronger legal requirement to cut international shipping emissions, in future there may be greater policy analysis capability in both the Committee on Climate Change and in the Department of Transport. As Carter and Jacobs (2014) highlighted, in the late 2000s the institutional change of the Climate Change Act and its attendant processes around carbon budgets "wedged open" the window for climate policies in the late 2000s for longer than just the passing of the Act. It may be that including shipping in carbon budgets will wedge the window open on maritime decarbonisation, particularly if civil society pressure on Governments to act on climate change intensifies.

A third potential area for progress is via the £23m 2021 Clean Maritime Demonstration Competition (CMDC), which may lead to a greater variety of innovators active in marine decarbonisation, better connected with each other and with a vested interest in pressing the Government in the politics stream. The CMDC, which is set to receive further funding up to around £200m, is likely to increase collaboration between innovators across the shipping sector, and the strength and depth of business lobbies for stronger decarbonisation policies. These strengthened capabilities would help address the political problems highlighted in the MSA analysis. However, tensions between and within actor groups may well persist, given the very diverse nature of the sector. For example, a given set of shipping operators visiting a port will have very different organisational perspectives and priorities on any set of technologies. These might vary depending upon the views of their parent-organisation, on the importance of tackling climate change, whether they see competitive advantage in being a late or early mover, and whether they see shore power as conferring other benefits. Better understanding of actor-motivations in shore power would be a helpful area for future research. In this respect, the Dynamic Capabilities approach of Teece (2007) and used in shipping by Stalmokaite and Hassler (2020) would be useful to include in further research.

5.7 Conclusion

If decarbonisation is to be the next major shipping transition (Pettit et al., 2018), then shore power is well positioned to play a vital role. However, supporting policy implementation in the UK is being blocked by the lowly status of shipping in UK political hierarchy. This influential jigsaw piece within the wider shipping system faces political, economic and cultural barriers that are interacting to stymie its deployment in the UK. Interrogating these barriers has identified policy instruments and ways to support their implementation.

Shore power faces difficulties in forming markets and mobilising financial resources, particularly as it requires coordination between multiple actors to be effective. As well as having high capital costs, shore power projects have long pay-back periods and struggle to compete with relatively untaxed marine diesel oil. Provision of capital funding and reductions in taxes that shore power faces could overcome some of these economic barriers.

In terms of cultural barriers, there is mistrust between some port and ship owners, with both sides stressing the need for greater collaboration to overcome this problem. There is also limited interaction between electricity networks companies and port operators, and there are also knowledge gaps and an absence of information sharing surrounding energy management and business cases. These issues could valuably be addressed through cross-sector working groups and centralised information services. Both are relatively simple to implement and would improve the functioning of the shore power system.

Measures to strengthen knowledge, capacity and networking between key shipping actors would provide an additional benefit. Economic policies on shipping are currently blocked by insufficient pressure for their implementation: better coordination between shipping actors would strengthen their ability to exert political pressure to enact necessary policies for shore-power and wider shipping decarbonisation. There are opportunities to do so – the review of the Clean Maritime Plan, the extension of the Clean Maritime Demonstration Competition, and the establishment of the UK-SHORE unit.

Shore power reduces air pollution, more closely aligns UK shipping greenhouse gas emissions with the Paris Climate Agreement and facilitates wider decarbonisation. Yet despite growing consensus on the imperative of shipping decarbonisation and shore power in particular, stronger policy is needed to ensure its quick and effective implementation. There exists in 2023 a rare chance to lengthen the open window of opportunity to accelerate shipping decarbonisation, but this requires urgent intervention. Increased coordination between actors, aligning knowhow, reducing electricity taxes and a provision of capital could unlock the current impasse in UK shore power deployment. This can pave the way for greater electrification of shipping fleets, integrating with energy and transport sector electrification, and in turn, elevate UK ports to become very low carbon energy hubs. Seizing rare opportunities to accelerate the energy transition is essential if our climate goals are to be met and shore power could be a critical catalyst that unlocks a much bigger prize.

Chapter 6 Improving shore power project economics at the Port of Aberdeen

This chapter is based upon the following published article:

Bullock, S., Higgins, E., Crossan, J. and Larkin, A., 2023. Improving shore power project economics at the Port of Aberdeen. *Marine Policy*, *152*, p.105625.
https://doi.org/10.1016/j.marpol.2023.105625

6.1 Abstract

Shore power is one of just a few technologies available to the shipping sector that has potential to deliver carbon reductions this decade in line with the Paris Climate Agreement. Shore power connects ships to land-side electricity grids, reducing fossil fuel use while at berth in port and at the same time improving air quality. It is also an enabling technology for the future deployment of electric vessels, allowing battery recharge. Despite being a proven technology, global deployment has been slow, with the literature pointing to clear economic barriers to its uptake. These include high capital costs for ports, high taxes on land-side electricity and the global lack of taxation on ships' fuel oils. Yet there is a gap in understanding around how to overcome these barriers. Here, a case-study of the Port of Aberdeen in Scotland is used to explore how the economic case for a shore-power system can be improved. A multi-criteria analysis and techno-economic assessment, coupled with port-user and supplier engagement, applicable to other port contexts, sheds light on how to create the much-needed acceleration of shore-power deployment. By building a collaborative approach between the port, ship operators and national government, project viability can be unlocked to more closely align the sector's future carbon pathway with the high ambitions laid out in Paris 2015.

Key words

Shore power, shipping, climate change, multi-criteria analysis, ports, techno-economic assessment

Highlights

Shore power cuts greenhouse gas emissions and improves air quality

Shore power is deployable now but has economic barriers

Government support on tax and capital funding can accelerate shore power deployment

Co-operation between ports, ship operators and Government can deliver viable projects

6.2 Introduction

Shore power is a proven technology which connect ships to land-side electricity grids, so they do not need to use their auxiliary engines to provide power for on-board activities while at berth in ports. This reduces fuel consumption, which lowers greenhouse gas (GHG) emissions if the local electricity grid has a lower-carbon intensity than the marine fuel oils it is replacing (Hall, 2010). Because of this, shore power is frequently cited as a technology in the portfolio of options for maritime decarbonisation (Balcombe et al., 2019, Bouman et al., 2017, UK Government, 2019b). Although it cannot deliver GHG emissions reductions of the scale of those which would accrue through fuel-switching at sea, shore power has four main benefits. First, it is deployable now, which is essential given the need for GHG reductions in shipping this decade (Bullock et al., 2022c). Second, it has co-benefits of reduced air pollution in ports, where air-pollution from ships is more likely to be damaging to public health than at sea. Third, it is an enabling technology for the likely greater deployment of hybrid and all-electric vessels, which will require battery recharging facilities. Fourth, in the longer-term hydrogen and ammonia are lead contenders to have replaced marine fuel oils. These fuels need to be made predominantly by electrolysis which is a more costly and energy intensive process than simply using electricity directly – so switching to shore power while in port will be the cheaper and more efficient option for ship operators.

A global review paper of barriers to shore power (Williamsson et al., 2022) found a range of issues that affect shore power projects' deployment, with difficult project economics featuring prominently, a finding confirmed in other review papers (Qi et al., 2020, Radwan et al., 2019, Chen et al., 2019), with recent case-studies in Ireland and Sweden also showing ongoing problems with projects' financial viability (Gore et al., 2023, Costa et al., 2022). The main economic barriers for shore power projects are their high capital costs, particularly for ports, and that they struggle to be cost-competitive with the alternative: ships continuing to use fuel oil on-board to produce electricity. This is because marine fuel oils face little taxation, a problem that is compounded in countries where shore-side electricity is highly taxed. Some EU nations have exempted shore-power from electricity taxation, which improves project economics. Proposed EU legislative reforms may make these exemptions permanent. But this is not the case in the UK, which is a missed opportunity as the decarbonisation benefits of shore power are high, given the much lower carbon intensity of UK grid electricity compared with marine fuels (BEIS, 2021a).

This paper assesses the technical options and economic case for shore power installation at the Port of Aberdeen. Aberdeen is chosen because it is a medium-sized, multi-modal port in north-east Scotland, servicing a wide range of vessel types which might use shore power, whereby analysis would also be useful in a broader UK and global context. The paper is a practical contribution to the literature that assesses the key parameters for consideration in developing an economically viable shore power project in a UK context, elucidating ways in which the financial case for investment could be improved, and the key enabling policies which would be required.

In the UK, beyond the military base at Portsmouth, the only commercial projects at scale are at Orkney and Southampton. Deployment is stymied by a lack of supportive national policy (Bullock, 2022a). There is however growing interest in shore power as a policy solution that meets the UK Government's strategic goals on both air quality and climate change. Policies to accelerate shore power deployment were the subject of a 2022 Department for Transport call-for-evidence (Department for Transport, 2022b), as the Government prepares to update its 2019 Clean Maritime Plan. There is also likely to be greater policy attention towards UK shipping decarbonisation following the inclusion in 2021 of international shipping emissions into the UK's legally binding Climate Change Act targets (UK Government, 2021a). This paper therefore aims to be both a timely contribution into how UK shore power deployment can be accelerated, whilst also providing wider learning for shore power deployment in other geographical contexts around the world.

Case studies of potential UK shore power projects are rare. One study by Innes and Monios (2018) of shore power in an area of Aberdeen Harbour found that the economic value of the social benefits from reduced pollution outweighed project costs. However, such broader social benefits are not included in private sector project appraisal in the UK, so the existence of large external benefits is not sufficient to drive towards a successful project. This UK example mirrors much of the global literature of case studies on shore power, in that they also tend to focus on demonstrating social benefits (Kose and Sekban, 2022) and attaching a monetary value to them (Piccoli et al., 2021), but with comparatively little focus on how projects could be delivered in practice. Some recent global studies start to assess projects' economic viability, for example Martínez-López et al. (2021), but overall there is a gap in understanding how projects might become viable, which this article aims to help address.

As well as demonstrating social and environmental benefits, Merkel et al. (2022) argue that shore power projects must address port and ship operator profitability, with for example Yin et al. (2020) advocating Government subsidy to address capital costs, and Dai et al. (2019) advocating subsidy of electricity prices. Wang et al. (2021)'s study of subsidies to accelerate shore power deployment describes three main interacting entities – port, ship operators and government. However, Wang et al. (2022b) state that previous research on policies to overcome economic barriers emphasises interactions between just two of these entities, with the use of single policies to address economic barriers also being criticised by Zhen et al. (2022). Moreover, such studies have an overwhelming focus on subsidy as the prime type of policy mechanism (Li et al., 2020), despite acknowledgement by Wu and Wang (2020) that this is an expensive approach. Studies on alternative approaches are rare, with one example by Dai et al. (2019) concluding that internalising environmental costs via an emissions trading scheme is insufficient on its own to ensure project viability, a similar conclusion to the study by Martínez-López et al. (2021) of port environmental charges. This highlights an absence of literature both on the analysis of the three-way interplay between national Government, port and ship operator, and on combinations of policy mechanisms beyond subsidies.

This paper therefore aims to assess how project viability could be improved at the Port of Aberdeen. It does this by answering three questions. First, which is the most promising area of the port for shore power provision. Second, what would be an optimal technological system for shore provision in this area, and what are its costs. Third, what are the main factors affecting project economics, and what measures could be used to improve overall financial viability.

6.3 Methods

This paper used a combination of stakeholder interviews, berthing and power data analysis, multi-criteria analysis and techno-econometric modelling to navigate a route through the complex mix of stakeholder requirements and uncertain future landscape and policy changes affecting shore power projects in the UK. There are three main sequential elements to this analysis, requiring different methodological approaches, see Table 6-1:

Shore power projects require three main infrastructure investments: i) berth infrastructure for ships to connect to land-side electricity grids, ii) port-side infrastructure to connect berth infrastructure to land-side electricity grids, and iii) ship infrastructure to connect to the berth infrastructure. The costs of each these investments vary greatly, but ship-side investments tend to be an order of magnitude lower than berth-side, with port-to-grid infrastructure investments having the greatest range. A pivotal issue for ports is whether there is sufficient land-side power supply from existing port grid connections to meet ships' shore power demand – if this is not available then either expensive grid reinforcement (such as new sub-stations) or dedicated new power supplies (such as an in-port wind-turbines plus battery storage) are needed. Two prerequisites for project analysis are therefore an assessment of likely power demand, and available power supply.

Table 6-1 Stages of methodology

Stage	Approach
1. Shore power demand assessment	Assessment of the potential shore power demand for electricity from ships visiting Port of Aberdeen, and how the emissions from these vessels' current electricity generation from fuel oil compares with emissions from other parts of the port estate. Identification of which might be the priority berths within the harbour for exploration of a more detailed financial case for shore-power installation.
2. Technical option assessment	Assessment of the technical options for shore power installation in a prioritised area of the port. It assesses the likely future demand for shore power, and then selects an appropriate and costed set of technological shore-power options, using multi-criteria analysis, given the demand profile and berth specifics.
3. Techno-economic assessment	Construction of a techno-economic model for the lead technical option to assess the project's financial viability under a range of different parameter inputs.

6.3.1 Shore power demand assessment

At a port-level, calculations for shore power demand can be made from top-down national studies, which take a broad overview estimate of shore power potential at a national or regional level, and then apportion this to individual ports. Unfortunately, in the UK there is an extreme range from such results, as shown in Table 6-2 as applied to Aberdeen:

Table 6-2 Literature top-down estimates of shore power demand at Aberdeen

	Potential shore power demand GWh/yr Aberdeen
E4tech and UMAS (2020)	230
Arkevista (2020)	11
Stolz et al. (2021)	5

While these studies' results have greater congruence at a national level, at individual port level it is the different methods of disaggregation that cause large variance. At port level, the value in Stolz et al. (2021) is an underestimate for Aberdeen, as their EU data set does not include offshore vessels, which are a large part of vessel traffic at an energy port like Aberdeen. At the other end of the scale, E4tech and UMAS (2020) ascribe national shore power demand to individual ports proportional to each ports' share of total port calls. This overestimates Aberdeen's shore power demand, as Aberdeen is characterised by a very large number of port calls by comparatively much smaller than average vessels.

Because port circumstances vary greatly, for individual port-level studies it is unwise to rely on such top-down estimates; instead, a more accurate bottom-up approach should be used - calculating demand from the summed contribution of individual vessel visits. One previous bottom-up study for Aberdeen (Innes and Monios, 2018) took this approach, but only covered one part of the port area (the Trinity/Jamiesons/Regent/Roro area in the North West of Figure 6-1**Error! Reference source not found.**). `

Potential shore power demand is a function of time at berth and power use/hour. Here, ship port call data for 2019 is provided by the Port of Aberdeen for every berth (main berths highlighted in Figure 6-1), to calculate the annual time spent by every vessel and vessel type at each berth in the port.

The potential annual shore power demand SPx at berth x is calculated by summing the electricity required for each individual visit to berth x over the year, as shown in the equation below, where $AE(i)$ represents the auxiliary power demand for the vessel in berth visit i, and $t(i)$ is the total time at berth. 1 hour is removed for connecting/disconnecting.

$$SPx = \sum_{i=1}^{N} AE(i).*\,(t(i) - 1)$$

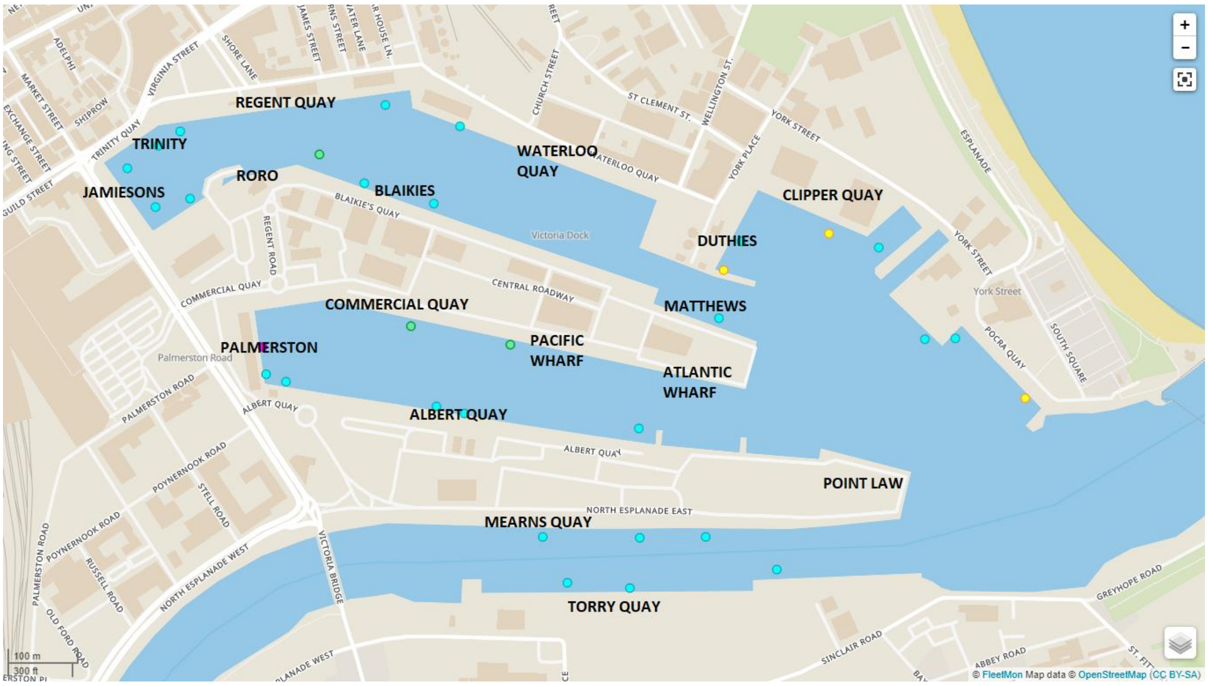

Figure 6-1 Port of Aberdeen, with main berths labelled

(circles represent berthed vessels)

Vessel data on auxiliary engine energy use at berth in the IMO's 4th Greenhouse Gas study (Faber et al., 2020) gives estimates for broad classes of vessel size and type, rather than individual vessels. Stolz et al. (2021) argue that the poor granularity of this data necessitates a different approach, and use a top-down evaluation using EUMRV data. However this is not appropriate at Aberdeen, as the main vessel classes under consideration do not come under EUMRV scope. Auxiliary power could be estimated from main engine power profiles, an approach taken by Kose and Sekban (2022), but here, energy usage data for individual ships is taken direct from ship operators, to ensure that the most accurate data on energy consumed is used for each ship and visit, an approach justified by its use in other studies (Kotrikla et al., 2017, Innes and Monios, 2018). Corrections are made to allow for the fact that not all ship electricity use at berth can be supplied by shore-grids, as it will take time to connect and disconnect ships to grids when they arrive and leave a berth. An estimate of 1 hour per visit is used here, following discussion with ship operators with experience of operational shore power systems in countries such as Norway. This value is also assumed in other studies, for example Martínez-López et al. (2021).

This analysis provides a power demand profile for each berth at the port, a prime input for assessing which berths might be most suitable for shore power deployment. Other factors affecting which berths might be most suitable for shore power include vessel demand profiles (for example which berths have long-stay, high-demand, frequent visitors), interest from ship-operators and available power supplies at each berth. This data was compared with values for available grid electricity supply, obtained through discussion with the District Network Operator. Finally, aggregate power demand is converted into values for pollutants, using standard emissions factors. These values are then compared with equivalent values from energy use from other aspects of port operation, to ascertain the relative importance for the port of tackling ships' at berth emissions. Further, reductions in these pollutants from adopting shore-power are quantified, and then monetised using standard methodologies, as used in other shore power studies (Zis, 2019, Ballini and Bozzo, 2015).

6.3.2 Technical option assessment

Discussion with the Port of Aberdeen highlighted three factors to determine a priority area for project development: high potential power demand, strong interest from ship owners and the associated port users, and sufficient shore-side power to obviate the need for major grid reinforcement.

The Port of Aberdeen stakeholders wanted a focus on the Albert and Mearns berths on the Point Law peninsula – there had been interest in shore power expressed by some of the oil companies that use the peninsula berths, and discussions with the DNO indicated that there would be sufficient spare power at the nearby substation to meet large potential demand.

In stage 2, detailed analysis of the most up-to-date ship movements in the year to October 2021 were combined with interviews with ship operators to ascertain their likely future use of the port: as recent movement patterns are not necessarily an accurate guide to future use. This analysis also looked at the Torry berths to the south of the River Dee, as the oil companies' use of these three berthing areas has varied over recent years, with some operators switching from one area to another. The analysis focus is on likely frequent-visit[8] vessels – on the basis that investing in ship-side infrastructure would only be worthwhile for frequent-visit vessels.

[8] Set here at >700 hours/yr

With a view of likely future demand profiles, site visits were used to ascertain appropriate locations and types of shore-power equipment, for example so as not to interfere with dock operations. Building on literature assessments of necessary system components (Costa et al., 2022, Pruyn and Willeijns, 2022), a process of stakeholder engagement with equipment providers, the District Network Operator (DNO), ship operators and the port elicited a short-list of costed technical options, through a series of interviews and a tendering process. This process of option identification follows that taken by Innes and Monios (2018), however this approach was then built upon by the use of multi-criteria analysis (MCA) to determine which combination of the short-listed options had the best-fit with the overall requirements of the port, using the linear weighted-average MCA approach advocated in the UK Government's Green Book guidance on project appraisal (DCLG, 2009). MCA assessments were performed for the three main components of the system: the shore-power housing, the ship-quay connection point, and cable management. The weighting of core parameters in the MCA was designed in collaboration with the Port of Aberdeen and set out in Table *6-3*.

Table 6-3 MCA weighting

	Weighting
Cost	20%
Maintenance	15%
Quality of design solution	10%
Inherent risk	15%
Supplier track record	10%
Impact on existing port operations	10%
Flexibility	10%
Lifetime/future proofing	10%

The combination of these assessments delivers a preferred option for a more detailed techno-economic case to be developed.

