Financiers’ expectations and the risk of stranded assets in the shipping industry

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I, Marie Fricaudet, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the work.

Abstract

Asset stranding is pertinent to shipping stakeholders for several reasons. First, due to their extended lifespan, the modelling undertaken in this thesis showed that around 40% of the existing and ordered ships will need to transition to cleaner technologies during their operational lifetime or face premature scrapping to align with a 1.5°C pathway. However, several of those technologies are still in their infancy and offer a variety of potential options. This creates an environment of uncertainty for investments. Second, because ships are predominantly financed through debt, asset devaluation is potentially a significant concern for lenders.

This thesis aims to study the interplay between:

- Financiers' expectations of the upcoming transition in shipping;
- The investment decisions by shipowners; and
- The materialisation of the risk of stranded asset.

To do so, this thesis establishes a theoretical framework building on the Multi-Level Perspective which describes of five archetypal behaviours which the financiers could adopt in the future. The expectations and behaviours of shipping financiers are investigated through the lens of this framework using a mixed methods approach. The results show that that after decades of inertia, shipping financiers are now expecting a transition to low-carbon shipping to take place, although the shift in expectations is partial and ambiguous. In-depth interviews with financiers have shown that this ambiguous shift and the importance of the relationships and trust with their existing clients mean that they have expressed the intention to support them in the upcoming transition to low-carbon shipping, but are wary of supporting new entrants and some of financing unproven technologies. Furthermore, a regression analysis of loans spreads has shown that banks are now providing cheaper loans to shipowners with higher climate performance, but not to less carbon-intensive ships. The consequences of such a behaviour have been investigated in a scenario analysis. The modelling results show that regardless of the behaviour of the financiers, , should the shipping industry align with a 1.5°C trajectory, the amount of stranded capital could reach up to the full fleet value, if retrofit was uneconomic or unavailable, but can be reduced by around 50% if retrofit is possible. However, if financiers' expectations of stranded assets translates into concrete behaviour, and if financial policy is further implemented, this leads to an early uptake of zero-/low-carbon ships in the 2020s which significantly accelerates the transition, reduces the amount of stranded assets (by up to 44%) and reduce cumulative emissions by up to a 25% over the period to 2050.

Impact statement

This thesis aims to explore the expectations and roles of financiers in the ongoing low-carbon transitions, with a particular focus on the shipping industry. Traditionally, finance has been seen as a passive and external resource in transition studies and energy modelling, in particular when studying shipping. This work has shown that financiers have evolving expectations of stranded assets; and that their behaviour can have an influence on how low-carbon transitions unfold, making the case for a more realistic consideration of their role in future transition research and in energy modelling. This would enable a more realistic representation of low-carbon transitions in shipping and in other sectors. To do so, this thesis has proposed a new theoretical framework and has tested several methods on how to characterise the expectations, preferences and the role of financiers. The findings have been published in two academic papers (one in pre-print but pre-accepted after passing being approved by the reviewers) and presented at two academic conferences.

The thesis has modelled the consequences of financiers' behaviour and associated differentiated cost of capital by technology on the unfolding of a low-carbon transition in shipping and the resulting stranded assets. The results have several implications for policy-makers at the national, regional and international (International Maritime Organisation, IMO) level. First, policy-makers should consider the role of existing non-aligned ships during this transition and whether mandates for retrofitting, under-utilisation, or scrapping should be imposed. Second, the findings support the argument for enhancing disclosure initiatives, intensifying monitoring efforts, or implementing more interventionist policies to regulate the financial sector, focusing not only on shipowners. If these measures are implemented early and supported by proactive financiers, they can facilitate a smoother and more cost-effective transition to low-carbon shipping. Furthermore, this study provides a potential blueprint for developing more refined conceptual tools for guiding industry and financial policy approaches to ensure that the transition to low-carbon shipping avoids creating unnecessary stranded assets. Such novel insights and policy approaches could be gained by understanding the way the access and cost of capital in shipping varies not only depending on the nature of the technology and investor, which is the focus of this thesis, but also on the country of the industry player.

Finally, this work has highlighted some of the risks of stranded assets that financiers and investors are facing, enabling them to better anticipate these risks, based on the premise that stranded assets are avoidable surprises. These findings have already been applied in the private sector through two UCL reports and two academic articles. The results have been shared via presentations at the Marine Money Forum, a workshop with shipping financiers, a podcast, and several press articles including the Financial Times. A key implication of these results is that financial institutions do not fully anticipate transition risks aligned with a 1.5°C future, and therefore few vessels investments are climate-resilient. Such expectations are particularly relevant as policy measures which have the potential to trigger such risks are either coming into force (e.g. inclusion of shipping in the EU ETS, IMO short-term measures) or are currently being discussed (IMO mid-term measures).