6.3.3 Economic assessment

Stage 3 constructs a new techno-economic model to calculate what levels of mark-up on grid electricity would be required to be charged to ship operators by the port for given ranges of values for different cost variables. This model was constructed according to standard methodologies on project appraisal as set out in the Five Case Model (HM Treasury, 2018) as part of the wider guidance within the UK Treasury Green Book (HM Treasury, 2022). These variables include the rate of return required by the port, project length, total capital costs, and the level of capital funding from Government, for given values for capex, repex, opex and inflation. This builds upon the analytic approach in the case-study by Innes and Monios (2018) by including multiple sensitivity tests performed on all parameters, and considering variations in the required rates of return by the port[9].

From both the port and ship-owner perspective, the port's required mark-up on electricity is a key parameter and a major barrier to project viability. Government policy to ensure this mark-up is acceptable to both parties is justified on the grounds that it would unlock wider environmental and social benefits that are not included in financial project appraisal. Such policies include subsidy, electricity taxation and carbon pricing. The interplay between these potential options is considered in the discussion section, elucidating a potential collaborative approach between port, ship operators and Government which in combination could lead to an economically viable project.

6.4 Results

6.4.1 Prioritising berths

Potential shore power demand at Aberdeen was calculated at 53 GWh/yr. This is broken down by vessel type in Table 6-4.

The CO_2 emissions from this 53GWh are almost 35,000 tCO_2/year, over 20 times higher than the CO_2 emissions from the ports' buildings, see Table 6-5. This dominance of ship emissions in port inventories mirrors findings at other ports, for example Gothenburg (Gothenburg Port Authority, 2021) and Chennai (Misra et al., 2017).

[9] The detail of this model is commercially sensitive, so we are unable to present this here.

Table 6-4 Potential shore power demand, by ship type

Vessel type	Hours at berth/yr	Shore power demand (MWh)	% of total shore power demand	Number of vessels	Hrs/yr per vessel	MWh/yr per vessel
Multi-Purpose Supply Vessel	127,539	31,650	60	176	725	180
Diving Support Vessel	9,941	8,281	16	18	552	460
Standby/Safety Vessel	24,103	2,772	5	84	287	33
Ferry	4,711	1,905	4	4	1178	476
General Cargo Vessel	7,044	1,663	3	120	59	14
Refined Oil Tanker	3,276	948	2	15	218	63
Ro/Ro Vessel	4,375	921	2	5	875	184
Research Vessel	3,215	855	2	10	321	86
Anchor Handler	2,809	709	1	15	187	47
Other vessel classes (16 types)	18,879	3,110	6			
Total	**205,892**	**52,815**				

(Strong candidate values shaded grey. Source: author analysis)

Table 6-5 CO_2 emissions in different parts of the port

	CO_2 t/yr	% total
Vessel electricity at berth	34,541	78.0
Vessel fuel in port transit	8,224	18.6
Building electricity use	435	1.0
Building gas use	1,071	2.4
TOTAL	44,271	100

(source: author analysis)

The economic viability of shore-power infrastructure depends upon the extent to which facilities will be used. Determining the best locations for infrastructure provision depends both on grid power availability, but also on the likely annual power demand from the vessels at those locations. Some vessel classes out of the total of 53GWh would be a lower priority – for economic or practical reasons – for a first wave of shore power installations. For example, although standby/safety vessels are in port the second longest time, their average power demand is very low. Similarly, although general cargo ships have the fifth highest time in port, and have high power demands, these vessels are very numerous and infrequent visitors, so the port would be relying on a large number of vessels having shore-power compatibility, in order for port-side infrastructure to have high utilization rates. Based on Table 6-4, four vessel classes stood out as priority candidates (see Table 6-6):

Table 6-6 Priority vessel classes for shore power

Priority vessel classes	Detail
Multi-Purpose Service Vessels (MPSVs)	This class represents 60% of all potential shore-power demand at Aberdeen. These vessels do not have very high power-demand (around 250kW), but they are very frequent visitors with long stays, leading to high annual hours at berth. A difficulty is that there are a large number of them – 176 in 2019 - with complex ownership and operator arrangements. Fitting 176 ships with shore-power capability would take time. Frequent-visit vessels should be prioritised within this group.
Diving Support Vessels (DSVs)	There are far fewer DSVs – just 18 – and they have high power demands (around 800kW) and long, frequent visits.
Ferries	Although ferries account for just 2% of all hours at berth, there are only 4 ships in this class, and the majority of those hours are concentrated in just two relatively high power-demand vessels.
Ro-Ro vessels	Similarly, only 5 vessels. Although these have lower power demand than the ferries, their frequent visits and long stays mean they are a good potential candidate, particularly as two of these vessels are also run by the same company as two of the ferries.

(Source: qualitative analysis of results in Table 6-4)

The breakdown of shore power demand by berth is set out in Table 6-7. The Albert, Torry and Mearns grouping of berths are prime candidates for shore power, with high power demand from MPSVs. Other berths such as Jamiesons, Regent, Blaikies and Trinity also have high demands from MPSVs and other vessels. However, these latter berths are characterised by visits from many infrequent-visit vessels. Albert and Torry by contrast tend towards a smaller number of more frequent visitors. These vessels are also contracted by a smaller number of shipping companies, such as Shell, Total and BP. This is preferable from the port perspective, as it requires negotiating agreements with fewer shipping entities. For similar reasons, the Clipper berth is a strong candidate - servicing a small number of large dive-support vessels – as is the RoRo berth for the two ferries Hrossey and Hjaltland.

Table 6-7 Potential shore power demand by berth

Port area	No. of berths	time (hrs/yr)	Shore power (MWh/yr)	hrs/berth	Shore power MWh/berth
Torry	6	26,669	6,427	4,445	1,071
Albert	7	24,307	6,033	3,472	862
Clipper	1	6,414	4,521	6,414	4,521
Regent	4	18,442	4,363	4,610	1,091
Blaikies	4	19,011	4,014	4,753	1004
Waterloo	4	15,170	3,774	3,792	943
Jamiesons	1	11,840	2,851	11,840	2,851
Trinity	1	10,929	2,707	10,929	2,707
Matthews RR	2	10,877	2,051	5,439	1025
Mearns	3	8,104	2,000	2,701	667
Pocra	3	7,239	1,889	2,413	630
RoRo	1	3,766	1,770	3,766	1,770

(Source: author analysis)

6.4.2 Feasibility study

Section 6.4.1's berthing analysis combined with the Port's positive engagement with the oil and gas operators using MPSVs focussed the detailed project development on shore power installations for MPSVs, at the Albert and Mearns berths on the Point Law Peninsula.

Further interviews with the oil and gas companies suggest that five main companies would, in future, use twenty frequent-visit vessels between them for a total 24,200 annual hours at berth, with a further eight companies using nine vessels for an additional 8,100 hours. These vessels' average power demand is 250kW, giving a plausible maximum shore-power demand of 7,500MWh/yr, displacing marine fuel oil derived electricity. This has two principal social and environmental benefits. First, it reduces the local noise and air pollution faced by ships' crew, dock workers and local residents, particularly NOx and particulate emissions. Second, it reduces greenhouse gas emissions, given the low CO_2 intensity from Scottish grid electricity. There are ethical and practical difficulties in ascribing a financial value to these benefits (Ackerman and Heinzerling, 2001), however Table 6-8 sets out these values using the standard methodologies advocated by the UK Government (BEIS, 2021c, DEFRA, 2022).

Table 6-8 Shore power project's environmental and social valuation

Social value addition	Lifetime value of benefit (Social Net Present Value) (£m)
Carbon abatement vs counterfactual	12.7
Air quality improvement vs counterfactual	6.8
Overall social value addition vs counterfactual	19.5

(Source: author analysis)

The multi-criteria assessment of the Ports' needs (see supplementary information: Chapter 8.4) concluded that the most appropriate design option for the Albert and Mearns berths is:

- A centralised shore power E-house, for transforming and frequency conversion equipment;
- Trenched low-voltage cabling connecting the E-house to above-ground quayside connection boxes;
- Manoeuvrable cable reels to link connection boxes to vessels;
- 7 x 500kVA connection points across the berths.

Decentralised systems allow power to be distributed with lower losses, however this benefit was outweighed by requirements for frequency conversion and transformation at each berth. In addition, a centralised power E-house has lower costs and reduced space requirements on a busy quayside. Above ground connection boxes were preferable to below-ground options on cost and ease of maintenance grounds. Their disadvantage is potential hindrance of quayside operations such as crane movements, but this problem can be obviated through choice of connection location. Manoeuvrable cable reels were more flexible than fixed cable reel options, with no cost penalty. Their disadvantage is slower connection and disconnection times, but this is less problematic for berthing profiles involving long vessel stays, as is the case at Albert/Mearns.

A schematic of this system is shown in Figure 6-2, with an overview of the system components shown in in Figure 6-3.

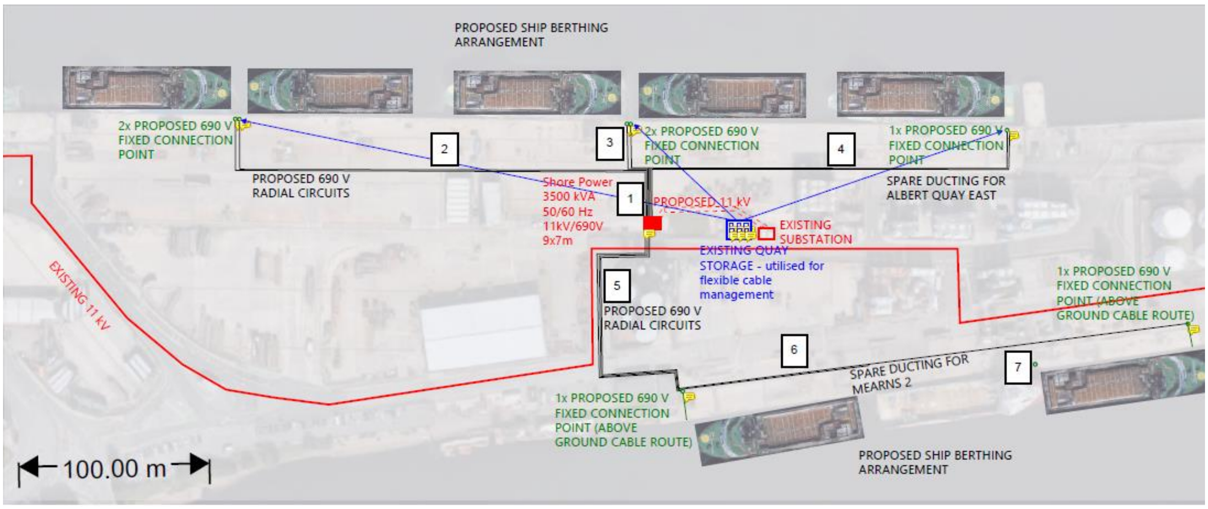

Figure 6-2 Schematic for shore power infrastructure at Albert and Mearns Quays

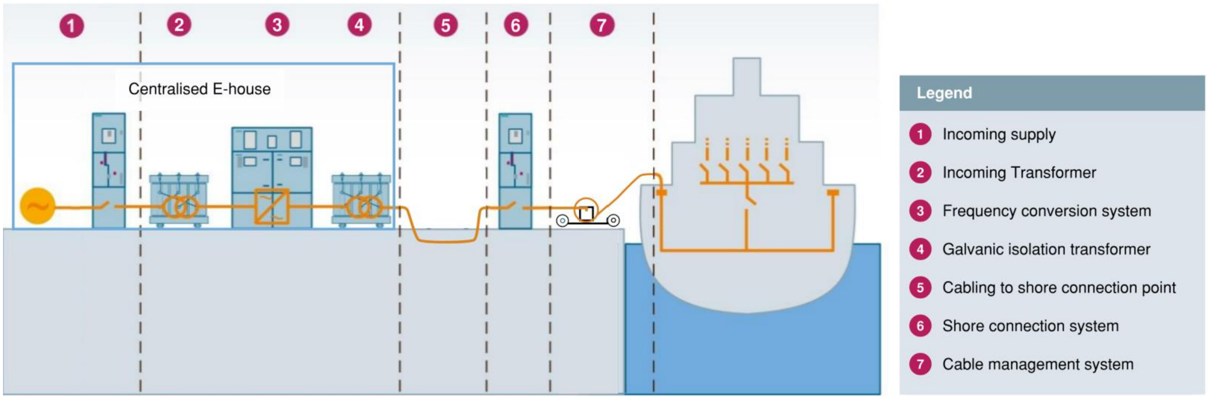

Figure 6-3 Components of proposed Aberdeen shore power system

Quotes obtained from various equipment providers help to ascertain values for total capex and annual opex. The baseline capital cost estimates for the project are £8m. This cost is broken down in Table *6-9*:

Table 6-9 Results of shore power capex analysis

Cost element	**Detail**	**£k**
Shore power unit	Centralised unit, outlet points, transformer, frequency converter, groundworks	2,750
Cable management	7x cable reel systems	680
Port side connection	7x port side connection boxes	250
Low voltage network costs	Trenching, duct and cable work around quayside	1,840
Network ancillary equipment	Cable protection systems	140
Cable storage building	8m by 8m steel structure with insulated cladding	135
Electricals	Upgrade to existing DNO mains electrical system	200
Design	Design fees for contractor at 2% of works value	120
Site set-up and management	Set at 11% of the works value	660
Contractor overheads/profit	Main contractor overheads/profit 10% of works value	600
Contingencies	10% of works value; minimum prudent allowance	600
Total		**8,000**

6.4.3 Economic viability

The port needs to recoup capital costs, via sales of electricity to ship operators. For a given price of grid electricity B (see

Figure *6-4* Factors affecting shore power economics for ship and port operators

), the port will need to charge an electricity price premium X to ship operators, in order for the port to recoup its financial outlay over a defined operational period. In deciding whether to switch to shore power, ship operators would compare this shore power price, of C=B+X, with the price A of electricity produced from its own auxiliary engines.

A critical issue in realising shore-power in the UK, and which will apply in other countries, is therefore the interplay between three prices: grid electricity price to the port, the port's required premium, and the cost of marine fuel oil (the latter determining the cost of electricity supplied by the ship's engines). This interplay is made more complex by the highly volatile nature of marine fuel oil prices, and to a lesser extent the volatility in grid electricity prices. For example, marine fuel oil (VLSFO) has seen a six-fold variation in price in between April 2020 and August 2022[10], with a high of $1,019/t and a low of $150/t. However, despite this large volatility, marine fuel oil has been consistently cheaper than UK grid electricity, in the range of £40-90/MWh[11]. Consequently, from the ship operator perspective, it would not be attractive to pay a large additional premium, given shore power is already more expensive than electricity generated from its own fuel oils. But, as shown in Table 10, port operators do need to charge a premium on top of the price of grid electricity, even if government funding is available, in order for the port operators to recoup their capital costs from investment in shore power.

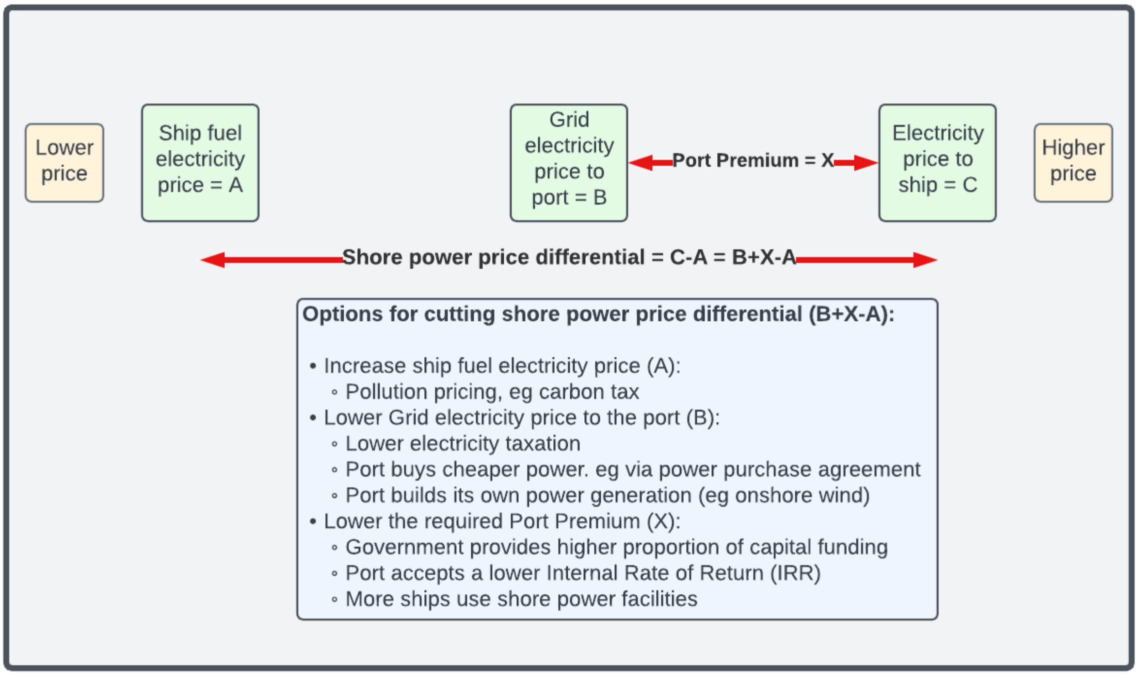

Figure 6-4 Factors affecting shore power economics for ship and port operators (source: author)

These issues are analysed in the techno-economic model, to ascertain the power premium the port needs to charge to ship operators, for differing values for parameters such as the Internal Rates of Return (IRR) for the project, shore power price, power demand and the level of Government capex support. Ranges of the necessary premium on top of the grid electricity price, to deliver a given IRR for the port and under different assumptions for the

[10] https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#_MGO
[11] See https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector for grid electricity prices, shipandbunker.com for ship fuel prices, with standard conversion factors.

percentage capital funding provided by Government, are set out in Table 6-10. For example for a 9% IRR, with 50% grant funding the required price premium would be £114/MWh (yellow cell in Table 6-10). This would give a total price to the ship operator (C=B+X) of £150+£114 = £264/MWh, if the grid electricity price to the port (B) is £150/MWh.

Table 6-10 Electricity premium required for different Internal Rates of Return and levels of Government support

Premium in £/MWh	% Government grant funding			
	25%	50%	75%	100%
6% IRR	123	92	61	29
9% IRR	156	114	72	30
12% IRR	194	139	85	32

(Source: author analysis)

Multiple sensitivity analyses were performed across all assumptions. The impacts of all sensitivities, relative to a base case of a 20 year project with 9% IRR, are show in Table 6-11. The greatest sensitivities are for fuel costs, capex, shore power sales price and annual power demand, with their impacts on the project's Net Present Value shown in Figure 6-5.

Table 6-11 Results of analysis of effect of sensitivities on required electricity price mark-up

Base case assumptions: Grant funding 50%, 20-year project length	Electricity price mark-up (kWh), compared with base case mark-up of £114/MWh	
Sensitivities:	Low (£/MWh)	High (£/MWh)
Grant funding 75% or 25%	72	156
Project length, 40 years/10 years	90	293
Power demand +/- 30%	91	157
IRR 6% or 12%	92	139
Capex costs -/+ 20%	97	131
Inflation +/- 1%	105	124
Opex costs -/+ 15%	113	115
Repex costs -/+ 15%	113	115

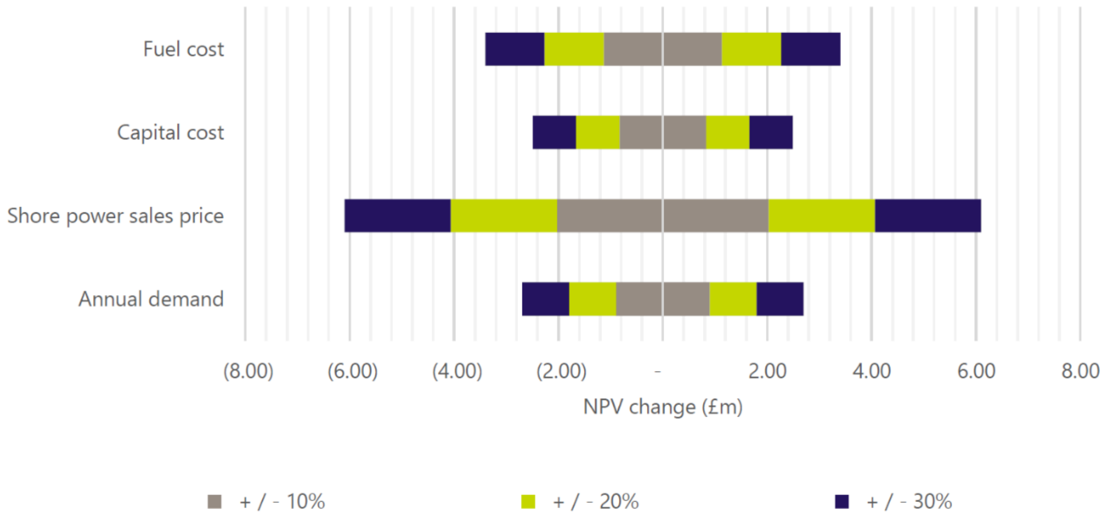

Figure 6-5 The effect of sensitivities on project Net Present Value

The social and environmental benefits of using shore power do not accrue to the Port – they are wider benefits not costed in the formal business-case. Overall, the social Net Present Value of the project is £19.5m (Table 6-8), compared with port capex of £8m. The project also modelled these benefits from the ship-operator perspective, comparing the electricity costs for vessels connected to a shore power network versus a counterfactual with electricity costs from burning marine fuel: over a 20-year project life-time, the carbon tax cost required to deliver equal Net Present Value between these two scenarios is £108/MWh.

6.5 Discussion

Grid electricity in the UK is £40-90/MWh more expensive than the power a ship could provide itself from burning marine fuel oil. A further premium needs to be added to the grid electricity price to ships, in order for the port to recoup its capital and operational costs such that shore power can be a commercially viable proposition. Table 6-10 showed a wide range in this required mark-up, from £29/MWh to £194/MWh, on top of grid electricity already being more expensive.