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Finally, I am deeply grateful to my family and friends for their continuous support, especially during the modeling period when my mood was often dictated by whether Python was bombarding me with error messages or cooperating. A further special thanks to my friend Xochilt Armenta, who, on top of providing this emotional support, has proofread most of the text presented here.

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Publications resulting from this thesis

Fricaudet, M., Prakash, V., Sohm, S. Smith, T. and Rehmatulla, N., Fossil fuel carrying ships and the Risk of Stranded Assets. A report by the UCL the Bartlett Energy Institute and Küne Foundation.

Fricaudet, M. Sohm, S. Smith, T. and Rehmatulla, N., Fossil Fuel Carriers and the Risk of Stranded Assets. PREPRINT (Version 1) available at SSRN: https:ssrn.comabstract=4788592 or http:dx.doi.org10.2139ssrn.4788592 Part of the results are integrated in Chapter 4, but the results in the ”Newbuild until 2030”, which explore the impact of further newbuilding after the year of writing, have not been included in this thesis.

Fricaudet, M., Parker, S., & Rehmatulla, N. (2023). Exploring financiers' beliefs and behaviours at the outset of low-carbon transitions: A shipping case study. Environmental Innovation and Societal Transitions, 49, 100788. https:doi.org10.1016j.eist.2023.100788 The method and part of the results are integrated in Chapters 6 and 5, but results regarding demand-side risks are not included in this thesis.

Fricaudet, M., Ameli, A. & Smith, T. (2023). "Lower margins are tied to companies' ESG rating rather than to low-carbon assets", PREPRINT (Version 1) available at Research Square [https:doi.org10.21203rs.3.rs-2586927/v1] The method and the results are including in Chapter 6

Fricaudet, M., Rehmatulla, N., & Smith, T. (2022). Understanding the Scale of the Stranded Assets Risk in the Shipping Industry. PREPRINT (Version 1) available at SSRN Electronic Journal [https:doi.orgPreprint at 10.2139/ssrn.4036552] The method and the results have been expanded to those included in Chapter 4

Fricaudet, M., Taylor, J., Smith, T. & Rehmatulla, N. (2022). Exploring methods for understanding stranded value : case study on LNG-capable ships. A report by the UCL the Bartlett Energy Institute The method is included in Chapter 7, but the report focuses on a smaller subset of the fleet (LNG-capable ships) than Chapter 7.

Co-authored publications:

Donnelly, D., Fricaudet, M., Ameli, N. (2023). “Accelerating institutional funding of low-carbon investment: The potential for an investment emissions intensity tax”, Ecological Economics, Volume 207, 107755, ISSN 0921-8009, https://doi.org10.1016j.ecolecon.2023.107755. The results are not directly included, but have been used to inform the discussion.

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Chapter 1

Introduction

In his address titled ”Breaking the Tragedy of the Horizon”, the Governor of the Bank of England highlighted how climate change could impact the performance of financial firms (Carney, 2015). Climate-related risks may manifest as a result of extreme climate events and asset stranding, which occurs when the abrupt implementation of climate policies leads to the sudden devaluation of certain assets (Batten et al., 2017; Caldecott and McDaniels, 2014). The latter issue, which is the focus of this thesis, is particularly pertinent to shipping stakeholders for several reasons.

First, due to their extended lifespan – which is approximately 25 years – most of the ships ordered in this decade will need to transition to alternative fuels during their operational lifetime or face premature scrapping to align with a 1.5°C pathway (Bullock et al., 2020; Caldecott et al., 2018). However, the zero/low-carbon marine fuel market is still in its infancy and offers a variety of potential options. This creates an environment of uncertainty for investments.

Second, because ships are predominantly financed through debt, asset devaluation is potentially a significant concern for lenders. Historically, most ship financing has been sourced from private equity and loans provided by commercial banks. Although there is a growing proportion of non-banking sources – such as leasing, alternative lending, private equity funds, public markets and equity investors (Del Gaudio, 2018; Drobetz et al., 2013) – banking debt still represents the largest share of external shipping finance (Alexandridis et al., 2018).

The following sections provide further context on the issue of decarbonising shipping; the role of financiers in shipping; and the rationale for investigating their role in the transition. The main concepts which will be used in this thesis are then defined and a brief overview of its structure is provided.

1.1 Elements of context: shipping transitions and climate change

Shipping can be impacted by two distinct low-carbon transitions (Smith et al., 2015):

- A shift towards zero/low-carbon shipping, aimed at minimising the carbon footprint of ships themselves (*supply-side* risks).
- Numerous socio-technical transitions within onshore industries; notably in the electricity generation and road transportation sectors, if they move away from fossil fuels and embrace renewables. This could lead to reduced transportation of fossil fuels such as coal, oil, and possibly Liquefied Natural Gas (LNG), while simultaneously creating potential new shipping demands for activities such as offshore wind farm operation, CO2 transport, and bioenergy shipment. These, coined by Smith et al. (2015), are defined in this thesis as *demand-side* risks and opportunities.