Clearly, from the ship operator perspective, this is not attractive. In the absence of regulatory requirements, a ship operator may accept some level of price premium, in order to meet corporate environmental or social goals. However this premium, and therefore the total price to ship operators, cannot be too high, or ship operators would simply not use shore power, and instead continue to rely on cheaper electricity produced from ship's fuel. And if ship operators baulk at high prices and do not use shore power, then demand for shore power falls. This would further weaken project economics, as Table 6-11 shows, raising the required premium further, making the project even less attractive to the ship operator – a vicious circle. This issue is pivotal: high utilisation rates are essential for port operators to improve project economics.

Previous studies of shore power economics tend to focus on one policy measure to improve project viability (Dai et al., 2019, Wu and Wang, 2020), an approach criticised by Zhen et al. (2022). This paper extends this literature by offering a novel contribution based on assessing combinations of potential policies. It sets out three categories of actions which could reduce the shore power price ship operators would be required to pay: i) reduce the price of grid electricity, ii) reduce the required premium, and/or iii) increase the price of marine fuel oils. Options for doing this are set out in Table 6-12, and these options and their combinations are then analysed.

Table 6-12 Options to improve project's financial viability

Lower price of grid electricity to the port:	Lower the required port premium:	Increase the price of electricity from ship's fuel:
1. Lower electricity taxation	4. Higher level of Government capital funding	7. Global carbon pricing
2. Port buys cheaper power, eg via a power purchase agreement	5. Port accepts a lower IRR	8. National/regional carbon pricing
3. Port builds its own power generation (eg onshore wind)	6. More ships use shore power facilities	9. Port charges vessels for not using shore power.

(Source: author analysis)

Two of the main options in Table 6-12, options 1 and 4 on electricity taxation and grant funding, are in the remit of the UK Government. The main grounds justifying such Government intervention is that the reductions in pollutants are a clear social benefit which would otherwise not occur. The costs of using marine fuel are externalities currently borne by society at large. Transforming marine fuels into electricity creates 25-40 more air pollution damage per kWh than using grid electricity (Faber et al., 2020, BEIS, 2021c, DEFRA, 2021)[12], and shore power also helps the Government achieve its strategic goals of mitigating climate change. Overall, the Aberdeen project would deliver lifetime carbon abatement benefits of £12.7m and air quality improvements valued at £6.8m, using standard UK Government valuation methodologies, offering a clear justification for Government policy support.

The Government can act in two main ways. First, grant funding is one of the options with the largest potential to reduce the level of required premium (Table 6-11), and has been necessary in all projects worldwide (BPA, 2020). This point also applies to potential shore power projects at other ports. Project economics at other ports will differ to Aberdeen, depending for example on the level of electricity grid reinforcement that might be needed, and different berthing profiles and power demands of visiting vessels. To account for this variability, the Government's policy support package for maritime decarbonisation could include a sliding scale of grant funding for shore-power, for example 50-80% - similar to rates seen in other parts of the world (BPA, 2020, Qi et al., 2020) - with projects with more favourable economics obtaining the lower end of the available grants. This suggestion is bolstered by the findings of Wang et al. (2022a) that required subsidy levels are lower at busy ports with higher shore power demand.

Second, the Government can implement taxation reform. UK grid electricity is much lower carbon than marine fuel. But it is expensive by European standards and faces taxes of around £50/MWh from policies such as Contracts for Difference, the Renewables Obligation, the Feed-in tariff and the Climate Change Levy. Electricity generated on ships from marine diesel oil on the other hand is untaxed by global convention, is very high carbon, and pollutes the local environment. Given that Government policy aims to internalise external costs, and deliver carbon reductions, these incentives are the wrong way round. The UK can start to address this market failure by removing environmental taxes from grid electricity used by ships, as Germany, Sweden, France, Denmark, Italy and the

[12] Using Faber 2020 for values for pollutant emissions per tonne marine fuel, DEFRA 2022 values for damage costs per tonne pollutant, and BEIS 2021b values for air quality damage costs per kWh electricity. Range depends on assumptions regarding proximity of populations to pollution sources

Netherlands have done (Bullock, 2022a). A precedent exists for this type of exemption in the UK: Energy Intensive Industries are not required to pay 85% of the costs of Contracts for Difference, Renewables Obligation and Feed-in-tariff policies (BEIS, 2022a).

Options 7 and 8 related to carbon pricing. The results section calculated that a carbon tax equivalent to £108/MWh would give shore power an equivalent NPV to using marine fuel oils. If £50/MWh had been removed from shore power via tax exemptions, then the remaining £58/MWh is equivalent to a carbon price of £89/tCO_2, which is around 100 Euros/tCO_2. There is an impasse at the IMO level on Market-Based Mechanisms, however the EU has recently introduced proposals to include maritime emissions in the EU Emissions Trading Scheme (EUETS). In early 2023, the EUETS price is around 100 Euros/tonne CO_2, indicating that it is possible in future that carbon pricing might have a major positive effect on shore power economics. This is of course dependent on the scope of the scheme. The UK is not part of the EU, or the EUETS. And even if it were, the size of vessels covered by the policy (>5000 Gt) means that for example at Aberdeen the majority of the vessels which might use shore power would not be covered by the policy.

There are also actions that the port operators can take (Options 2, 3, 5 and 9). The Port of Aberdeen can improve project economics by accepting a lower Internal Rate of Return (IRR). One way to do this is to choose a financial model where they take a greater stake in the project, essentially in-housing risk. An IRR of 9% is at the low-end of usual IRRs for UK port projects; Aberdeen's status as a Trust Port makes a 9% IRR a possibility. Similarly, assuming a longer project lifetime would improve project financial viability, but would also entail additional risk, given the relatively-new nature of shore power projects. Ports can also potentially improve project economics by building their own renewable power projects. The viability of this option will vary from port to port and country to country, and much shore power literature assesses the potential for renewable energy projects to complement shore power (Gutierrez-Romero et al., 2019, Prousalidis et al., 2017). However, at Aberdeen these options are at present limited given a lack of physical space. Sourcing Power Purchase Agreements may become a more viable option in future as greater numbers of offshore wind farms are built off the North Scotland coast. Individual port charges for non-use of shore power is not considered a viable option given that the dangers to port competitiveness mitigate against their introduction.

The ship operators can improve the financial case by accepting a higher price for electricity: paying a premium for provision of a less polluting energy source. This would be on top of the cost of ship-side installation of shore power equipment. These costs are typically lower than for ports, at around £80,000-£100,000 for a multi-purpose supply vessel. These costs would be borne by the ship owners, but passed on to the ship operators, for example in higher day-rates for vessel hire.

One of the non-economic barriers to shore power has been the "chicken and egg" problem whereby ship operators will not invest in shore-power, because they can't plug-in, and port operators won't invest, as ships cannot use it. This impasse requires greater collaboration between these entities.

The need for research into how improved collaboration can be delivered was a main conclusion of the shore power barrier review paper by Williamsson et al. (2022). One possibility to overcome both the economic and non-economic barriers is to reframe shore power as a three-way collaboration between ship operators, port owners and Government. In this reframing, a three-way compromise between these entities could be sufficient to get projects over the line in the short term. The port accepting lower IRRs, and the ship operators paying a premium for shore power electricity, could be seen as a quid pro quo for the Government providing capital funding and tax reforms. The Government's involvement is essential - without some level of capital funding, either the return on investment for the port would be too low for the project to be feasible, or the power mark-up would be too high for the ship operators to use the facility. In the medium term, increasing carbon prices at global or regional level could further improve project economics.

Overall, using the example above in Table 6-10, combined actions of port, ship operators and Government described above can deliver a financially viable project at Aberdeen. Assuming grid electricity prices of £150/MWh, then with Government funding of 75%, and a 9% IRR - requiring a premium of £72/MWh - and a removal of £50/MWh of taxes/charges related to environmental and social policies (BEIS, 2022c)[13], Aberdeen could provide shore-power at £172/MWh. This is higher than the assumed price for ship-fuel electricity

13 Medium industrial electricity consumer (2,000-19,999 MWh/year), value includes any taxes or charges relating to environmental or social policies but excludes VAT.

(£110/MWh), but within the range that vessels have been paying for ship-provided electricity in 2021-2022.

9% IRR is lower than is standard for port infrastructure projects in the UK. Consequently, we note that such an approach or similar involves a stake from all main stakeholders - port, ship operator and Government. The port is taking lower IRR, ships are paying a greater price, Government is providing financial and policy support. This collaborative approach would unlock the high net societal benefits that this shore power project can deliver.

A limitation of this study is that it was conducted against a background of major uncertainty around the future impact on shipping fuel oil prices of various incoming or potential market-carbon pricing mechanisms in the maritime sector, at the UK, EU and IMO levels. An avenue for future research would be to examine the extent to which this uncertainty negatively affects port and shipping operators' willingness to invest in shore power or other decarbonisation infrastructure investments.

6.6 Conclusion

Shore power projects are an important element of the necessary decarbonisation transition in shipping, but high capital costs and market distortions in favour of more polluting marine fuel oils are preventing its deployment. This case-study presents a novel analysis of the interplay between ship operator, port and national Government and the mix of policies which could improve project viability, supporting its deployment both in the UK and providing learning applicable in other geographical contexts.

Shore power is not necessarily the ideal solution to reducing emissions at all berths at all ports, highlighting the importance of carrying out detailed analysis of berthing patterns, ship energy demands and power availability to identify where the largest benefits are possible. Specifically, high utilisation rates are shown to be an essential pre-requisite to improve project economics.

In the longer-term, shore power projects will become financially viable if the international community introduces a strong global carbon price in the maritime sector. However, given the urgency for short-term cuts in greenhouse gas emissions from shipping, and need for emissions cuts from the existing fleet (Bullock et al., 2020) it is not sufficient to wait for international carbon pricing to make shore power project economics viable. Crucially, these projects are important and technically viable options for delivering carbon reduction now, and moreover, have added co-benefits of improving air quality while readying ports for a greater deployment of hybrid and all-electric vessels, and in the longer term, e-fuels.

Delivering these benefits, at Aberdeen and elsewhere, requires collaboration between ship and port operators, in addition to a supportive and clear policy environment from national Government - policy support on both capital funding and tax reform is essential to unlock shore power's benefits. Given the ubiquitous global nature of the failure to price carbon from marine fuels, government intervention of this nature will be needed, and justified, in other countries also.

Critically, a three-way collaboration between port operator, ship operators and national governments can unlock shore power's multiple benefits, generating the essential acceleration needed to align shipping's decarbonisation plans with the Paris Agreement's goals.

Chapter 7 Discussion and conclusion

This concluding chapter is in eight sections. Sections 7.1 to 7.4 summarise the main results for each of the papers in chapters 3 and 6. They set out the novel contributions made in each chapter, link their findings back to the existing literature, set out how this research has been disseminated in the context of ongoing policy deliberations, and prioritise one main avenue for further research. Chapters 3-6 analyse shipping at different levels – global, regional, national and local – Section 7.5 assesses the interlinkages between these levels in terms of governance. Section 7.6 investigates potential avenues for future shipping transitions research, against core research challenges set out in the broader sustainability transitions literature. Section 7.7 then summarises the main contribution and results of the thesis, and Section 7.8 concludes with some reflections on the four years of this PhD.

7.1 Carbon budgets and emissions reductions pathways for shipping

The novel contribution of Chapter 3 is demonstrating that achieving deep emissions reductions this decade is an absolute priority for the shipping sector. It shows that if the shipping sector does not reduce its emissions this decade, it would need to claw-back this lack of progress with more rapid decarbonisation in the 2030s. However, a delay of even a few years would dictate a rate of decarbonisation that is too rapid to be achievable, given the long asset lifetimes in the sector.

Previous literature has identified that more stringent targets than the IMO's current target of 50% reduction in shipping GHG emissions and zero emissions sometime this century are needed to be compatible with globally agreed goals on climate (Traut et al., 2018, Smith et al., 2015). Building on this, Chapter 3 makes a novel addition to the literature by focussing on the concept of global carbon budgets to spotlight the critical issue of the shape of the pathway followed towards any given long-term target, with pivotal implications for near-term action. It also updates previous work (Traut et al., 2018, Smith et al., 2015) to take into account of advances in ship emissions methodologies and the most up-to-date climate science, emissions and shipping data.

Chapter 3 establishes that climate change is a problem of cumulative greenhouse gas emissions, not end-points. It is cumulative emissions over time that determine global temperature rise. Relying solely on a long-term zero emission target masks the fact that there are multiple possible pathways to zero emissions that would have very different cumulative emissions, and hence very different temperature implications.

Figure 7-1 shows data from Chapter 3 for international shipping's contribution to tackling climate change. It shows red, yellow and green pathways each with the same cumulative emissions - and hence same effect on temperature - equivalent to a 50% probability of keeping temperature rise to below 1.5°C. These pathways show different rates of transition over time. Chapter 3 highlights that if emissions reductions in the 2020s continue to be slow (the red line in Figure 7-1), then emissions reductions in the 2030s would need to be more rapid to be compatible with the Paris Agreement to limit global heating to 1.5°C. Chapter 3 argues that the remaining carbon budget for shipping is now so constraining that if emissions reductions are slow throughout the 2020s, then the required transition in the 2030s would be untenably rapid. Table 3-3 shows that delay until 2030 would then require a full transition in 8-11 years, well under half the average ship lifetime of 25 years.

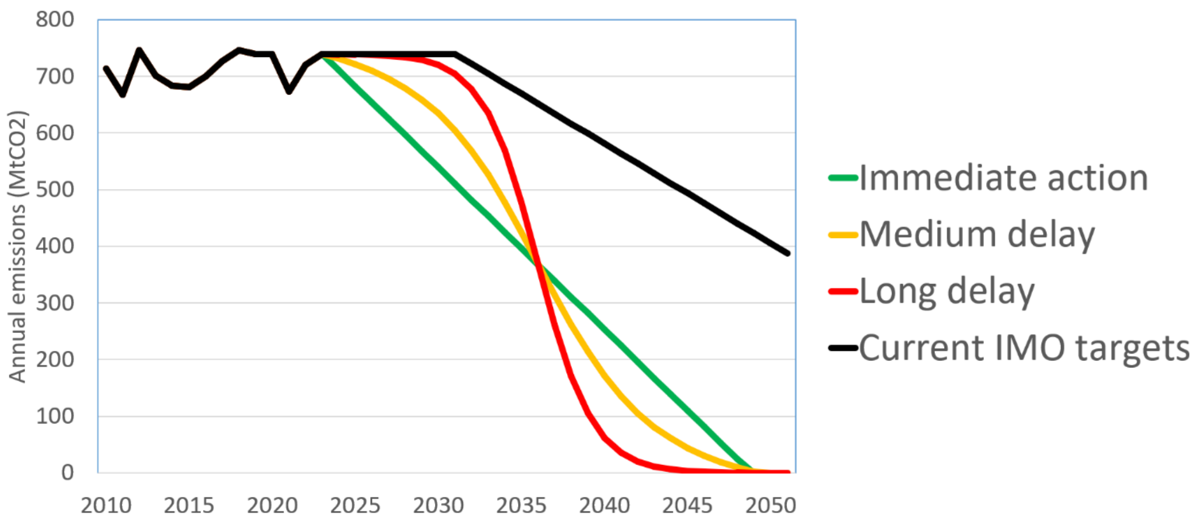

Figure 7-1 IMO's current targets compared to Paris-compatible 1.5 C pathways (2020 baseline)

Source: data in Chapter 3.

Chapter 3 concludes that not only does shipping need to reach zero CO_2 emissions before 2050, it needs to make around 34% cuts by 2030. This is in stark contrast to the current 2030 IMO target, which is equivalent to emissions remaining constant at 2008 levels. A limitation (acknowledged in Chapter 3) is the focus on CO_2, rather than all greenhouse gases, however the 1.5° trajectories are very similar, given the 98% dominance of CO_2 emissions in shipping greenhouse gas emissions. This issue is returned to in Section 7.5 on further research.

Figure 7-1 shows the inadequacy of current IMO targets (black line) compared with 1.5°C pathways. This PhD started in 2019, the year after the initial IMO climate change strategy was published. A core aspect of the work in this PhD has been to disseminate its research into ongoing IMO processes, ahead of the strategy revision in 2023.

The findings presented in Chapter 3 have been disseminated widely to global and national policy makers, with the aim to inform the strategy's revision, due at MEPC 80 in summer 2023. They have been used as an input into national and international decision-making processes, for example being cited in the UK Government's October 2022 paper to the IMO (IMO, 2022c) and the Science Based Targets Initiative's report on shipping targets (Bonello et al., 2022), and used as the basis for IMAREST's 2021 submission to the Intersessional Working Group on Reduction of GHG Emissions (IMO, 2021a), their follow-up 2022 submission (IMO, 2022a), and as the basis for the targets advocated in a consortium Maritime Review on shipping targets to the UK Government ahead of the IMO's strategy review (Smith et al., 2022a).

When its results were first disseminated, Chapter 3 presented an ambitious perspective on emissions reduction. Today it is becoming more widely recognised that the IMO's target of a 50% reduction by 2050 is insufficient, and that a zero or net zero target by this time or earlier is closer to what is required to be Paris-compatible, with the IMO committee at MEPC 77 in late 2021 "*recognising the need to strengthen the ambition of the Initial IMO GHG Strategy during its revision process*" (IMO, 2021d). The majority of nation submissions to the latest IMO MEPC meeting, MEPC79 in December 2022, called for stronger 2050 targets, nations such as Japan and the Marshall Islands have called for interim 2030 or 2040 targets to help ensure the overall strategy is compatible with the Paris climate goals (Smith et al., 2022b, IMO, 2022b), and in February 2023 Canada, the USA and the UK submitted a paper to the IMO calling for GHG reductions of at least 37% by 2030 and 96% by 2040 (IMO, 2023b). The pivotal decisions on new targets will be taken at the IMO MEPC80 meeting in July 2023. Chapter 3 concluded that "*it is time for the IMO to grasp the nettle of what 'at least' means in its target setting and face head-on the stark gap between what it is currently proposing and what is needed to be Paris-compliant*".

Beyond the issue of global carbon budgets and pathways for the shipping sector assessed in this thesis, further research could usefully analyse national contributions towards shipping's climate goals. National governments have responsibility for domestic shipping emissions. Traditionally international shipping emissions are deemed to be the responsibility of the IMO (although this is disputed (O'Leary, 2022)). However, the need for polycentric governance in shipping implies that front-runner national governments can also usefully put in place policies to reduce their appropriate share of international shopping emissions too, complementing work at IMO.

Methods for ascribing a share of international shipping emissions to nations have however two main difficulties. First, how to split global shipping emissions into international and domestic components is contested. The IMO 4th GHG study recommends a change that would fully align reporting with the requirements of the IPCC guidelines and has the effect of assigning a greater proportion of global shipping emissions to domestic shipping but this has not yet been agreed by the IMO council. Second, how to assign international emissions to nations. Currently, many nations do this by reporting emissions based on their international bunker fuel sales. This is inaccurate, for example it will distort the contributions of countries who have major bunkering ports, such as Rotterdam and Singapore. However, alternatives have different problems, with multiple complexities and no clear-cut conclusions (Gilbert et al., 2010, CCC, 2011, Selin et al., 2021). A pragmatic approach would be to align with emerging emissions reporting (eg EU MRV) and policy (eg EU ETS), which would entail measuring each voyage's emissions and splitting equally by departure and destination country. However, there remains a large research agenda to consolidate understanding of appropriate assignment of emissions between domestic and international, and how to split international emissions by country, and how such approaches could be best aligned with emerging policy responses to deliver on Paris-compatible pathways.

7.2 Committed emissions and the existing fleet

The novel contribution of Chapter 4 is its use of the committed emissions methodology to show that to meet 1.5°C pathways, multiple measures applied to the existing fleet will be needed in the 2020s. These measures include slow steaming, operational practices, fuel blending and shore power. A sole focus on new fuels is insufficient for shipping to play its part in meeting overall climate goals.

Having established the rate and extent of change needed in Chapter 3, Chapter 4 examines what technology and practice changes are required for 1.5°C pathways, by estimating the "committed emissions" from existing ships. Committed emissions is a widespread concept used in the literature (Davis et al., 2010) for other sectors such as power (Pfeiffer et al., 2018), and in the transport sector generally (Tong et al., 2019), but it had not been applied specifically to shipping before. 'Committed emissions' represents the future pollution from infrastructure's remaining operational-life; this is a particularly important concept in shipping, because of ships' very long-lifespan. As set out in Chapter 4, a new vessel ordered today will still be in operation in 2050, and the turn-over of the global shipping fleet is very slow. Chapter 4 made three main points. First, it demonstrated quantitatively that the committed emissions from existing vessels in the EU fleet would exceed Paris-compatible carbon budgets, and that these budgets would be breached even further due to new ships built in the 2020s which would also run on fossil fuels. Second, it showed that even with rapid deployment of zero-carbon fuels in new ships from 2030, and also with the retrofitting of existing ships to use these fuels, carbon budgets would still be breached (Table 4-9). Third, however, it set out that if extensive operational measures cutting the energy required to transport a tonne of product were applied to existing ships in the 2020s, as well as the introduction of low-carbon fuels, then it is still possible to stay within Paris-compatible carbon budgets.

These insights have major implications for the current focus of shipping policy on climate change. Section 2.5 set out four options for reducing shipping's cumulative emissions (repeated below in Figure 7-2)

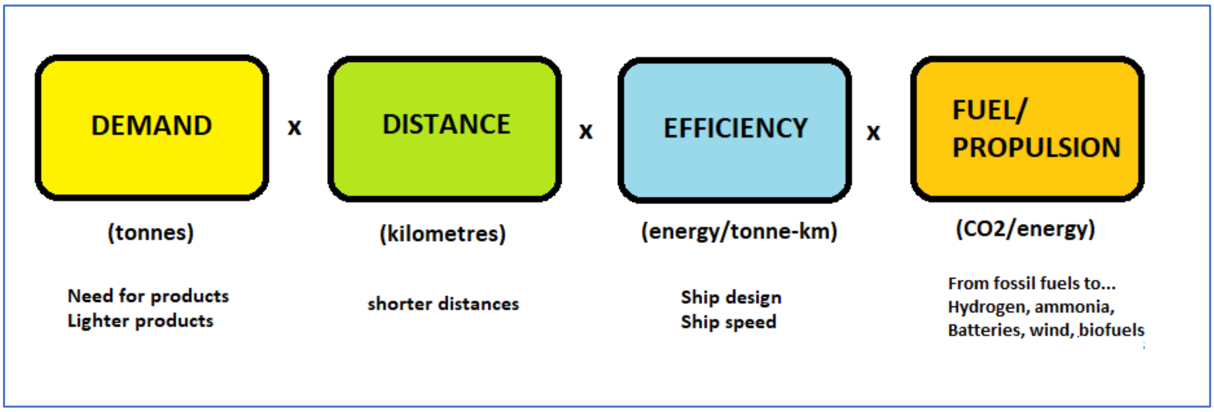

Figure 7-2 Four options for cutting emissions from shipping (source: Fig 2-4)

The first two options of reducing demand or distance are not currently on the agenda of the IMO or the wider industry as potential options. Chapter 4 demonstrates that although strong measures on option four on fuels are essential, they are not sufficient, and only scale-up beyond 2030. On option three on efficiency, the IMO is working through a detailed and complex set of policy measures[14] aimed at improving the energy efficiency of existing and new ships in the decade to 2030. However, these measures are all designed around meeting the IMO's target to improve energy efficiency by 40% by 2030. This energy intensity target in combination with the sector's expected growth, leads to no anticipated overall fall in the sector's emissions by 2030. However, Chapter 4 demonstrates that it is pivotal that operational measures deliver deep cuts in the emissions of existing ships in the 2020s. Chapter 3 set out the need for a strong target for 2030. To address the committed emissions difficulty set out in Chapter 4, the IMO will also need to set a far stronger 2030 carbon intensity target, and revise its Carbon Intensity Indicator policy accordingly. If this does not happen, then the committed emissions from existing vessels would be too high to be Paris-compatible, requiring either an unprecedented short-term scrappage programme, or a reduction in demand, if it is to play its fair part in the mitigation challenge.

The global lack of emphasis on emission reduction this decade is mirrored in UK shipping policy. The UK could be said to be one of the more progressive nations within the IMO, for example having co-authored a 2021 paper in the run up to MEPC 77 (IMO, 2021b) calling for the IMO to set 2030, 2040 and 2050 targets consistent with a 1.5°C aligned pathway. It also

[14] EEDI, EEXI, SEEMP and CII – see footnote 5 section 2.5

has one of the world's first national climate mitigation strategies for the shipping sector. However, this strategy also has a focus on the long-term, and there are explicitly no short-term targets, implying – in line with the global results for Chapter 3 and 4 – that the UK's overall cumulative shipping emissions would breach 1.5°C cumulative carbon budgets. The UK's maritime strategy assumes no carbon mitigation in the 2020s and an overwhelming focus on the later deployment of ammonia to deliver the 2050 end-goal, meaning that there is little political imperative to deliver policy to support other, faster means of carbon reduction in the sector in the 2020s. This point is further reinforced by the 2022 UK Government consultation on a strategy for the UK's domestic maritime decarbonisation, which excludes pathways with emissions reductions in the 2020s (Department for Transport, 2022d).

The analysis in Chapter 4 and its conclusion of the need for emission mitigation measures applied to existing vessels this decade, has been used in inputs to the UK Government's strategy development around maritime decarbonisation, such as the 2022 Course to Zero consultation (Bullock et al., 2022b), in submissions to UK Parliamentary Select Committee inquiries into maritime and transport decarbonisation (Gallego-Schmid et al., 2021, Larkin et al., 2021), and has been cited by the UK Parliamentary Office for Science and Technology and in the IPCC's 6th Assessment Report (UK Parliament, 2022, IPCC, 2022a).

Chapter 4 is the first paper to consider the committed emissions in existing shipping fleets. It focussed on operational measures and deployment of new fuels as the prime means to reduce these committed emissions. Recent research by Mahmoudi et al. (2023) is focussing on the practical contribution of retrofit options for decarbonisation, but a further useful avenue for research would be to assess the potential for reducing committed emissions through the early retirement of high-carbon vessels, and how such measures could be aligned with broader sustainable development goals. This is particularly important given the current tendency for old (and more polluting) ships to be resold to serve markets in developing countries, and for ships to be scrapped on beaches under desperately poor conditions for workers in countries such as Bangladesh and Pakistan.

With the scale of the challenge made clear within the first two papers, measures that are deployable this decade are required. One such measure is shore power, to be discussed in the next section.

7.3 Barriers to UK shore power deployment

Chapter 5's novel contribution is two-fold. First, it combines the Technical Innovation System and Multiple Streams Approach frameworks in the shipping transitions literature for the first time. This analysis shows clear economic barriers to shore power deployment in the UK, and that political barriers are preventing the introduction of policy solutions that can address them. The analysis also identifies barriers to collaboration between actors within the sector. Second, it uses insights from the Punctuated Equilibrium framework to suggest that three recent shifts in UK shipping policy venues could help address these multiple barriers – by increasing collaboration between innovators across the shipping sector, creating more effective alliances lobbying for policy change.

Chapters 3 and 4 make the case that mitigation measures are urgently required in this decade. Shore power is an option that can help deliver on more ambitious 2030 targets: it is a mature technology which can be deployed rapidly. However, shore power's global deployment is slow. The existing literature points to a range of primarily economic barriers to its uptake (Williamsson et al., 2022), that can be addressed through policy interventions. However, the literature reviews in Chapters 2 and 5 highlight a gap in the literature on why in practice these barriers continue to be difficult to overcome. The transitions literature offers valuable tools for analysing change in the shipping sector, but studies to date tend to either take a global or a very local focus and concentrate on analysis of geographic areas where there have been positive changes – such as Scandinavia. There is comparatively little shipping transitions research to date analysing the geographical area of the nation-state, and in particular in nations where transition is comparatively slow and blocked, compared with the more advanced nations such as Norway.

The absence of UK shore power deployment highlights the practical implications of the current policy focus on long-term targets, set out in sections 7.1 and 7.2. Chapter 5 established that there is broad consensus within the UK shipping sector on the need for action on climate change, and policy to support this. In addition, there is support in the UK from industry stakeholders for shore power as an option to cut both greenhouse gas emissions and tackle air pollution. However, shore power in the UK struggles financially to compete against incumbent marine fuel oils, which receive major tax exemptions. Consequently, in the UK there is no protected "niche" (using the terminology of the Multi-

Level Perspective, section 2.2.1) in which shore power can grow. Because the UK's Maritime decarbonisation strategy does not have clear emission reduction targets, particularly short-term ones, there is no strong imperative from within the Department for Transport to develop policies to allow shore power to compete. Chapter 5 used the Technological Innovation System (TIS) framework to explore the weak points in the technological innovation system for UK shore power, in combination with a political and policy analysis, using the Multiple Streams Approach (MSA). This shows that although policy packages to accelerate shore power are identifiable, the greater problem is in their adoption and implementation, due to blockages within UK shipping policy making, and a relative lack of political pressure to address them. The main barriers to shore power and policy interventions to address them are summarised in abridged form in Table 7-1.

Table 7-1 Summary of main UK shore power barriers and interventions

Barriers to shore power deployment
High capex costs for port and ship operators coupled with lack of grant funding
High levels of taxation on land-side electricity coupled with untaxed marine fuel oils
Weak/mistrustful relationships between port and ship operators, and with DNOs
Shipping advocates having low political power
Energy not being a core business area for ports
Interventions to accelerate shore power deployment
Capital funding for projects, particularly for ports
Introduction of carbon pricing and/or reductions in land-side electricity taxation
Collaborative cross-industry working groups on smart-grids and sharing shore power best practice
Government provision of one-stop information service
Development of a zero-emission-at-berth regulatory standard to drive demand

(Source: abridged from Table 5-3, Table 5-4 and section 5.5.2)

In the UK, the relative lack of power of the shipping segment of the wider transport sector within the Department for Transport (DfT), and of the DfT in relation to the Treasury, makes it difficult for shipping policy to be a political priority. This, combined with the relative lack of collaboration between potential port and ship operator advocates to pressure Government for greater action, means that stronger shipping decarbonisation policy is hard to deliver. As a result, there is insufficient political pressure for policy change. However, Chapter 5 highlights that a "window of opportunity" may be opening for greater action in shipping in general terms, both at national and global levels, with major policy reviews at both scales due in 2023.

For shore power, Chapter 5's use of TIS to assess weaknesses in system function, combined with the MSA analysis of politics and power, enables it to make a novel contribution by highlighting ways in which the national window of opportunity in shipping might be extended. This uses the concept of "punctuating the equilibrium", as set out by Jones and Baumgartner (2012), as means to accelerate transition.

This acceleration can occur by reframing an issue, or by shifting policy venues where decisions are taken. Chapter 5 suggests that reframing could occur for shore power by casting it as a solution that tackles two problems together – that of rising greenhouse gas emissions and local air pollution – with the imminent potential for policy integration via the refresh of both the Clean Maritime Plan (climate change) and Clean Air Strategies for ports (air quality).

Chapter 5 also suggests that there are three potential ways in which new policy venues could open up for shipping decarbonisation more generally in the UK, and not just for shore power. First, the formation of the new UK Shipping Office for Reducing Emissions (UK-SHORE) unit, which could mirror the success of the similar UK Office for Zero Emission Vehicles, which has overseen the accelerated deployment of electric vehicle charging infrastructure. Second, the inclusion of international shipping emissions in the UK's formal carbon budget process, requiring greater formal scrutiny from the Climate Change Committee. Third, the potential for much greater collaboration between port, ship operators and other maritime actors as a consequence of the extension of the Clean Maritime Demonstration Competition.

Chapter 5 highlights that greater collaboration between maritime actors is pivotal both for successful project delivery, and for improving advocacy to policy makers, which is currently less successful compared with other transport sectors such as aviation and roads.

The methodological approach taken in Chapter 5 is a novel contribution to the literature – combining the TIS and MSA frameworks for the first time. It is suggested here that the use of more than one framework is certainly an advantage – it allows different perspectives to be obtained upon undoubtedly complex problems. The use of MSA is considered here to be a worthwhile adjunct to more widely deployed frameworks such as TIS – it helps to foreground the pivotal issues of politics and power within sustainability transitions.

However, other frameworks are available – future studies might combine TIS with the use of Historical Institutionalism (Lockwood et al., 2017) for example, or as flagged in Chapter 5, the issue of heterogeneous actor motivations is relevant at all levels of the shipping regime, and so the Dynamic Capabilities approach of Teece (2007) might be appropriate in further shipping transitions studies, by assessing different ways in which actors might be motivated to act on climate change, as being pioneered by Stalmokaite and Hassler (2020).

The results of Chapter 5 have been disseminated widely to UK policy makers (Bullock, 2022b) and within the port and shipping sectors (Bullock, 2021), and is cited in the DfT's call-for-evidence on shore power (Department for Transport, 2022a), and in the Climate Change Committee's 2021 annual progress report (CCC, 2021).

Regarding potential further research, Chapter 5 showed that it in the UK it is difficult to implement policies on shipping due to insufficient political pressure in favour of their implementation, and strong blocking forces within UK Government. This mirrors the situation in other parts of the UK decarbonisation debate – the UK's Climate Change Committee states that policies across multiple sectors are inadequate to meet the UK's carbon budgets (CCC, 2022). This suggests there is a cross-sector priority in the UK climate mitigation debate for research, building on analyses by Averchenkova et al. (2021), Lockwood (2021) and Gransaull et al. (2023), into how UK political and institutional barriers to adoption of climate policies can be overcome, in all sectors, not just shipping. The problem is not availability of technology or potential policies.

A second research priority concerns shore power's potential to enable the wider electrification of shipping, particularly short-sea shipping. A recent paper by Kersey et al. (2022) argues that past assessments of the potential for ship electrification have relied on assumptions of high battery costs and low range, which are now very outdated. They argue that electrification of container vessels is now economical on routes up to 1500 km, a range that includes six of the world's top ten maritime trading routes (Shanghai-Busan, Felixstowe-Rotterdam, Rotterdam-Antwerp, Felixstowe-Antwerp, Antwerp-Hamburg, Port Kelang-Singapore). This suggests that a strong candidate for further research is in assessing, for example, the potential for electrification of North Sea container and general cargo shipping, learning from the increasing roll-out of electric ferries in Scandinavia.

7.4 Deploying shore power in practice: Aberdeen shore power

The novel contribution of Chapter 6 is to assess, for the first time, the combination of economic policy instruments that would be needed to make a shore power project economically viable, in the ongoing absence of regulation or a strong carbon price. It emphasises the critical role for a three-way collaboration between port operators, ship operators and national Government, with capital funding and tax incentives being essential for project viability. A further contribution is the identification of a three-stage process for assessing project viability, and methodological improvements in how to conduct these stages.

Chapter 5 highlights that economic issues are a core barrier to UK shore power deployment. Chapter 6 is a case-study of how these economic barriers apply to ongoing shore power project development, highlighting the critical polycentric nature of policy-making affecting shipping projects. The shore power literature's focus on economic issues has tended to emphasise making an economic case for shore power projects by putting a price on the societal benefit of averted air pollution and climate change damages (Piccoli et al., 2021). However, the practicalities of what economic support measures are necessary to make projects financially viable is a gap in the literature that Chapter 6 addresses.

The analysis in chapter 6 identifies a range of potential interventions to improve shore power's viability, set out in Table 7-2. Options 2,3 and 9 are less feasible at Aberdeen, but the paper concludes that national Government policy support on taxation and funding (options 1,4) can unlock project viability, with national or global carbon pricing being a longer-term supportive action. These issues are discussed briefly below Table 7-2.

Table 7-2 Options to improve shore power project viability

Lower price of grid electricity to the port:	Lower the electricity premium ports need to charge ship operators:	Increase the price of electricity from ship's fuel:
1. Lower electricity taxation	4. Higher level of Government capital funding	7. Global carbon pricing
2. Port buys cheaper power, eg via a power purchase agreement	5. Port accepts a lower IRR	8. National/regional carbon pricing
3. Port builds its own power generation (eg onshore wind)	6. More ships use shore power facilities	9. Port charges vessels for not using shore power.

(Source: based on Table 6-12)

Chapters 6 and 5 were both clear that the relative high price of grid electricity compared with marine fuel oil is a major barrier to economically viable UK shore power projects. This price difference is caused by high levels of taxation on UK grid electricity, compared with no taxation – by global convention – on marine fuel oils. Carbon pricing for shipping sector fuel has been discussed on and off over the years at the IMO since the first proposals were mooted in 2008, but an actual implemented policy appears to be many years away still – even a modest proposal for a \$2/tonne fuel to fund R&D failed to progress at the IMO's MEPC 78 meeting in June 2022 (ICS, 2022). This R&D proposal would have been equivalent to a carbon price of less than \$1/tCO_2, compared with the average EU ETS carbon price in 2022 of 80 Euros/tCO_2 (Ember, 2023), or the \$250-300/tCO_2 levy proposed by the shipping logistics company Trafigura as necessary to see widespread deployment of low-carbon fuels (Trafigura, 2020).

In response to this lack of progress, the EU has decided to take unilateral action, and plans to include international shipping emissions into its emissions trading scheme (European Council, 2022). Since Brexit, the UK has set up its own UK ETS scheme (BEIS, 2022b), but although this is aligned with the EU ETS in some ways, its proposals for maritime are weaker. A consultation in Spring 2022 (UK Government, 2022) proposes to only include some of the UK domestic shipping emissions in the UK ETS – the proposal argues: "*We are not considering policies for decarbonising international maritime in this consultation but* *continue to fully support the work of the International Maritime Organization (IMO) to tackle global shipping emissions"* (p103*).* This approach matches that in the UK's July 2021 Decarbonising Transport plan – it focusses primarily on domestic emissions, leaving the UK's international shipping emissions to be dealt with at IMO level, despite the decision in June 2021 to formally include the UK's share of international shipping emissions in the UK's carbon budgeting process (UK Government, 2021a).

In some respects leaving international shipping emissions to the IMO is inconsistent with other shipping decisions the UK has taken, for example the UK's championing of the multi-lateral "green corridors" Clydebank Declaration at COP26 (UK Government, 2021b). But consistency aside, the practical effect is that there is likely to be a weak carbon price for most of UK-related shipping. For UK shore power and other UK maritime decarbonisation options then, the failure so far of efforts to set a carbon price on marine fuels at an international level, combined with the unwillingness to act at UK level on carbon pricing for shipping, is problematic. Carbon pricing is a core means to improve the economic viability of shore power projects, but the UK – unlike the EU – is leaving this option primarily to the IMO. Unless there is a breakthrough on market-based mechanisms at this Summer's MEPC 80 meeting, there is low likelihood that the IMO will introduce carbon pricing at levels that would positively affect project economics in the timescales required for shore power to play the part it can do in meeting the Paris targets.

In improving the UK's shore power economics, the other options are for the UK Government to provide capital funding, and to act on national electricity taxation. However, as Chapter 5 discusses, these options are difficult in the current UK political context for shipping. Both options cost money. The Treasury is the key decision-making body, and the Department for Transport would need to persuade the Treasury of the political and economic merits of measures on shipping and climate change. Within the Department for Transport (DfT), shipping is a relatively under-resourced and less powerful sub-sector than rail, aviation and roads, who all have strong and very well-resourced external lobby organisations, as well as a greater staff capacity within the Department itself. Shipping's climate and air pollution impacts are also less visible to the public than in other more high-profile transport sectors such as aviation and road transport, so there is less external pressure from civil society on the Government to address shipping's climate emissions. Overall, the DfT has limited political capital in debates with the Treasury, and what little it has is more likely to be spent proportionately on these other transport modes. The 2022 DfT call-for-evidence document on policies to support shore power (Department for Transport, 2022b) did not even include capital funding as one of the possible options, despite every shore power project worldwide having received national or regional funding support.

Chapter 6 concludes that a three-way collaboration between port operator, shipping operators and the Government can make individual shore power projects financially viable, even in the absence of strong carbon pricing. This builds upon the work of Williamsson et al. (2022) who identified clear economic barriers to shore power deployment, with Chapter 6 analysing how these barriers can be overcome. It also builds upon the tendency in the literature on the economics of shore power to have a narrow focus on single policies – Chapter 6 elaborates how policy combinations can deliver improved project viability. The results from this research have been disseminated to policy makers through a joint submission with the Port of Aberdeen and Buro Happold Engineering (Bullock et al., 2022a) to the UK Government's 2022 call-for-evidence on shore power.

On further research, background interviews for Chapter 6 and Chapter 5 highlighted the growing belief among industry stakeholders that port-wide electrification strategies are likely to be necessary in future. Shore power would be just one element of such strategy, alongside ports generating their own renewable electricity, having large battery storage facilities, electrifying their port-operations (gantries, cranes etc), and providing charging facilities for visiting vessels, lorries, vans and cars, all requiring sophisticated electricity management software services for balancing imports, generation, use and exports of electricity. This would elevate energy and electricity management to being a core component of a port's function, rather than a second or third order concern as is mostly the case at present. Research is ongoing on the technical requirements of such a transition (Alzahrani et al., 2021, Sadiq et al., 2021), effectively making ports smart green energy hubs. However, the experience from Chapters 5 and 6 is that cultural factors around collaboration are likely to be an impediment to this transition, implying that further research is necessary to ascertain how District Network Operators, port operators, vessel operators, local authorities and others can work together to deliver these new models.

7.5 Linking global, national, and local results

The value of the multi-scalar approach taken in this research is that it reveals a common thread - that greater co-ordination is needed between three levels of shipping governance, at local, national and international levels. This mirrors the suggestion by Gritsenko (2017) that such a poly-centric approach is required in shipping. However, at present instead of coordination, in shipping the existence of the potential for other levels to enact policy is used as a justification for inaction. At IMO level, climate-progressive nations blame blocking nations for the slow pace of IMO policy making, however the same climate-progressive nations – with the exception of the EU – are not prepared to introduce measures of their own. In the UK – a relatively progressive nation on shipping and climate change – the Department for Transport will only countenance measures that affect domestic shipping emissions, with action on international shipping emissions deferred to the IMO, including the pivotal issue of carbon pricing (UK Government, 2022). Further, the UK has no pathways that involve any shipping emissions reductions this decade, counter to the analysis in Chapter3 of what is required to be Paris-compatible. It is apparent from chapters 5 and 6 that given the current focus of policy deliberations, there is little evidence to suggest that UK Government maritime decarbonisation policies and strategies will deliver a sufficiently rapid emissions reduction pathway for Paris-compatibility.

Nevertheless, leaving action to the IMO is fraught with danger, given for example the IMO's repeated failure to introduce market-based measures for carbon pricing. The IMO GHG strategy revision in 2023 is likely the last chance for stronger targets and policies such that shipping can make a Paris-compatible contribution to tackling climate change.

Chapter 5 suggests that this issue of actors preferring to defer responsibility for climate mitigation to entities at other tiers of governance does not just exist between national and international levels, but also within the more local level, such as between industry entities who will need to collaborate more to make decarbonisation a reality. For example, as shown in Chapter 5, rightly or wrongly, ports often blame the lack of progress on shore power on shipping companies for not making their vessels shore power compatible, while shipping companies say the same lack of progress is because of ports not installing shore power equipment.

The rapidly decreasing carbon budget for shipping means that these local, national and international impasses must be overcome, and quickly. At a national level in the UK, a three-pronged multi-level strategy seems imperative. First, in its global role Chapters 3 and 4 suggest that the UK will need to champion and forge stronger alliances to argue for Paris-compatible global 2030 and 2050 targets in the IMO strategy refresh this year. Priority needs to be given to amending the IMO's energy efficiency policies (CII/EEDI/EEXI) to be aligned with these new 2030 targets, and Market-Based Measures brought in to address the fuel price disparity problems set out in Chapter 6. Second, the UK's Clean Maritime Plan refresh also needs to set strong Paris-compatible 2030 targets for both its domestic and share of international shipping emissions. Reducing its share of international shipping emissions would require a broader focus than solely pursuing progress through its negotiating role at the IMO. In line with the findings of Chapter 5, meeting such targets will require the introduction of stronger national policies, such as on capital funding and taxation. Third, it would not be prudent to assume that sufficiently stronger UK or IMO policies will be delivered at these crucial upcoming strategy revisions – there appears to be too many political barriers both within even climate-progressive nations and within the processes of the IMO. In this situation, additional options are essential. One major opportunity for the UK is to use its influence to cut international emissions, acting in the middle ground between domestic and IMO arenas: i.e. positively affecting international shipping emissions that are not the UK's direct responsibility. Some examples of such a role could be:

- Short-sea shipping in the Irish Sea, English Channel and North Sea is an area where the UK has major potential influence over emissions through collaboration with other nations and shipping stakeholders, but one which will be missed if its strategy focus is solely on domestic maritime.
- The UK has other areas of global expertise in shipping, for example in maritime contract law. The UK could champion reforms to include climate objectives within charter contracts.
- The precedent that already exists for acting in this "middle ground" – the UK championed the Clydebank Declaration on green shipping corridors at COP26. As a

bilateral measure, this sits in the grey area outside of domestic emissions, and not being a global IMO initiative.

Beyond national and IMO policies, there are other areas for potential progress – the most likely is for “coalitions of the willing” to move first. The EU are one example of this – 27 nations who are acting to introduce much stronger policies than the IMO, including the introduction of carbon pricing for shipping via the EU ETS, and regulations on low carbon fuels and shore power infrastructure. Further examples are industry initiatives such as CoZEV and the Getting to Zero Coalition. Such initiatives also have the broader advantage of strengthening the collaborations between shipping entities, which Chapter 5 argues are necessary for greater advocacy and thereby increase the likelihood of governments that have little time or priority for shipping interventions, implementing maritime decarbonisation policies.

In this context of increasing urgency, combined with a slow pace of national and international policy making, three areas for research stand-out. First, building on the research of Psaraftis and Kontovas (2020b), Psaraftis (2021), Prehn (2021) and Bach and Hansen (2023), research is needed on what reforms may be needed to IMO processes to enable more rapid decision-making in line with the requirements of the Paris goals, and crucially how these reforms could be delivered.

Second, the EU’s approach – faced with its frustration at the slow pace at the IMO – has been to enact its own policies (EUMRV, EUETS). This has been deeply contentious, with accusations that it will lead to other nations or regions doing the same, ending with a “patchwork” of bureaucratic and inefficient policies (Hughes, 2020). There are counter-claims that such measures are necessary in the face of IMO inaction, and their adoption will put pressure on the IMO to raise its game (Wissner and Cames, 2022). Given that the EU is a very large entity and global player in shipping, and the reality that its new shipping policies will come into force in some form, a priority research question is how to effectively integrate regional and global policy regimes in shipping.

Third, at a UK level, research is needed on how UK shipping climate policy can most effectively be designed to integrate with both EU and IMO policy, given that the UK, EU and IMO all have policy influence over the UK’s domestic and its share of international shipping emissions. A specific opportunity is around shore power. In 2023, the UK will be consulting on measures to accelerate UK shore power deployment, as part of the Clean Maritime Plan strategy refresh, at the same time as the EU finalises its policy package on shore power. There is an opportunity here for research with EU and UK policy makers, and with port and ship operators, on how best to integrate the approaches in these two jurisdictions, to maximise environmental gains and minimise inefficiencies.

7.6 Future challenges for shipping transitions researchers

This PhD began in September 2019 at a time of new momentum on shipping decarbonisation both globally and in the UK. The IMO had in the previous year set out its initial climate strategy. The UK had just published its Clean Maritime Plan in July 2019.

As set out in Chapter 1, the PhD aimed to answer 4 Research Questions (RQ), designed to be relevant to ongoing deliberations around the goals and targets for these strategies and how to implement policies to deliver them:

- What contribution should shipping make towards meeting the aims of the Paris Agreement on climate change?" (Chapter 3)
- Which technologies and practices, deployed at what time scales, could enable the shipping sector to meet Paris-compatible pathways? (Chapter 4)
- Why has shore power been slow to deploy in the UK, despite the UK's position as a leader on climate change mitigation and given its technological maturity and clear environmental and social benefits, and what solutions might overcome barriers to its deployment? (Chapter 5)
- What are the main financial and technical requirements for a UK shore power project, how are they interlinked and what can be learnt and applied more broadly to the shipping transition?" (Chapter 6)

The preceding sections 7.1 to 7.4 have set out answers to these questions, the main contributions of this thesis, their implications for shipping policy, and potential areas for future research. RQ 1 and 2 are explicitly framed around global goals and relevant technologies and practice changes. RQ3 and 4 ask – for one of those relevant technologies – which policies can accelerate its deployment, and how can those policies be enacted in the face of political inertia? Given what has been learnt during this thesis, these have indeed been valid and relevant questions, and it is hoped that the answers suggested are useful to policy makers and the academic community.

A broader question is how this thesis contributes to the broader challenges facing the sustainability transitions research community, and in particular research on shipping transitions, especially given the transition focused upon in this thesis has very different drivers to those that have gone before. The paper by Köhler et al. (2019) on future agendas for broader sustainability transitions research can be used to help guide such an assessment. This paper set out seven challenges to the sustainability transitions community, paraphrased in Table 7-3 below. The final part of this section assesses this thesis against those challenges and suggests priority areas for future research.

Table 7-3 Seven challenges for sustainability transitions researchers

Challenge	Key question
1. Urgency	"Time is running out so quickly". How can ST research support accelerated transitions?
2. Global politics	Which current global political trends could increase chances for international collaboration?
3. Cross-sectorality	Systems interact (food, energy, transport); how can research address transitions across interconnected systems?
4. Phase-out	How can unsustainable industries be phased out more rapidly, while also addressing social and economic sustainability?
5. Sustainability	Sustainability is multi-dimensional but there is a tendency to focus on one aspect at a time, risking conflicts between goals. How can we work with this inherent complexity?
6. Demand-side	Demand-side issues are difficult to address. How can society support transitions to alternative social and economic systems?
7. Researcher engagement	To what extent should researchers have a practical impact and engage with real-world actors, transitions and systems, and at which levels should they focus?

(Source: abridged from Köhler et al. (2019))

Given the urgency set out in challenge 1 of Table 7-3, the choice of RQ1 and RQ2 seems correct. It is essential to be clear not just on the scale but on the speed of transition required. This clarity has been lacking in the literature and in policy debates. The results from RQ1 and RQ2, with their conclusion of the criticality of emissions reductions this decade, have been used to inform global and national shipping transition debates on this pivotal issue of urgency.

The results from RQ1 and RQ2 also touch on aspects of challenges 2-5, which combine to suggest a strand of research inquiry related to global and national shipping governance. Addressing climate change requires the phase-out of unabated fossil fuel combustion, in shipping but also in all other sectors (challenge 4). Shipping is however not just a consumer of fossil fuels, it transports these fuels in the global economy. Transport of fossil fuels currently represents over a third of all global shipping trade by tonnage (Clarksons, 2021). Shipping's transition is therefore bound up in the wider global economy transition, particularly the global energy system (challenge 3). This deep embedding of fossil fuels within the shipping regime also affects the speed at which the IMO can take decisions – it is a consensus-based organisation, with decisions taken by member states, many of whom have economic and political interests deeply tied to continued fossil-fuel production and consumption.

The issue of phase-out of fossil fuel consumption therefore affects both the shipping system's future functioning, in terms of its links to the wider energy system through transporting energy products, and also the shipping regime's resistance to policies that would reduce reliance on fossil fuels. This is also linked to challenge 2 on global politics – recent global events have had gargantuan effects on the global economy (COVID-19, Russia's war on Ukraine), but their medium-long term impacts on sustainability transitions are unclear. The response to COVID-19 showed that governments, if they wish to, can deploy vast quantities of financial, physical and human resources to addressing urgent threats to humanity. It weakens the argument that states cannot take transformative action on climate change. Similarly, Russia's war on Ukraine has shown a possibility that geo-political ruptures can potentially radically change countries' long-standing policy positions very rapidly – for example in relation to energy security and developing policy to reduce reliance on imported fossil fuels. But on the other hand, increasing tensions between major nations (such as between the USA and China over Taiwan) suggest that the consensus and collaboration needed between nations in forums such as the IMO and UNFCCC may be harder to achieve.

A further critical issue around sustainability (challenge 5) is that the necessary collaboration needed to drive transition in shipping and in wider climate negotiations can be stymied if nations do not appreciate each other's different sustainability perspectives and reach compromise. In the IMO, countries such as the UK who wish to see stronger 2050 targets need to build a stronger constituency for such change, for example with developing countries. For these countries however, the issues of financial support to enable their shipping transition are pivotal. Countries such as the UK will likely need to develop stronger positions on the global equity aspects of shipping transitions before these more powerful alliances could develop. This mirrors the situation at successive COPs, where until very recently, the rigid refusal of developed nations to countenance any measures on Loss and Damage has diminished their capability to deliver a stronger alliance on measures in order to keep the 1.5°C target achievable. Bringing together these four challenges on phaseout, global politics, cross-sectorality and sustainability suggests that research on whether or how groupings of nations can build more powerful alliances within the IMO would be very timely.

Challenge 5 on sustainability also refers to the often-reductive way in which climate change can be analysed. This is not just that climate change mitigation or adaptation goals can be analysed or discussed with comparatively little study of impacts on other environmental goals (such as biodiversity) or on social and economic goals (such as on hunger or any of the other UN sustainable development goals). But it is also that even within climate change, some aspects are foregrounded at the expense of others. For example, in shipping (and in RQ1) the explicit focus is on reductions of CO_2, as it represents 98% of the sector's current greenhouse gases (GHGs). However, measures to reduce CO_2 could increase the emissions of other GHGs at the point of combustion, or increase GHGs elsewhere in the fuel's lifecycle. For example, ammonia has near-zero GHG emissions when burned, but may have very high or very low GHG emissions associated with its production, depending on the processes employed. A further example is in the promotion of LNG as a short-term measure to reduce shipping CO_2 emissions. LNG has lower GHG emissions at the point of combustion than marine fuel oils, however methane-slip on ships, and methane emissions during production processes, means that in practice LNG can be a worse option for climate mitigation than existing use of marine fuel oils. Given the urgency in challenge 1, it is imperative that technologies adopted this decade do not lock the sector into high greenhouse gas emissions in decades to come. Research is ongoing by multiple researchers on the full lifecycle emissions of shipping fuels (Law et al., 2021, Mondello et al., 2021); this research will need to be integrated as quickly as possible into technical and regulatory standards in the IMO, ISO and elsewhere.

The largest gap in the analysis undertaken for RQ2 is around issues of demand (challenge 6) – with its assumptions that overall demand for shipping transport would increase. This reflects a pragmatic decision that even strong efforts to address demand would struggle to outstrip the inherent growth in shipping trade implied by the longstanding link between trade, shipping trade and global economic growth. Analysis in RQ2 assumes that the greatest impact of demand measures would be to keep shipping demand constant at today's levels. Research into ways in which shipping demand could be constrained, while still meeting social and economic sustainability objectives, is a priority.

Finally, Challenge 7 asks how researchers practically engage with systems and actors to affect transitions, as opposed to simply observing them. Challenge 1 was taken here as a call to attempt the former, rather than attempting to be just a neutral observer. This PhD is taking an interventionist rather than solely an observer stance, on the grounds that the extreme urgency posed by worsening climate change impacts requires research that is explicitly aimed at accelerating sustainability transitions. This has affected the choice of direction of research in this thesis, with the aim of focussing on processes where it might be possible to influence the long-term direction of shipping strategy. In mid-2019, these opportunities were around providing greater clarity on the targets and policies required from the then-nascent shipping climate strategies, from both the IMO and the UK Government. This approach is in line with the thinking of Meadows (1999) that interventions at the level of goals/strategy is likely to have a higher level of impact than those at levels such as regulations and prices. In retrospect, this focus has been justified, given the continued and growing interest in shipping decarbonisation at both these levels. But during this time there has been a rapid growth in attention paid to shipping by other actors and at other levels of governance – in particular the EU, and the growth in industry coalitions such as Getting to Zero Coalition and the Cargo Owners for Zero Emission Vessels (coZEV).

The urgency expressed in Challenge 1 and the analysis from Chapters 3 and 4 suggest that research on shipping transitions should focus on areas where it is perceived that there are major near-term opportunities for change – whether these are a particular grouping of actors (such as the IMO), or a particular technology in a particular sub-sector of shipping or geographical area. However, a two-fold complement to this is necessary. First, given the rapid growth of interest in shipping decarbonisation at all levels, regular "horizon-scanning" of emerging opportunities or initiatives for more rapid decarbonisation, and analysis of where additional research may support these initiatives. Second, a focus on greatest opportunities would mean that by definition, options that are currently politically unpalatable (such as demand reduction) would always be deprioritised for research. It is suggested that a useful function for a grouping of shipping sustainability transitions researchers could be to delineate three broad areas for guiding future research: greatest opportunities, horizon-scanning, and spotlighting the unpalatable.

7.7 Summary of results and conclusion

This thesis has made a mixed-method, multi-scalar assessment of the dynamics of sustainability transitions in shipping. It focussed first on the contested goals of this transition, second on pathways for decarbonisation, and third on how to overcome the economic and political barriers to implementation of policies to accelerate transition. It has demonstrated that there is a complex interplay between governance at local, national and global levels – these levels of governance need to be more effectively co-ordinated in order for the sector to contribute sufficiently to meeting the Paris climate goals.

Chapter 3 demonstrated that achieving deep emissions reductions this decade is an absolute priority for the shipping sector. If this does not occur, then the required rate of decarbonisation in the 2030s would be too rapid to be achievable. This insight has been disseminated to policy makers ahead of the pivotal IMO strategy revision in summer 2023, and is a deep challenge to the previously prevailing focus at the IMO on long-term 2050 targets. Chapter 4 complements this research through the first application of the committed emissions concept to shipping, showing that meeting Paris-compatible pathways requires a focus on measures to reduce the emissions of existing ships this decade, as well as a focus on new zero-carbon fuels deployed at scale in the 2030s. This is also a deep challenge to the current policy consensus, at both UK and international levels, which assigns very little urgency to operational measures this decade.

Chapters 5 and 6 assessed the practicalities of accelerating deployment of measures for existing ships, by analysing the barriers to deployment of one technology – shore power – in the UK. The recent academic literature is clear that economic barriers are often a major barrier to uptake of shore power, however there is a gap in this literature in ascertaining why these barriers have not been overcome. Chapter 5's first novel contribution is to combine two methodological frameworks from the sustainable transitions literature (TIS and MSA) to show that it is political barriers that are preventing the implementation of economic policies to accelerate deployment, and that cultural factors are affecting the ability of industry stakeholders to successfully increase the pressure on policy makers to address these political barriers. Its second contribution is to use insights from punctuated equilibrium theory to suggest ways in which these political barriers can be overcome. Chapter 6 presents analysis of the specific economic policies required to deliver a financially viable shore power project, and the level of compromise and collaboration required by three key stakeholders: port operator, shipping operators and National policy makers.

In combination, these four chapters demonstrate that there is a polycentric governance challenge for shipping decarbonisation. The need for an accelerated transition is urgent, but policies to deliver this transition in time will require the co-operation and integration of policies at multiple levels. This is evident from the local and national case studies of UK shore power in Chapters 5 and 6: shore power requires not just the co-operation between local stakeholders such as ports, electricity networks and ship operators, but a clear and supportive policy environment, which requires the integration and alignment of multiple policy regimes at national, continental and global levels.

In conclusion, globally the overriding priority is for the IMO to set Paris-compatible targets for 2030, and policies to meet them. At the UK level, the UK Government's priority should also be to set and deliver on Paris-compatible 2030 targets, including both its domestic and share of international shipping emissions. Meeting targets in both the UK and globally requires a focus on reducing emissions from existing ships. But joining-up governance between levels is also crucial. Policy at one level cannot be deprioritised because it is assumed it will be picked up at a different level; there is no longer any time left for further delay. National, continental and global approaches must not be in competition or isolation – instead, this thesis contends that shipping policy makers at these different levels will need to ensure that policy measures at their level are fully integrated with those at other levels, into a polycentric set of policy instruments.

7.8 Final remarks

It's been a privilege to work on shipping and climate change from 2019-2022, a period of dramatic change in the sector. As recently as 2016, the annual survey of main environmental concerns for European Ports did not even place climate change as a top ten issue (ESPO, 2016). Now, almost all industry stakeholders and Government regulators have raised climate change to a top-level concern for the sector. Climate change dominates the agenda of the MEPC at the IMO. There are multiple industry climate initiatives, such as the Getting to Zero Coalition, coZEV, the Poseidon Principles and the Clydebank Declaration. Sophisticated, integrated policy packages to cut shipping emissions are being introduced at the EU level, promising deep changes in the years to come. Yet despite all this and more, shipping emissions are not falling, there is entrenched opposition to stronger global targets and policies, and the sector remains deeply linked to the wider fossil-fuelled global economy, with transport of oil, coal and gas representing a third of the sector's entire business.

It is hoped that this PhD will have made a contribution to the essential task of accelerating shipping's climate change transition. The first two papers show the need for stronger targets, with a novel contribution around the pivotal issue of urgency: the IMO and national governments must focus on deep emissions reductions this decade, or the sector will not be able to play its part in meeting the Paris' Agreements climate goals. These insights have been disseminated to key decision-makers over the last two years, with the hope they will inform the setting of new global targets for shipping at the IMO in summer 2023. The third paper uses a novel combination of methodologies in the transitions literature to illuminate the political causes for why economic barriers to UK shore power deployment have not been overcome, and in suggesting how these political barriers could be surmounted. The fourth paper shows for the first time in the shore power literature what practical combinations of regulatory measures could unlock shore power economics, if these political barriers to stronger policy making could be overcome.

Linking all four of these papers is a central thread and an as yet unanswered question around governance. What combinations of local, national and global governance will deliver the accelerated transition which is so urgently needed? There is deep frustration at the slow rate of progress at the IMO – a rate that will have to increase if the Paris goals are to be met. In the face of this delay some actors – such as the EU – are taking deep unilateral action. Others – such as the UK – fail to include international shipping emissions in their national strategies, deferring responsibility fully to the IMO. But the actions of the EU mean that in practice the world will be developing both global and sub-global approaches, no matter which approach might theoretically be the most efficient or effective. A pragmatic response, in the face of the overwhelming necessity for urgent action, is to develop collaborative, polycentric governance models in international shipping, that integrate national, regional and IMO approaches. The message for the UK is to set goals for reducing its share of international shipping emissions in line with Paris, and to develop policies to meet this goal, which are aligned and integrated with ongoing policy development at the EU and IMO levels. The message for the IMO is that it if wants to retain relevance and authority over climate change issues in its sector, it will need rapid reform of its decision-making processes to allow faster responses to what are now very time-limited challenges.

Finally, if this thesis is advocating that policy makers at different levels need to collaborate more, and integrate their governance approaches, there should be some similar reflection on what greater collaboration means for shipping transitions researchers. Köhler et al. (2019) note that “time is running out so quickly”, asking how sustainable transitions research support accelerated transitions. They also ask to what extent should researchers engage with real-world actors, and at which levels should they focus. Given the urgency, engagement with real-world actors is – I would argue – absolutely essential. The question is focus. The discussion section suggested three areas. First, working with actors where there are major opportunities for short-term deep emissions reductions. Second, horizon-scanning for emerging opportunities or initiatives for more rapid decarbonisation, with analysis of where additional research may help. Third, some priority given to currently politically unpalatable options such as demand reduction, which may ultimately be essential, but are currently always deprioritised for research. This is already a broad agenda, and it is suggested that some coordination between a network of committed shipping researchers will be needed.

I hope the results from this PhD research have added some clarity on the urgency of the challenge facing the shipping industry, but have also stressed that the necessary changes are feasible. The sector has the ingenuity and drive to succeed, but also the entrenched power and division to cause further failure-inducing delay. The next few years are crucial, delay is not an option, every tonne of carbon saved matters.

Chapter 8 Appendices

8.1 Supplementary material to Chapter 3

This supplementary material section covers eight methodological points for Chapter 3 in greater detail.

8.1.1 COVID-19

Global CO_2 emissions fell in 2020 due to the impact of COVID-19. Le Quéré et al estimated in May 2020 that global CO_2 emissions would fall 4% (2-7%) if pre-pandemic conditions returned by June, and 7% (3-13%) if some restrictions remained in place worldwide until end 2020 (Le Quéré et al., 2020). As restrictions were still in place this paper assumes the higher end of the Le Quéré estimate for global emissions reductions in 2020, at 7%. The Le Quéré analysis is now backed up by Global Carbon Budget Project Data in late 2020, which also calculates a 7% fall (Friedlingstein et al., 2020). The Le Quéré paper assumed a 20% fall in shipping emissions, based on WTO trade data in April predicting a 13%-32% fall in world trade in 2020 (WTO, 2020a). The WTO since reduced their trade-impact estimate, predicting in October a global fall of 9% in 2020, with a 7% rebound in 2021 (WTO, 2020b). As the falls in global trade are half those initially predicted by the WTO, this paper assumes that shipping emissions fell 9% in 2020. Although some shipping sub-sectors have been hit harder than others, global goods trade is a strong proxy for global shipping emissions – although cruise and ferry segments have been very badly hit, they only accounted for 6% of emissions in 2018, compared with the 90% for the 8 large trade-based segments (containers, bulk carriers, oil tankers, liquefied gas tankers, chemical tankers, general cargo vessels, vehicle carriers, refrigerated bulk vessels) (Faber et al., 2020).

8.1.2 Carbon Budgets

Choices of global carbon budgets are not purely scientific; they require societal judgements as to what level of risk of exceeding a given temperature goal is acceptable. Here, given the Paris Climate Agreement's goals to keep emissions "well below" 2 degrees, and "pursue efforts" to keep warming to no more than 1.5, the view is taken that this goal is equivalent to a carbon budget based on a 50% chance of keeping to 1.5 degrees. Other approaches are possible, for example Anderson et al 2020 (Anderson et al., 2020) use a larger global carbon budget, compatible with a 50% chance of 1.7 degrees. Alternatively, 50% might be considered to be bad odds for something global governments are trying to achieve, in which case a lower carbon budget would be appropriate. Using IPCC data (Rogelj et al., 2018) and the same methodologies as in the main article, a 33% and 67% chance of keeping to 1.5 degrees would set a post-2020 global carbon budget at 633 and 213 GtCO_2 respectively. Carbon budgets are set for CO_2, budgets assume falling non-CO_2 emissions also, with assumptions set out in (Rogelj et al., 2019). Current IMO targets do not extend beyond 2050 – the values in Table 2 assume that emissions would fall to zero by 2060 or 2070 – this is a fast transition for the remaining 50% of cuts; assuming a slower transition would make the cumulative emissions under the current IMO strategy in Table 3.2 even higher.

8.1.3 IMO GHG report methodology changes

The IMO 4th GHG report sets out a new method for calculating what proportion of total shipping emissions should be counted as "international". This new "voyage-based" approach is better aligned with IPCC emissions accounting guidelines. The report acknowledges a difficulty in back-calculating "voyage-based" values before 2012, due to data gaps, and makes an estimate only for 2008. In this study, we needed to extrapolate values for the years 2009-2011. We considered 4 methods; a sensitivity analysis showed that the greatest difference between the method chosen and any of the other methods did not change the zero-emission end date for any of the sub-scenarios. In summary, we believe the method chosen is the most appropriate given data limitations, but other methods would not have a material impact on the overall results.

The method chosen was that in IMO GHG 4, international shipping's voyage-based emissions were 73% of total shipping in 2012; this 73% value was applied to total shipping emissions in 2009-2012.

Other approaches were method 2, which used the same approach, but using 70%, the international shipping % in 2018; method 3 was based on IMO 3rd GHG report values (IMO, 2014a). IMOGHG3 gives old ("vessel-based") method values for international shipping CO2, 2008-2012, and method 3 applied the percentage annual change on those values 2009-2012 to the IMO GHG4 2008 value. Method 4 took the "voyage based" IMO GHG 4 value for 2008 as a % of the IMO GHG 3 2008 value for 2008 (68.34%) and applied this % to the IMO GHG 3 total shipping values.

The IMO GHG 3 and 4 reports have overlap in 2012. Their total global emissions values are significantly different for that year (34793 vs 35640 $MtCO_2$): comparison with Global Carbon Budget data shows that the IMO GHG4 years' values are all accurate to 0.1% of the GCB data, whereas IMOGHG3 are 0.6-2.4% higher. For this reason, here we chose the methods which had the lowest reliance on IMO GHG3 data – i.e. methods 1 and 2. Of these, 1 was chosen as based on a closer date (2012 vs 2018) to the years required (2009-2012).

8.1.4 End year

When this article refers to a zero-emission end date, it means the year in which emissions fell to zero, rather than the first year in which total emissions for that year were zero. So, if the trajectory had zero emissions in August 2046, this would be given a zero-emission end year of 2046, rather than 2047 (the first year in which total emissions would be zero).

8.1.5 CO_2 vs GHG

Current IMO targets are expressed in GHGs; this carbon budget analysis is expressed in CO_2. This difference does not have a significant impact on the analysis in this paper. The IMO 4th GHG report says that CO_2 = 98% of international shipping's current and 2008 GHGs. All CO_2 reduction measures should be taken with the need to ensure other environmental impacts (eg other GHG emissions, full life-cycle emissions, local air pollution impacts etc) are also minimised.

8.1.6 Logistic functions

Recognising that a linear reduction pathway is unrealistic in practice, the analysis in this paper also calculates a carbon emission trajectory using a logistics function. The logistics function is described by the formula:

$$f(x) = L - \frac{L}{1 + e^{-k(x-x_0)}}$$

Here, L represents the initial levels of emissions, k is the growth rate factor, which dictates both the shape and steepness of the curve, and x_0 is the midpoint year. The choice of midpoint year dictates the cumulative emissions for each case. Therefore, for each curve generated with the logistics function, the total cumulative emissions are calculated to ensure consistency with the carbon budget of each scenario. The growth rate factor is then varied to obtain emission trajectories with different levels of short-term action.

8.1.7 Annual reduction rates

The variation in annual % reduction on initial levels for the pathways are set out below:

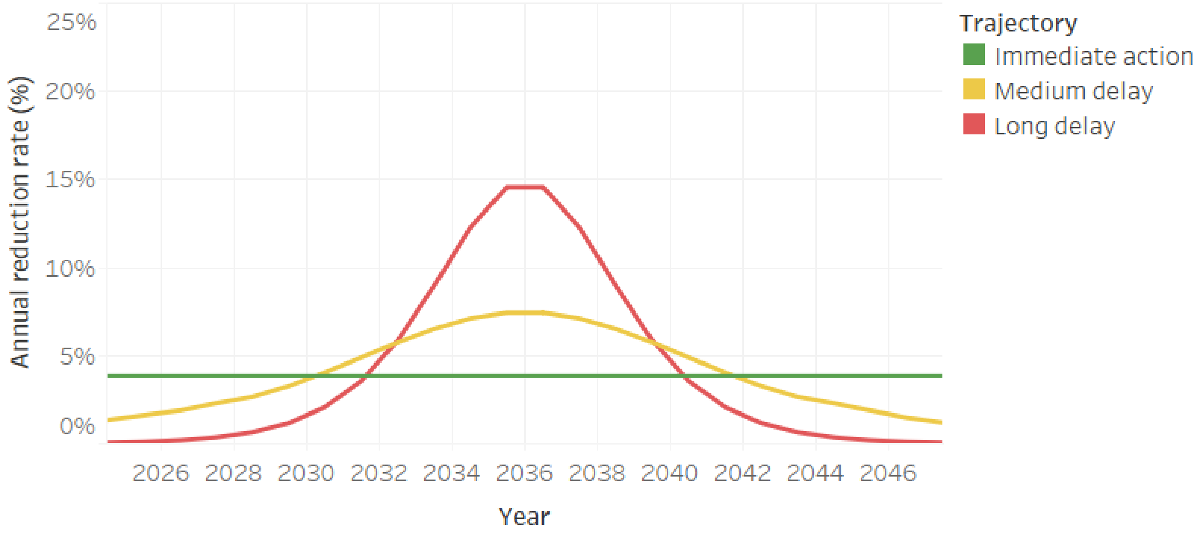

Figure 8-1 Annual reduction rates with IMO 2008 baseline used for calculating carbon budgets

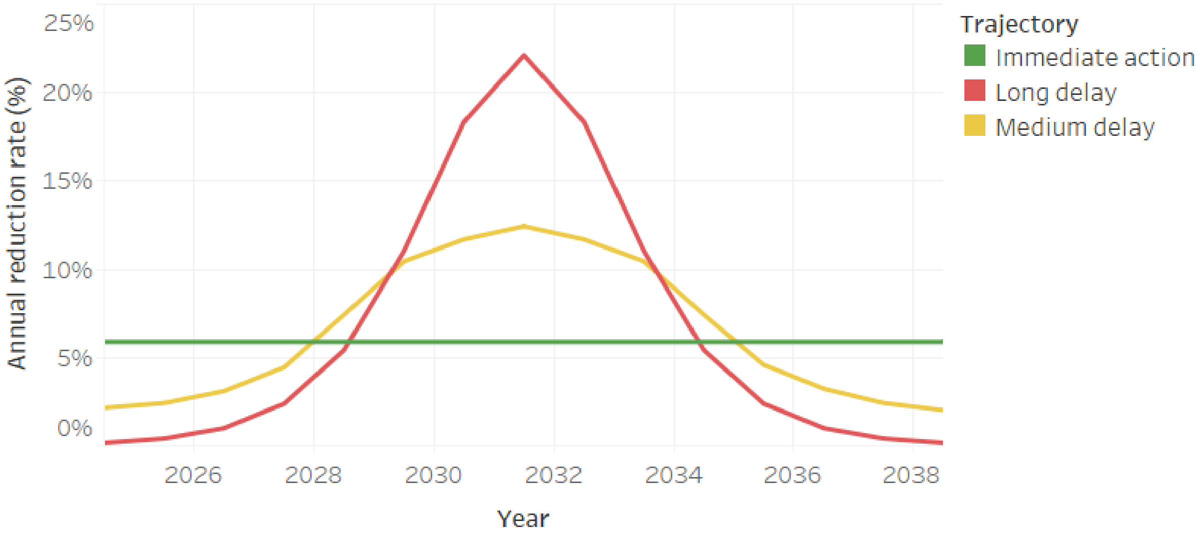

Figure 8-2 Annual reduction rates with 2020 baseline used for calculating carbon budgets

8.1.8 Shipping lifetimes

The average lifespan of ships varies between ship type. The average age of ships scrapped between 2009-2018 was 28.2 years, with cruise ships having an average life of 44.5 years, and 3,000-8,000 TEU container vessels 19.7 years. The average scrappage age across all ship types over the last decade has varied from 25.5 to 30.2 years (Bullock et al., 2020).

8.2 Supplementary information for chapter 4

This section contains additional information on methodology. It covers four issues: i) data quality; ii) calculating baseline committed emissions; iii) measures to reduce baseline committed emissions; and iv) EU versus global carbon budgets. There is an accompanying spreadsheet showing calculations and inputs regarding issues ii) and iii).

8.2.1 Data quality

There is very high congruence between Clarksons and EU data, by matching ship name to ship IMO number across the two datasets. There are around 20 ships (0.18%) in the EU set not in Clarksons – checking against a third source (fleetmon.com) shows that the reason for all but one of these is that they have been put out of service since the EU data was published[15]. These 20 ships are not included in the calculations for baseline committed emissions.

There are very few outlier values in the EU CO_2 data. The majority appear to be recording errors. The EU says it is not responsible for any errors, and these should be brought up with the relevant ship data verifier[16]. Some five instances were clear errors (e.g. a value several orders of magnitude higher than every other vessel) so these ships were removed from the analysis. There was also a persistent occasional error where the ratio of fuel to CO_2 for a ship was more than double that for every other ship in that type. Again this was assumed to be a simple verifier error, affecting 20 ships, and the CO_2 value was corrected so that it is the same ratio to fuel consumption as every other ship in that type. In total, these errors account for less than 0.2% of the fleet. Finally, 597 ships have no CO_2/fuel data – these ships are simply not used in the analysis.

The EUMRV data set is new, and there is not yet detailed analysis in the literature of the reliability of this data. Panagakos et al. (2019) discuss aspects of the data set in detail, and are for example critical about the validity of some of the EUMRV's ship efficiency data. However, the values for these efficiency indicators are by definition more subject to uncertainty than simple fuel consumption data: for example an efficiency measure of fuel consumption/tonne-mile is product of fuel consumption, distance, and cargo – tripling the

[15] Third source was www.fleetmon.com. EU data covers the year 2018; Clarksons data is for September 2019.
[16] Personal communication with EU MRV staff

sources of potential uncertainty compared with simple reporting on fuel consumption. In our study, the focus is on absolute CO_2 emissions, a direct product of fuel consumption and standard fuel emission factors, so this data is likely to be more reliable than for efficiency measures. However, data quality is an ongoing issue for EUMRV and subsequent analyses of it, and we note Panagakos' suggestions for improvements, for example addressing the issue that reporting obligations fall to ship owners rather than ship operators.

Table 8-1 Number of ships in EU MRV database compared with EU and Global totals

Number of ships	In the EU MRV system	Total (including smaller ships)
EU ships	11,566	21,029
	Global	Total
Global ships of the same type	64,029	97,645
EU as % of global	18%	22%

Source: EU and Clarksons data (EU Parliament, 2015, Clarksons, 2019c)

8.2.2 Calculating baseline committed emissions

The baseline committed emissions of an individual ship, $E(i)^{ship}_{baseline}$, across its remaining lifetime with no carbon reduction measures applied, is calculated by multiplying the ship's future life in years by its annual emissions in 2018, $E(i)^{ship}_{annual}$ (equation 1). A ship's future life is calculated by subtracting its current age, $t(i)_{ship\ age}$, from the average age at scrappage for that ship's type and size, $t_{scrappage}$. For some ships this gives a negative value – ie ships who are already older than the fleet average scrappage age. In this calculation, these ships are assumed to be scrapped next year. This assumption will therefore underestimate committed emissions, as not all of these very old ships will be scrapped next year, however their expected lifetime is sufficiently low, and the number of ships it affects (0.7%) means this assumption will have a far lower than 1% impact on the final value.

The total baseline emissions from each ship class, $E(i)^{class}_{baseline}$, is calculated by summing across the total number of ships in each class, N_T, where i represents each individual ship.

The total baseline emissions from the full fleet, $E^{fleet}_{baseline}$, is then calculated by summing across the total number of classes, N_{class}.

$$E(i)^{ship}_{baseline} = [t(i)_{ship\ age} - t_{scrappage}] * E(i)^{ship}_{annual} \quad (1)$$

$$E(i)^{class}_{baseline} = \sum_{i=1}^{N_T} E(i)^{ship}_{baseline} \quad (2)$$

$$E(i)^{fleet}_{baseline} = \sum_{class=1}^{N_{class}} E(i)^{class}_{baseline} \quad (3)$$

The mean age a ship is scrapped is estimated, by taking the values of average scrappage age for each ship type and sub-type, for each year in the last ten years' publications of Clarkson's World Shipyard Monitor (WSM), and taking an average value across these ten years. Compared with the 2018 value the overall ten-year average value is approximately 5% lower (see Figure 8-3), however, ten-year averages were deemed more appropriate given the short-term cyclical nature of shipping scrappage markets (Stopford, 2009).

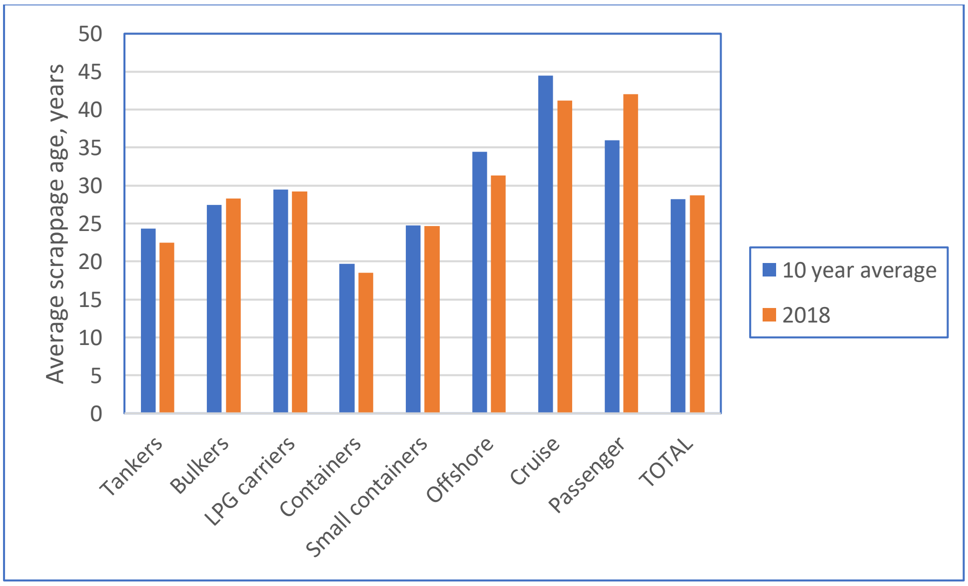

Figure 8-3 Average scrappage age by ship type, 10 year average (2009-2018) vs 2018 value

Source: Clarksons World Shipyard Monitor, multiple years.

Clarkson's World Fleet Register contains values for the current age of every ship. This database is merged with the EU MRV database and the WSM average scrappage age results to give a value for the average predicted remaining life for each ship in the EU MRV database, referencing against each ship's IMO number.

A baseline committed emissions value for each ship is then calculated using the equations above, assuming each ship continues to be used at the same rate as in 2018, with the same level of annual emissions. This assumption, that newer ships are not used more frequently or used on longer routes than older ships, cannot be verified directly, however, analysis of fleet time-at-sea data offers some insight (

Figure **8-4**). Correlation between ship age and time at sea is a statistically significant but very weak positive relationship (Spearman's rho = 0.19, $p < 0.0005$ two tailed). Further analyses were also conducted for all 14 ship types, and sub-divisions within them (for example ships only undertaking non-EU-EU journeys and only undertaking intra-EU journeys), with similar results. However, there are two major caveats over the use of this time-at-sea vs age data to infer potential different assumptions around emissions over time. First, this insight is of new ships now versus old ships now, rather than of a ship's emissions profile over time. For this we would need multiple years' EU MRV data. Second, this data does not include time at sea for journeys which do not involve any EU port. To get accurate time at sea vs age data we would need a global system. Here then we acknowledge that the emissions profile over time is currently an unknown, which will only become clear with a global monitoring and reporting system with multiple years of data. For now, this study assumes constant emissions over time for a given ship.

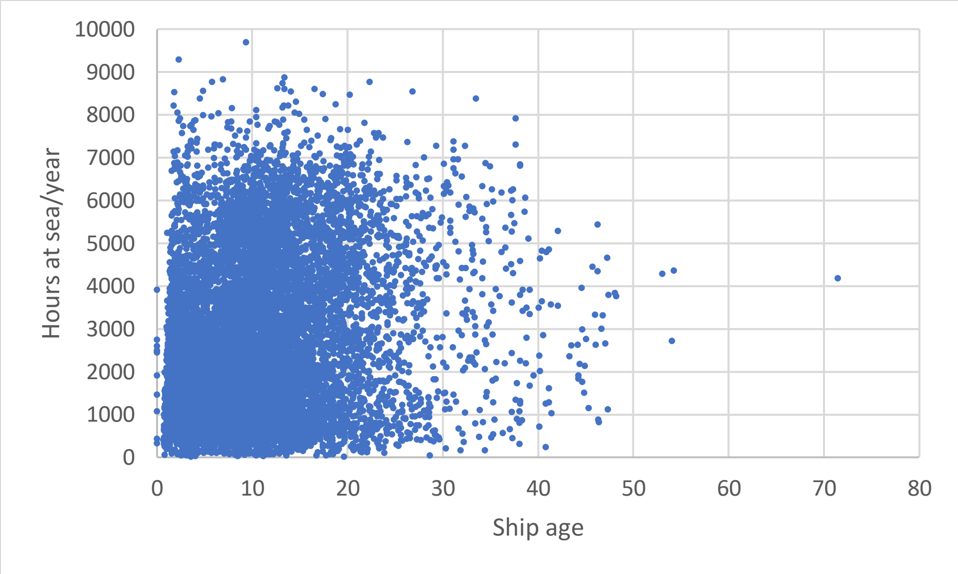

Figure 8-4 EU MRV fleet, age vs time at sea.

Matching the age data with ship size data highlights variations within ship types. For example, within the container ship type it is newer container ships that are responsible for the highest committed emissions (Figure 8-5). Despite newer container ships being much more efficient (Figure 8-6, Spearman's correlation coefficient rho = -0.567, $p < 0.001$), the recent trend for container ships to become much larger (Figure 8-7, Spearman's correlation coefficient rho = -0.575, $p < 0.001$) has a greater impact.

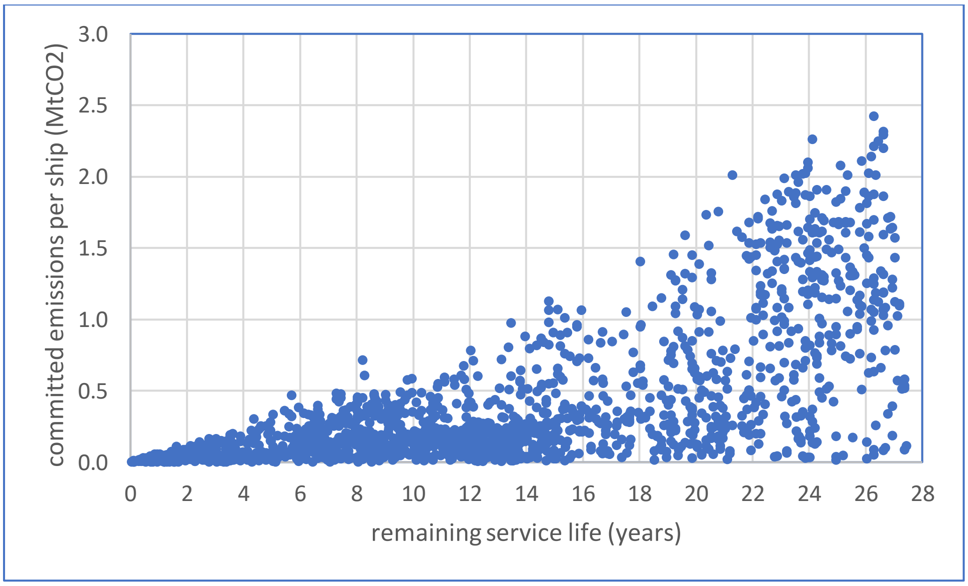

Figure 8-5 Container ship committed emissions vs remaining service life

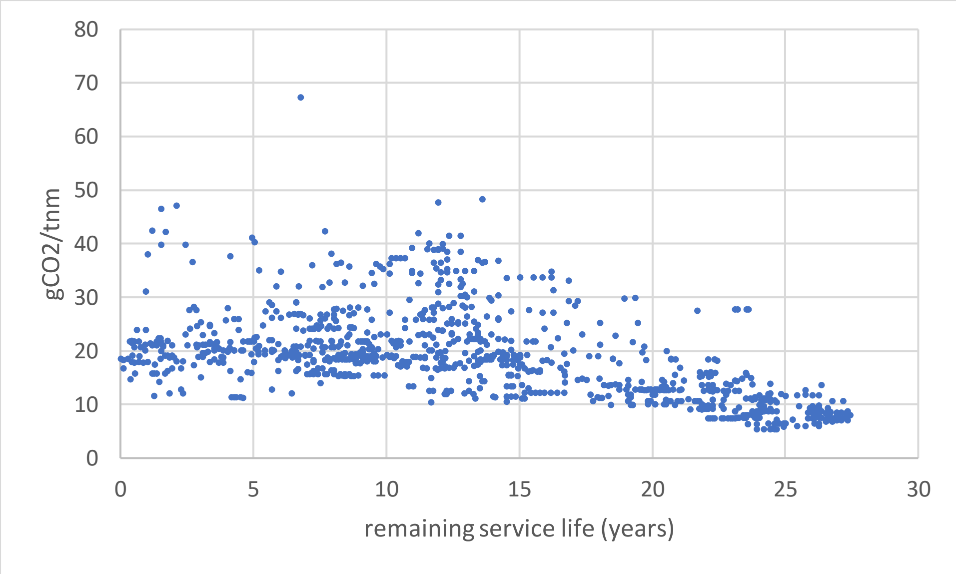

Figure 8-6 Ship technical efficiency (gCO2/t nm) vs years remaining service life, container ships

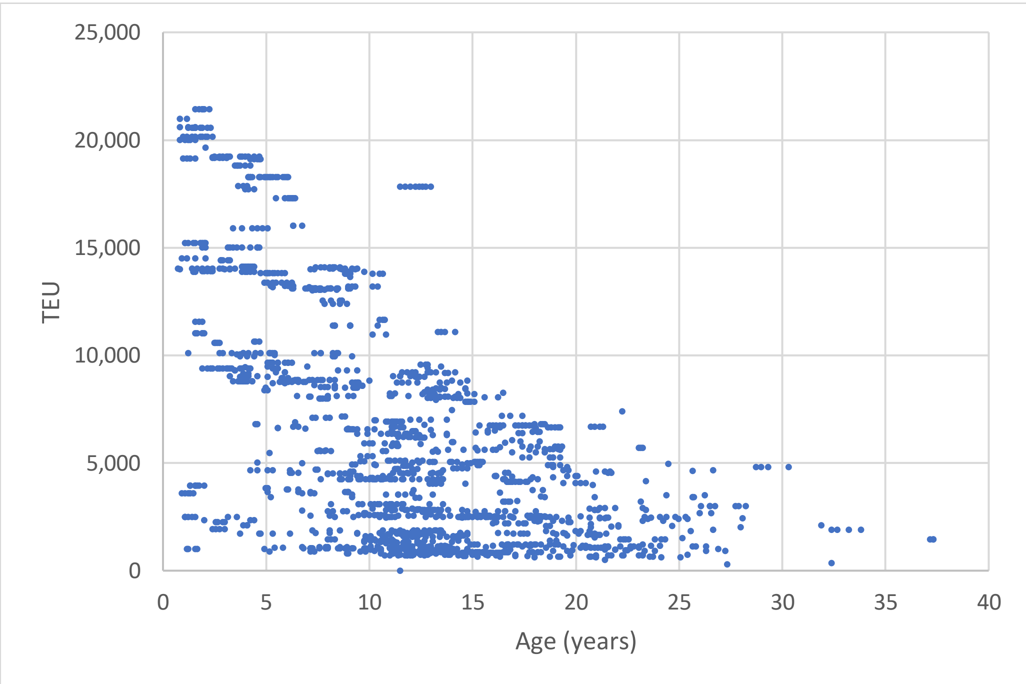

Figure 8-7 EU container fleet: size in TEU compared with age in years

8.2.3 Measures to reduce baseline committed emissions

In the model constructed for this paper, four types of measure were applied sequentially to reduce baseline committed emissions: slower speeds, operational improvements, blended fuels, and zero-carbon fuels. This section sets out the assumptions underpinning the values used for each of these measures (see Table 4-2) the equations for how each measure individually affects the baseline emissions value, and the equations for how the four measures are applied sequentially.

The spreadsheet accompanying this paper allows users to alter their chosen input parameters for these four measures for each ship type.

The assumptions behind the values set out in Table 4-2 are:

Slow speed

The effect of speed reductions on fuel consumption is complex. The power required for a ship's propulsion is proportional to speed cubed (Lindstad et al., 2017). But if speed is lowered, that power is required for longer to cover the same distance, so energy saving at lower speed is less than a cubic factor. In addition, for each ship there are different optimal speeds for efficient engine operation, and for a given value of transport demand, there are potential rebound effects due to the need for more ships to transport the same quantity of goods in the same time (Smith, 2012). Overall the literature cites large potential savings in fuel consumption from lower speeds, but with wide ranges: the review by Bouman et al. (Bouman et al., 2017) cites savings from 1-60%, depending on assumptions, with a range of 15-35% between first and third quartiles, which is used here, similar to the range of 13-33% cited by Faber et al. (Faber et al., 2017). Slow steaming has been occurring to some extent already, and it is uncertain how much further reduction is possible. Rutherford et al. (Rutherford et al., 2020) show that the engine operating power of container ships, bulk carriers and tankers in 2018 were largely between 20-50% of an engine's Maximum Continuous Rating (MCR). Therefore, in some cases, achieving high savings from speed reduction would require innovative solutions, such as engine de-rating (Rehmatulla et al., 2017).

Speed reductions can occur voluntarily, and can make sense when fuel prices are high, but here it is assumed that widespread and long-lasting uptake speed reductions would require regulation, agreed at IMO level. This issue is on the table at IMO Marine Environment Protection Committee (MEPC) meetings, however progress has recently stalled (Marine Log, November 15th 2019). A minimum of three and a maximum of ten years before regulations would be enacted is assumed here, and three to ten years before these are fully applied. In addition, sensitivity analysis were performed to understand the effects of non-application for particular ship classes, where speed restrictions may be more problematic. As an example, assuming that Ro Pax/Passenger/Reefer had speed factor improvement of 1 instead of 0.75 (mid) increases their committed emissions by 26%, but increases total committed emissions for all ships by just 5%.

This analysis integrates emission reduction measures by applying an emission reduction factor to the *annual* baseline emissions from each ship class. The annual baseline committed emissions from a class, $E(t)^{class}_{annual}$, is calculated by summing across the annual baseline committed emissions of each individual ship of that ship class.

$$E(t)^{class}_{annual} = \sum_{i=1}^{N} E(t,i)^{ship}_{annual} \qquad 4$$

Where

$$E(t,i)^{ship}_{annual} = \begin{cases} 0, & t_{ship\ age} \geq t_{scrappage} \\ E(i)^{ship}_{annual}, & t_{ship\ age} < t_{scrappage} \end{cases} \qquad 5$$

The total committed emissions for each class including speed reduction, E^{class}_{speed}, is then calculated by applying a speed reduction factor to the classes annual emissions each year, $E(t)^{class}_{annual}$, and then summing the reduced annual emissions across the total number of years, from a start year of 2019 (t_0) to an end year of 2060 (t_{end}). The calculation assumes a start year for speed reductions as t_{start}, the percentage number of ships implementing speed reduction of $N_s(t)$, an emission reduction factor for speed reduction, f_s, and annual baseline emissions, $E(t)^{class}_{annual}$ (equation 6). $N_s(t)$ is a function of time and increases from 0 to 1 from a start year of t_{start} to a year of full fleet implementation, t_{full}, which are both set manually. $N_s(t)$, therefore, depends on the number of years taken to achieve fleet-wide implementation of speed reduction, assuming a linear year-on-year adoption rate.

$$E(t)^{class}_{speed} = \sum_{t_0}^{t_{start}} E(t)^{class}_{annual} + \sum_{t_{start}}^{t_{end}} E(t)^{class}_{annual}(1 - N_s(t) f_s) \qquad 6$$

Where

$$N_s(t) = \begin{cases} 0 < N_s(t) < 1, & t_{start} < t < t_{end} \\ 1, & t \geq t_{end} \end{cases} \qquad 7$$

Technical and Operational factors

A very wide variety of operational measures could be applied, such as voyage optimisation, the use of wind-power (rotors, sails), shore power, and resistance reduction devices. The evidence from Bouman et al. and other sources (Bouman et al., 2017, DNV GL, 2018) suggest that these mostly operate in the 0-10% improvement range, and not all are applicable to every vessel type – for example Flettner rotors are more appropriate for bulk carriers than for containers. There would also be a lag in deployment. For example, some improvements require retrofits in shipyards, and capacity is limited: the current rush to fit scrubbers to existing ships to meet the 2020 IMO air pollution regulations has seen just 3,000 vessels retrofitted(Clarksons, 2019a). We assume that overall, the sum of operational measures could deliver 5-35% improvements across the fleet, with deployment taking 8-15 years.

The committed emissions including technical and operational measures are calculated through the same process as for speed reduction, but replacing the emission reduction factor for speed, f_s, with the reduction factor for technical/operational measures, f_t, and using updated assumptions for t_{start} and $N_t(t)$.

Blended fuels

There is the potential for ships to use a proportion of zero-carbon fuel in their engines, and there are uncertainties over which zero-carbon fuels will dominate in the long-term. Shipping companies are starting to explore the use of biofuels, for example Maersk recently trialling the use of up to 20% blended biofuels on a containership journey from Rotterdam to Shanghai (Maersk, 2019). Use of blended fuel is constrained however by cost, scalability and the uncertainties over whether fuels are genuinely low or zero-carbon, for example biofuels (Gilbert et al., 2018). On biofuel carbon emissions, the literature shows wide ranges in greenhouse gas emissions (Gough et al., 2018), for example between –634 and +260 kgCO2/MWh for UK bioenergy sources (Welfle et al., 2017). On scalability similarly, there are very large ranges for the potential global bioenergy resource (Slade et al., 2011), eg 22-1272 EJ (Slade et al., 2014), let alone the proportion of this which could be realised without negative impacts on other sustainability goals. Any use of biofuels in shipping would need strict sustainability standards to ensure genuine emissions savings, and to ensure its production was not in conflict with other sustainability goals. Here, it is assumed that blending will become more commonplace in the 2020s, with ships using blended fuels increasing 2-4% a year, and the proportion of blended fuel also increasing at 2-4% a year, and this use of biofuels would deliver 100% emissions savings over use of conventional diesel fuel.

This study assumes that ships increase the amount that their fuels are blended by δ each year, with the percentage number of ships using blended fuel increasing by ΔN_b per year. Therefore, in the n^{th} year, the committed emissions from ships *not* using blended fuel is

$$E(t)_{no\ blend} = E(t)_{annual}^{class}(1 - \Delta N_b n) \tag{8}$$

As ships percentage fuel blend increases by δ each year, in the n^{th} year ships using blended fuel will produce annual emissions of $E(t)_{annual}^{class}(1 - \delta n)$. However, as the total number of ships using blended fuels increases by ΔN_b each year, the committed emissions from ships using blended fuels in the n^{th} year is

$$E(t)_{blend} = E(t)_{annual}^{class}\left[\Delta N_b(1 - \delta n) + \Delta N_b\big(1 - \delta(n-1)\big) + \Delta N_b\big(1 - \delta(n-2)\big) + \cdots\right] \tag{9}$$

Simplifying this, equation 9 becomes

$$E(t)_{blend} = E(t)_{annual}^{class}\Delta N_b[n - \delta(n + (n-1) + (n-2) + \cdots)] \tag{10}$$

As $\sum(1 + 2 + \cdots + N) = {N(N+1)}/{2}$, equation 10 becomes

$$E(t)_{blend} = E(t)_{annual}^{class}\Delta \mathrm{N_b}\left[n - \delta\frac{n(n+1)}{2}\right] = E(t)_{annual}^{class}\Delta N_b n\left[1 - \delta\frac{(n+1)}{2}\right] \tag{11}$$

Using the above equations, the committed emissions for implementing blended fuels is calculated, $E(t)_{blend}^{class}$, assuming an implementation year of t_{start}, with the percentage number of ships using blended fuels of $N_b(t)$ each year and the proportion of blended fuel increasing by δ per year.

$$E(t)_{blend}^{class} = \sum_{t_0}^{t_{start}} E(t)_{annual}^{class} + \sum_{t_{start}}^{t_{end}} E(t)_{no\ blend} + E(t)_{blend} \tag{12}$$

Combining equations 8, 11 and 12 gives

$$E(t)_{blend}^{class} = \sum_{t_0}^{t_{start}} E(t)_{annual}^{class} + \sum_{t_{start}}^{t_{end}} E(t)_{annual}^{class} \left[1 - \Delta N_b(t - t_{start}) \frac{\delta(t - t_{start}) + 1}{2}\right] \quad 13$$

As ΔN_b is the percentage *increase* in the number of ships using blended fuels each year, then the percentage *total* number of ships using blended fuels in that year, $N_b(t) = \Delta N_b(t - t_{start})$, where $N_b(t)$ is subject to the same constraints as equation 7. Therefore,

$$E(t)_{blend}^{class} = \sum_{t_0}^{t_{start}} E(t)_{annual}^{class} + \sum_{t_{start}}^{t_{end}} E(t)_{annual}^{class} \left[1 - N_b(t) \frac{\delta(t - t_{start}) + 1}{2}\right] \quad 14$$

$$E(t)_{blend}^{class} = \sum_{t_0}^{t_{start}} E(t)_{annual}^{class} + \sum_{t_{start}}^{t_{end}} E(t)_{annual}^{class} [1 - N_b(t) f_b] \quad 15$$

Where

$$f_b = \frac{\delta(t - t_{start}) + 1}{2} \quad 16$$

LNG is a fuel which can reduce local NOx and SOx air pollution. It can also have lower CO_2 emissions than diesel fuel, although the extent of this reduction is uncertain, given issues around methane slippage (Ushakov et al., 2019). Even if slippage were not an issue, there are still considerable lifecycle LNG GHG emissions and Gilbert et al. (Gilbert et al., 2018) conclude that without on-board CCS, there is *"limited opportunity to reduce GHG emissions from LNG".* The use of LNG is growing, but it should not be seen as solution to shipping's CO_2 mitigation challenge. Shipping, like all sectors, will need to be zero carbon by 2050 to meet the Paris 1.5 degree goal (IPCC, 2018b). As ships have an average lifetime of 28 years, ships built to use LNG in the early 2020s will need to be subsequently retrofitted to use genuinely zero carbon fuels.

Zero-carbon fuel retrofits

Zero-carbon energy for ships could come in a number of forms – chiefly ammonia, hydrogen, and batteries, amongst others. There are uncertainties about scalability, cost, range, and carbon benefits for these alternative fuels (Lloyd's Register, 2019, Ryste, 2019). In addition, large-scale deployment of any options may take many years, for instance DNV-GL note that it has taken LNG 20 years to reach 1% global deployment (Longva, 2019). A global consortium of 60 companies have set a goal of deployment of zero-carbon vessels by

2030 (Reuters, 23rd September 2019). Earlier dates may be possible – for example the UK Government has set a similar goal for 2025 (Department for Transport, 2018). In this study we assume a range of 2025-2035 for deployment of zero-carbon vessels, and a corresponding date range for the start of conversion of existing ships to use zero-carbon fuels. This transition may take many years – it is assumed here that the imperative of climate change would drive full deployment within 10-15 years.

This study calculates the committed emissions including the uptake of zero-carbon fuels, $E(t)^{class}_{zc}$, assuming the percentage number of the fleet using zero carbon fuels increases by $N_{zc}(t)$ per year.

$$E(t)^{class}_{zc} = \sum_{t_0}^{t_{start}} E(t)^{class}_{annual} + \sum_{t_{start}}^{t_{full}} E(t)^{class}_{annual}\big(1 - N_{zc}(t)\big) \qquad 17$$

Combining emission reduction measures

When multiple measures are applied in a single year, the committed emissions for that year, $E(t)^{class}_{combined}$, is calculated by applying the measures sequentially.

$$E(t)^{class}_{combined} = E(t)^{class}_{annual}(1 - N_s(t)f_s) * (1 - N_t(t)f_t) * (1 - N_b(t)f_b\ ) * \big(1 - N_{zc}(t)\big) \qquad 18$$

The committed emissions from that ship class, $E^{\ class}_{\ reduced}$, is calculated by combining all emission reduction measures with specified start dates and uptake rates for each measure.

$$E^{\ class}_{\ reduced} = \sum_{t_0}^{t_{end}} E(t)^{class}_{combined} \qquad 19$$

The committed emissions from all ships, $E^{\ fleet}_{\ reduced}$, is then calculated by summing this across the total number of classes, N_{class} (equation 20).

$$E^{\ fleet}_{\ reduced} = \sum_{class=1}^{N_{class}} E^{\ class}_{\ reduced} \qquad 20$$

These variables, equations and calculations can be seen in the sheets for each ship class, cells B15 to AT34, of the accompanying spreadsheet. The summed values across all classes can be seen in sheet "MASTER INPUT", cells C15 to R20.

8.2.4 EU vs Global carbon budgets

The carbon budget for the ships covered in the EU MRV is calculated from the range of the appropriate global budget and compared with the committed emissions values (see results section).

The analysis in this paper calculates committed emissions and a carbon budget solely for the ships covered by the EU MRV budget. It does not use the EU MRV data to estimate a committed emissions value for the global fleet. This is because there are significant differences within ship types between the characteristics of the ships in the EU MRV and their equivalents at a global level. For this paper we analysed the differences between EU and global data for two ship types – containers and refrigerated cargo vessels. For example, for containers, ships in the EU MRV are on average much larger than the global average, as shown in Figure 8-8.

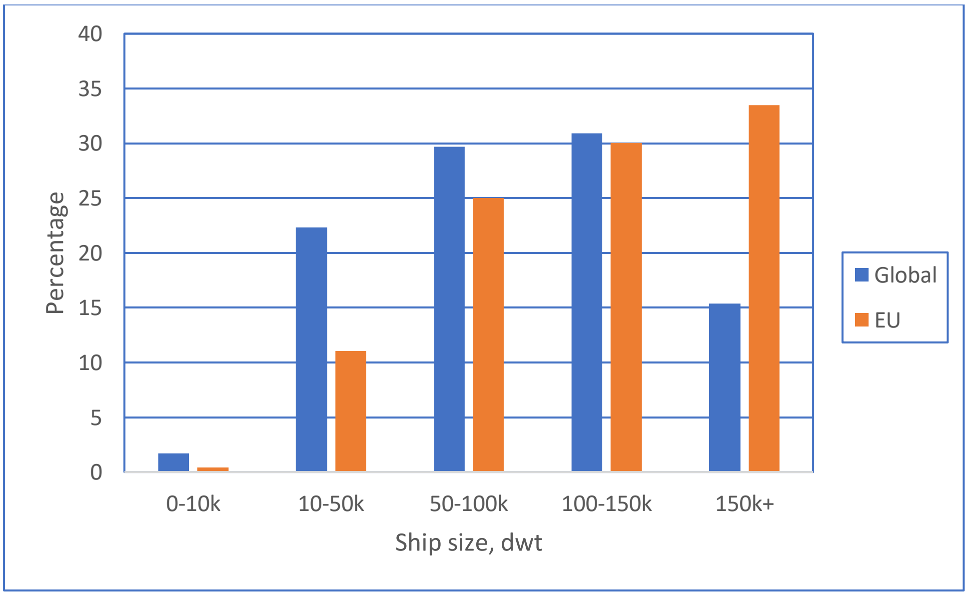

Figure 8-8 Percentage of container fleet tonnage in each size band, global vs EU MRV ships

For refrigerated cargo ships, EU MRV ships are on average three times larger and nine years younger than the global average. These results suggest it would not be appropriate to assume that analysis at an EU level could be translated up to the global level. Similar conclusions about the non-transferability of the EU MRV data to the global level are made by Panagakos et al. (Panagakos et al., 2019) in their paper on bulk carrier MRV data, with their analysis that Energy Efficiency Operational Indicator (EEOI) values are lower for ships in the EU MRV, compared with globally.

8.3 Supplementary material for Chapter 5

For reasons of brevity, Chapter 5's results section omitted detail on two components of the structure of the UK shore power system: its institutions and infrastructure. It also heavily abridged the analysis on the current functionality of the UK shore power system. This supplementary information presents these details in Sections 8.3.1-8.3.3, plus further methodological details in Sections 8.3.4-8.3.6.

8.3.1 Institutions

After the system's actors, the second structural component of the UK shore power system is the institutions that govern and guide its deployment: the 'hard' rules and regulations, set out in Table 8-2, and 'soft' norms and customs, such as whether or not energy use is considered a core element of ports' business models.

Table 8-2 Hard institutions for UK shore power

Level	'Hard' Institutions
Global	There are currently no global tax or regulatory policies supporting shore power via the IMO. There are comprehensive technical ISO electrical and safety standards governing ship, shore and ship-to-shore equipment.
Regional	The EU has a weak regulation for adoption of shore power infrastructure in ports. The EU is consulting on new maritime policies as part of the EU Green Deal, the Fuel EU Maritime Initiative (European Commission, 2021b) and revisions to the Alternative Fuel Infrastructure Directive (European Commission, 2021a), which include clauses to mandate shore power. The effect of potential new EU legislation on the UK will be indirect, following Brexit, yet it will continue to be important as ship owners who are required to connect to shore power at EU ports are likely to expect to be able to connect to the UK grid.
National	The UK has various strategies relating to shipping, including the 2019 Clean Maritime Plan (CMP) (UK Government, 2019b) and a Clean Air Strategy (UK Government, 2019a), with guidance on Port Air Quality strategies (Department for Transport, 2019b), although at present there is no formal requirement from the UK Government on ports to cut emissions, or on ports or ship operators to install or use shore power, nor policies to promote its deployment. The UK issued a call-for-evidence for policies to support shore power in February 2022 (Department for Transport, 2022b)

8.3.2 Infrastructures

The third structural component is the physical, financial and knowledge infrastructures – the resources necessary for actors to deploy shore power, which are set out in Table 8-3.

Table 8-3 Infrastructures for UK shore power

Infrastructures	Status
Physical	Electrical infrastructure owned or operated by ports is often old and in need of upgrade, compared with other parts of the grid. Ships operate increasingly sophisticated electrical systems, but these would need upgrades to accommodate far higher electrical loads required to replace their auxiliary engines' power supply.
Financial	Costs of shore power projects vary greatly, but a conventional project might cost over £1million port-side, and £100,000 per ship. These costs are non-trivial, particularly for ports, and no commercial scheme has gone ahead worldwide without some government financial support. Major funding streams for shore power exist in some other countries, but in the UK this is far more limited. Two shore power projects are in development with Government support from generic industrial funding streams: in Southampton with funding via the Local Enterprise Partnership, and in Orkney with joint funding from the Scottish Government and the EU. The UK's £23m Clean Maritime Demonstration Competition awarded £500,000 in September 2021 for work at Aberdeen, including a shore power feasibility study (Department for Transport, 2021a).
Knowledge	The shipping and ports networks have both operated separate working-groups looking at shore power, and there have been occasional cross-sector webinars in the last two years. The UK Knowledge Transfer Network has a shipping sub-group on decarbonising ports and harbours. There is a lot of knowledge and expertise at some individual ports and shipping companies on the practicalities and difficulties of UK shore power projects, and in the trade associations on the barriers affecting the sector as a whole.

8.3.3 Shore power system functionality

The three structural components interact to affect seven highly inter-dependent and mutually reinforcing or destabilising system functions (Table 5-2).

In terms of their relative strength in relation to UK shore power, this research revealed that most advanced function is Guidance of the Search (F4) – there is an increasingly clear narrative and direction from Government and other stakeholders that decarbonisation is essential and inevitable, and that shore power has a role to play in delivering it.

Almost all interviewees stated that the pressures on the sector to address climate change and air pollution have grown and are expected to increase, with consensus that shore power was one good solution among many others needing to be deployed,

> "*there won't be one solution for the future, there'll be a whole palette of different solutions*" [interviewee Shipping Operator 12],

and the view that shore power would be complementary with other technologies,

> "*I don't know what ship owner would choose to keep running on hydrogen or ammonia when they can simply plug in and turn all that off*" [interviewee Shipping Operator 5].

Interviewees stressed the pivotal importance of policies for shore-power being integrated within a clear, coherent and funded overall shipping decarbonisation strategy

> "*The EU for all its faults is pushing it, and is pushing it really hard. Because of that things are starting to happen, that's what we need to see from the DfT here*" [interviewee Shipping Operator 4]
>
> "*What's going to be the Government strategy? How do they see the shore power going? Somebody's got to provide a plan or a strategy and build a framework for how that's going to be funded with all the stakeholders*" [interviewee Shipping Operator 7].

Interviewees noted the UK's new Clean Maritime Plan (CMP) and its broad commitment to maritime decarbonisation, and its specific documentation on shore power. However, the lack of specific policies in the CMP to deliver either its wider goals or to support specific technologies was a widely expressed concern. In July 2021, after the interviews took place, the UK Government introduced the Transport Decarbonisation Plan, which contains stronger and more specific commitments to both maritime decarbonisation, and to developing policy to support shore power deployment. The Government is therefore now giving stronger "guidance of the search" to the maritime sector on shore power, but the specifics of how that support will manifest itself is still unclear. This adds to the perception within the sector that although shore power is a deployable technology now, it won't happen without policy support.

Knowledge Development and Knowledge Dissemination (F2&F3) are both reasonably advanced, though with notable gaps, particularly around absence or weakness in a number of critical relationships, for example between ports and DNOs, and in a lack of centralised repositories for key data or ideas, such as around business cases or electricity network upgrades.

Shore power was seen as a proven technology across all interviewee classes, with early technical difficulties having been addressed and ISO global industry technical standards covering all aspects of the technology. Literature on how shore power can alleviate local air pollution and cut carbon emissions is also comprehensive. A difficulty, identified particularly by port operators, was that there was comparatively little information on developing robust business cases for individual shore power projects, or on innovative business models on how a port could develop a more integrated and profitable energy ecosystem in which shore power may play a role. More generally, because energy and electricity management tends not to be a priority for ports, shore power tends not to be a priority either. Energy is not a core element of most ports' business models, and within this, the energy consumed by ships is often seen as something outside of a port's remit. One interviewee observed that for ports,

> "*Industrial electrical systems just isn't their day-to-day business. It's like asking a butcher to bake a cake*" [interviewee Other 2].

As shore power in the UK is not mandatory, and as the business cases are often weak, the drive for knowledge dissemination around how to deploy shore power is not driven by individual ship or port operators, but rather by trade associations, who tended to take a longer-term perspective. The culture of the sector is one of competition, and there is often an unwillingness to share information between entities who may be seen as rivals. The trade associations make concerted, sustained efforts to information-share, with working groups and webinars on issues such as shore power. However, there is little information sharing between ports. Some ports have built relationships with some ship operators, but it was striking how little interaction there was between ship and port operators on shore power or on climate change issues more broadly. The European port stakeholders interviewed stressed the critical importance to project success of developing strong relationships with shipping operators. Also, on interactions, there was perceived to be a lack of information-sharing between DNOs or electricity network regulators and ports around the issues of electricity pricing and grid upgrades. This was an area where ports felt that perceived complexity, cost and difficulty were major barriers to considering any electricity-related projects, shore power or otherwise. Institutionally, there is no one place where actors can go for comprehensive information on technical or economic issues concerning shore power. Finally, there is little dissemination of best practice or experience into the UK from EU countries and ports that have installed shore power

The weakest functions are Market Formation (F5) and Resource Mobilisation (F6) – with major problems around accessing grant funding, constructing compelling business cases and the lack of policy support around fuel and electricity pricing. Interviewees repeatedly stressed two main barriers. First, the lack of capital funding support from the UK Government, contrasted with Europe

> "*In Europe nearly all of them are 60-70% funded by the state, up to 90 in Germany*" [interviewee Other 4].

Partly this is because of the port-ownership structure in the UK, which is predominantly private, whereas in the EU, ports are more often owned publicly - making funding easier to obtain. A more strongly expressed view by interviewees was that the lack of funding is because shipping is a low political priority for the UK Government generally and also within the Department for Transport. Interviewees contrasted low funding for shipping with that available for other UK transport modes:

> "*Look at how much Government is spending on other segments: on automotive, rail, how much have they spent on marine? Almost nothing*" [interviewee Shipping Operator 8].

Such funding is however essential as no shore power project has gone ahead worldwide without some government support.

The second major barrier is that shore-power, and indeed all alternative fuel technologies, have to compete with untaxed marine diesel oil.

> "*What we tend to forget is the prices for these fuels are so cheap because everything has been subsidised in fossil fuels. So, we're comparing with something that has been enormously subsidised by dozens and dozens of countries around the world for decades*" (interviewee European Port 2).

This is a problem globally but compounded in the UK by high levels of electricity taxation:

> "*We have some of the most expensive electricity in Europe… so you end up spending ¾ of a million or whatever on a shore power installation, want to recoup the capital cost…it becomes quite a difficult commercial proposition*" [interviewee Port Operator 15].

Countries like Germany, France, Denmark and Sweden have all lowered the electricity taxes paid by shore power projects; the UK does not do this. A further barrier to market formation is that shore power projects are complex, requiring the co-operation of four main entities: port, shipping operator, DNO and equipment provider.

On resources (F6), ports are experiencing further difficulties mobilising financial resources to deploy shore power. The lack of capital grant funding from Government is compounded by its decision to remove the subsidy for red-diesel used by ports, with interviewees stating that this will introduce costs, reducing ports' ability to fund capital projects.

In addition, Covid-19 has led to major reductions in shipping demand, particularly for the cruise and ferry segments which are two of the more likely early-adopters of shore power, given their regular journey profiles, greater electricity demands and the more public-facing nature of their business. Shipping operators have consistently worked with small profit margins, however Covid-19 has reduced both available financial resources and organisational capacity as these resources are required to address immediate threats to their business. More broadly, Covid-19 and Brexit were cited as reasons that shore power would take lower priority in the short-term. A further actor-related issue is that the prevalent private port-ownership model in the UK means that projects with longer pay-back periods are harder to justify.

Old infrastructure was also identified as a barrier:

> *"Our electricity networks are old, not replaced with a frequency of a DNOs network. There isn't the throughput of electricity to pay for its maintenance, at the pace you'd do at a DNO. We've still got oil filled capacitors and cables" [interviewee Port Operator 3].*

Some interviewees also expressed concern regarding costs:

> "*It's inordinately expensive, especially to retrofit in an older port environment*" [interviewee Port Operator 11].

A final difficulty with resource mobilisation is a number of absent or weak relationships between critical actors. First, port and ship actors must work together effectively if shore power infrastructure is to be installed *and* used:

> "*The most important step [for a port] is to get a ship owner on board. Maybe just the one, but you need somebody signing up to use it [shore power] for a certain period of time and if you have that in place you have the first step and you can build on that. But starting to build without a ship owner on board, it's extremely difficult*" [interviewee European Port 3]

However there was a repeated frustration expressed about these relationships, with ports arguing that:

> "*The ship owners: they're not doing anything*" [interviewee Port Operator 16],

and ship owners that:

> "*We are waiting on port authorities to step up to the plate*" [interviewee Shipping Operator 10].

This leads to a "chicken and egg" problem, and interviewees often laid the responsibility for lack of action on each other. Many stressed that port and shipping entities need to collaborate more.

Another interaction tension is that ports tend to have very low levels of interaction with DNOs and the National Grid, despite uncertainty about grid capacity for shore-power projects repeatedly being cited as a problem. There was widespread frustration that:

> "*Generally DNOs aren't interested*" [interviewee Port Operator 3]

or that getting information or quotes was difficult:

> "*It's just wading through treacle at the moment*" [interviewee Port Operator 13].

Other interactions were also seen as important. For example, greater collaboration between shipping operators was seen as beneficial to build demand for shore power:

> "*We should talk to each other more… maybe together we can generate a demand in some areas that makes it more feasible if we share it…the ports are saying 'there's not the demand, so we've not put anything in' – well, let's generate the demand then*" [interviewee Shipping Operator 4].

Greater collaboration between port actors was also seen as conferring advantages, for example to create an effective network of shore-power berths [Interviewee European Port 4]. However there are major differences between ports, in ownership structures, purpose, function and size. Consequently, the concerns and priorities of port actors vary widely.

These market and resource barriers feed into low levels of Entrepreneurial Experimentation (F1), and problems of Creating Legitimacy (F7). Although there are established global companies offering shore power equipment and installation packages, as well as experimenting in response to customer needs, the complexity of projects, financial barriers and lack of policy support are preventing experimentation. Ports do not yet see energy as a core business, and shore power tended not to be seen by ship operators or ports as an entrepreneurial opportunity, but rather something that might be required by them in future in response to regulatory pressure.

Some ports expressed interest in entrepreneurial activities around the potential to become "smart-energy hubs:

> "*Smart energy hubs potential? That's one of the things I'm most excited about. It's an opportunity"* [interviewee Port Operator 16],

but they also expressed uncertainty about how such opportunities could be seized, given again that:

> "*Operating energy assets is not our core business*" [interviewee Port Operator 3].

Interviewees describe how shore power is increasingly seen to be a legitimate choice in reducing air pollution and greenhouse emissions, however that financial legitimacy for shore power is often hard to establish within the boardrooms due to the weak business case, project complexity, lack of regulatory drivers and competing priorities (notably Covid-19 and Brexit). Interviewees often stressed that shore power growth in other jurisdictions was likely to spur future deployment in the UK; the recent inclusion of stronger shore power regulation in the EU Commission's proposed "Fit for 55" package in July 2021 is likely to strengthen this perception. Positive signs are that lobbying for shore power has increased in the last two years, with the UK Major Ports Group, the British Ports Association, the UK Chamber of Shipping and the umbrella group Maritime UK all making interventions calling for stronger policy and support for maritime decarbonisation, including for shore power.

8.3.4 Example interview guide with ship operators

General views on climate change and shipping

Q1 Could you tell me how you see shipping in your sector developing over the coming 10 years in response to climate change challenges set out by the IMO and the Paris Climate Agreement, and air quality challenges?

General views on shore power

Q2 Turning specifically to shore power now, what are your views on the benefits or disadvantages of ships using shore power?

Q3 Do you feel that the pressures or benefits for shore power will be stronger in future? In which areas?

Turning now to your specific sector and company

Q4 Could you tell me about what the company monitors currently in terms of environmental performance?

Q5 Turning to SP as a possible solution within environmental management, what assessments have you made of shore power at your business and what was the motivation for this?

Barriers to shore power

Q6 Could you give your view of reasons why your business/sector/company might find it difficult to implement shore power?

Solutions: overcoming barriers to shore power

Q7 What measures do you think are most necessary to make shore power a viable proposition in shipping, and who is responsible for making these happen?

Q8 (if applicable) Your business clearly is not just operating in the UK. How important is what happens in the UK (eg ports or UK regulation) in terms of any decision you might make on SP?

8.3.5 Analysis of shipping transition papers:

The methods used in shipping transition studies are very varied, with the Multi-Level Perspective (MLP), Agent-Based Modelling, Technological Innovation Systems (TIS), Multiple Streams Approach (MSA), Value Chain methods, Dynamic Capabilities, Transition Management, Actor Roles Frameworks, New Institutional Economics and Practice Theory all used, reflecting the diversity of methodological tools highlighted by (Sovacool and Hess, 2017).

8.3.6 NVIVO deductive codes

	A	B	C	D	E	F
54	3.5 Barrier Electricity supply	0	5.1 Solution - Economics	0	5.4 Solution - complexity	0
55	3.5.1 Insufficient grid capacity	38	5.1.1 CAPEX capital grants	29	5.4.1 3rd party leasing	14
56	3.5.2 DNO general points	6	5.1.1 CAPEX economies of scale	2	5.4.2 guide to electricity charging	1
57	3.5.3 DNOs concern re peaky lo	2	5.1.1 CAPEX tax breaks	5	5.4.3 guide to network upgrades	1
58	3.5.3 DNOs don't want offgrid	1	5.1.1 Loans	1	5.4.4 Requirements documentatic	1
59	3.5.3 DNOs say no capacity	3	5.1.1 Tech options to cut costs	1	5.5 Solution - supply	0
60	3.5.3 DNOs say overgeneration	3	5.1.2 Fine tune business case	1	5.5.1 prioritise upgrades	3
61	3.5.4 DNO say too expensive	1	5.1.2 PRICING bulk buying	1	5.5.2 Shipping lines pressure ports	1
62	3.5.4 DNOs not interested	3	5.1.2 PRICING carbon pricing	7	5.6 Solution - Certainty	0
63	3.5.4 DNOs too busy	0	5.1.2 PRICING electricity chargi	22	5.6.1 contracts	9
64	3.5.4 DNOs too slow	2	5.1.2 PRICING govt incentives t	1	5.7 Solution - link to wider electric	7
65	3.5.5 DNO ports don't talk	2	5.1.2 PRICING Port incentives tc	2	5.8 Solution - policy packages	3
66	3.5.5 DNOs dont understand pc	5	5.1.3 COMPONENT suppliers	3	5.8.1 UK Govt strategy	24
67	3.5.5 Don't know who to talk to	2	5.1.4 R&D on SP hybrid links	1	5.8.2 Focus and quick wins	12
68	3.5.5 ports do proposals piecen	1	5.1.5 Mobile solutions	8	5.8.2 Integration between Govts	1
69	3.6 Barrier Project complexity	0	5.1.6 hybrid charging solution	5	5.8.3 Action at IMO	1
70	3.6.1 costs of capex componen	4	5.1.7 Cheap electricity financin	2	5.8.4 Port infrastructure planning	1
71	3.6.1 electricity charging comp	4	5.2 Solution - Regulation	0	6. Choice quotes	40
72	3.6.1 general complexity	3	5.2.1 ZE Berth standard	32		
73	3.6.1 multi stakeholder	7	5.2.2 SP regulation	19		
74	3.6.1 Not enough information	2	5.2.3 ZE Port standard	11		
75	3.6.1 Port ownership complexit	6	5.2.4 EU legislation	4		
76	3.6.1 regulatory regime comple	0	5.2.5 IMO regulation	3		
77	3.6.2 energy not core business	6	5.2.6 Standards for new ports ar	1		
78	3.6.2 Govt don't understand SP	2	5.2.7 Port incentives	7		

Figure 8-9 Screenshot showing some of the NVIVO deductive codes

8.4 Supplementary Information for chapter 6:

Results from Multi-Criteria Assessment of main components of shore power system:

Option	Cost	Cost matrix number	Maintenance	Maintenance matrix number	Quality of design solution	Quality of design matrix number	Inherent risk	Inherent risk matrix number	Supplier track record	Supplier track record matrix number	Effect on port operations	Effect on port operations matrix number	Flexibility	Flexibility matrix number	Lifetime / futureproofing	Lifetime / future proofing matrix number	Weighted matrix number	Rank
Decentralised	Highest cost	3	Higher maintenance cost as more units to service	3	Design not a simple or cost-effective solution	3	More HV cabling to protect	3	Less supplier options for fully decentralised	2	Most likelihood to effect operations	3	Flexibility to use shore power and cable management across the port	1	Good lifetime for equipment. Not futureproofed	3	2.7	3
Semi-centralised	Lowest cost than decentralised due to savings around single frequency converter and also minimising flexible plant around port	2	Lower maintenance costs but more units than centralised	2	For purpose of the port where LV solutions work the 2nd best quality design	2	Risk of HV transformers on dock side	2	Multiple suppliers able to offer	1	Some likelihood for operations impact	2	Centralised frequency converter mean other berthing area would need this too.	2	Good lifetime for equipment. Futureproofed	1	1.8	2
Centralised	Intermediate cost option due to centralised plant but need infrastructure for all berths	2	Lowest maintenance cost	1	Best quality design for the purpose	1	Least risk	1	Multiple suppliers able to offer	1	Minimal likelihood to effect operations	1	Infrastructure cannot be used on other berths without additional infrastructure	2	Not fully futureproofed due to cable size limits	2	1.4	1

Figure 8-10 MCA for centralised vs decentralised solution

Option	Cost	Cost matrix number	Maintenance	Maintenance matrix number	Quality of design solution	Quality of design matrix number	Inherent risk	Inherent risk matrix number	Supplier track record	Supplier track record matrix number	Effect on port operations	Effect on port operations matrix number	Flexibility	Flexibility matrix number	Lifetime / futureproofing	Lifetime / future proofing matrix number	Weighted matrix number	Rank
Fixed above ground connection point	Lowest cost option	1	General maintenance costs, easy maintenance access. Potential to get damaged by quayside operations	2	Has minimal impact to quayside operations if located close to quay edge	2	Risk involved in damaging the fixed connection point whilst in use. Construction of bollard around the connection point	2	Multiple suppliers able to offer	1	Has minimal impact to quayside operations if located close to quay edge. At the front of the ship to minimise disruption	2	Fixed solution	2	Good lifetime for equipment, fixed no moving parts	1	1.6	1
Fixed below ground connection point	Higher cost option	2	Higher maintenance cost due to buried construction. Access chamber could get damaged by quayside operations.	3	Access chamber would have to be closed to allow normal operations to continue	2	Risk involved in manual lifting the access chamber, water ingress into the chamber and crane movements around the access chamber	3	Fewer suppliers able to offer, often bespoke solutions	2	Access chamber would have to be closed to allow normal operations to continue. At the front of the ship to minimise disruption	2	Fixed solution	2	More moving parts, lower lifetime on equipment	2	2.3	2

Figure 8-11 MCA for cable connection

Option	Cost	Cost matrix number	Maintenance	Maintenance matrix number	Quality of design solution	Quality of design matrix number	Inherent risk	Inherent risk matrix number	Supplier track record	Supplier track record matrix number	Effect on port operations	Effect on port operations matrix number	Flexibility	Flexibility matrix number	Lifetime / futureproofing	Lifetime / future proofing matrix number	Weighted matrix number	Rank
Shore side fixed cable management point	Low-cost option	1	Some mechanical aspects to maintain	2	Has an impact of the port	2	Bespoke for connection	1	Multiple suppliers able to offer	1	Most likelihood to effect operations	3	Flexibility to use shore power and cable management across the port	2	Good lifetime for equipment. Not futureproofed as may need new infrastructure	2	1.65	2
Shore side flexible cable reel	Low-cost option and flexible	1	Low maintenance cost	1	Has an impact of the port	2	Cables to be moved	2	Multiple suppliers able to offer	1	Some likelihood for operations impact with long durations at port	2	Centralised frequency converter mean other berthing area would need this too.	1	Good lifetime for equipment. Futureproofed as cable can be easily replaced	1	1.35	1
Ship side flexible cable reel	More units required as on ship	3	Low maintenance cost but difficult to monitor maintenance	2	Has an impact of the port	2	Cables to be moved and dropped	2	Multiple suppliers able to offer	1	Minimal likelihood to effect operations	1	Infrastructure cannot be used on other berths without additional infrastructure	1	Not fully futureproofed due to cable size limits	1	1.8	3
Shore side port tracking connection	Very expensive	3	Highest maintenance costs as moving parts	3	Neat solution	1	Minimal safety risk	1	Fewer options available	2	Minimal likelihood to effect operations	1	Most flexible option	1	Would need to replace infrastructure if you were to change operations	2	1.9	4
Shore side buried cable reel	Buried service expensive and multiple required	3	Maintenance issues with buried solution	2	Neat solution	1	Cables running across the port	2	Buried option not a typical offer	2	Minimal likelihood to effect operations	1	No flexibility to move if required	2	Would need to replace cable for buried service if you were to change operations	2	2	5

Figure 8-12 MCA for cable-management system

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