Although these two transitions are distinct, they are likely to happen simultaneously because they share similar incentives to reduce greenhouse gas (GHG) emissions, that is to say, to avoid the catastrophic effects of climate change; as well as being driven by similar technological developments (e.g. renewables, electrolyser). Let us discuss those two transitions successively.

1.1.1 Transitions to low-carbon shipping

Shipping accounts for approximately 3% of the total GHG emissions (Faber et al., 2020); mainly from containers, bulk carriers and oil tankers, due to their large prominence in shipping activity (see figure 1.2). These emissions are expected to increase between 90% and 130% by 2050 compared to the levels recorded in 2008 (Faber et al., 2020). This increase is expected in various global trade scenarios unless there are swift improvements in the energy efficiency of maritime fleets and the adoption of zero-/low-carbon propulsion technology and fuels (Halim et al., 2018; Smith et al., 2023; Smith et al., 2019c; Traut et al., 2018).

Shipping is characterised by a variety of potential zero / low carbon options (Balcombe et al., 2019; Bouman et al., 2017; Mallouppas and Yfantis, 2021; Serra and Fancello, 2020). Many renewable technology solutions and energy efficiency devices are mature or in later stages of development. However, the market for zero / low carbon marine fuels is in its early stages, with many marine fuels still in the demonstration and pilot phase (Campbell et al., 2023; Kilemo et al., 2022), creating an environment of uncertainty for potential investors. Such uncertainty happens at a time where they should largely be investing in the transition, with Raucci, Bonello, et al. (2020) showing that 1.2-1.6 trillion USD investment are needed if shipping is to fully decarbonise by 2050.

Zero / low carbon options include practices such as reducing ship work and vessel speeds, and implementing energy saving technologies such as wind assistance and air lubrication (an extensive list can be found in Mallouppas and Yfantis (2021)). Many of these options are already cost efficient even in the absence of climate mitigation (Faber et al., 2020; Schwartz et al., 2020), so that Schwartz et al. (2020) argues that emissions can be abated by up to 50% cost-effectively. The emission reduction potential of those options is summarised on Figure 1.1.

However, these methods must be complemented by the integration of zero/low-carbon fuels to align with a trajectory that limits global warming to 1.5°C (Halim et al., 2018; Mallouppas and Yfantis, 2021; Serra and Fancello, 2020; Smith et al., 2023; Smith et al., 2019c; Traut et al., 2018). Candidates include biofuels and hydrogen-derived fuels, such as ammonia and methanol; and the use of CCS or battery-electric engines (Law et al., 2021; Mallouppas and Yfantis, 2021). Many are still in demonstration and pilot stages (Campbell et al., 2023). Although biofuels are generally found to be cheaper in the literature (Korberg et al., 2021; Law et al., 2021; Lloyd's Register and UMAS, 2020; see Figures 1.3 and 1.5), it is unlikely that they will be available at sufficient scale to power the whole fleet, especially if shipping is in competition with other sectors such as aviation. Within hydrogen-based e-fuels, there is still an ongoing debate on the cost and competitiveness of the various fuels. For example, Law et al. (2021) finds that e-methanol is by far the cheapest option (Figure 1.3); Korberg et al. (2021) finds that e-methanol, e-diesel and e-ammonia are similarly competitive; while Lloyd's Register and UMAS (2020) finds that e-ammonia is consistently the most competitive option (Figure **ref:lr˙tco**). Finally, Lagemann et al. (2023) shows that depending on the level of ambition regarding climate mitigation, various fuel would be the most cost-effective option (1.4). Despite its historical inertia, the shipping industry is under growing pressure from activist movements, governments, climate-conscious financiers, and a broader shift in public opinion to transition to carbon neutrality (Lister, 2015; Rayner, 2021; Serra and Fancello, 2020; Transport & Environment, 2021). Given that the vast majority of shipping activities occur across national borders, international action is imperative to effectively govern decarbonisation. The International Maritime Organisation (IMO) has the authority to establish legally binding and enforceable sectoral standards, including those related to reducing GHG emissions (Rayner, 2021). These distinctive characteristics could potentially facilitate progress (Rayner, 2021), but insufficient transparency and governance raise doubts about the ability of the IMO to drive change sufficiently fast (Lister, 2015; Rayner, 2021).

The initial steps driving the transition to low-carbon shipping include the IMO's adoption of an Initial Strategy in 2018, with the aim of achieving at least 50% reduction in the absolute GHG emissions of shipping by 2050 compared to the levels recorded in 2008 (Serra and Fancello, 2020; Shaw and Smith, 2022). Recently, the member states have further strengthened this goal by reaching an agreement to establish a net zero GHG emission target by 2050, along with interim targets (IMO MEPC, 2023), although only the higher end of the trajectory ("strive" targets") are compatible with a 1.5°C target (Bullock et al., 2023). Mandatory fuel data collec-

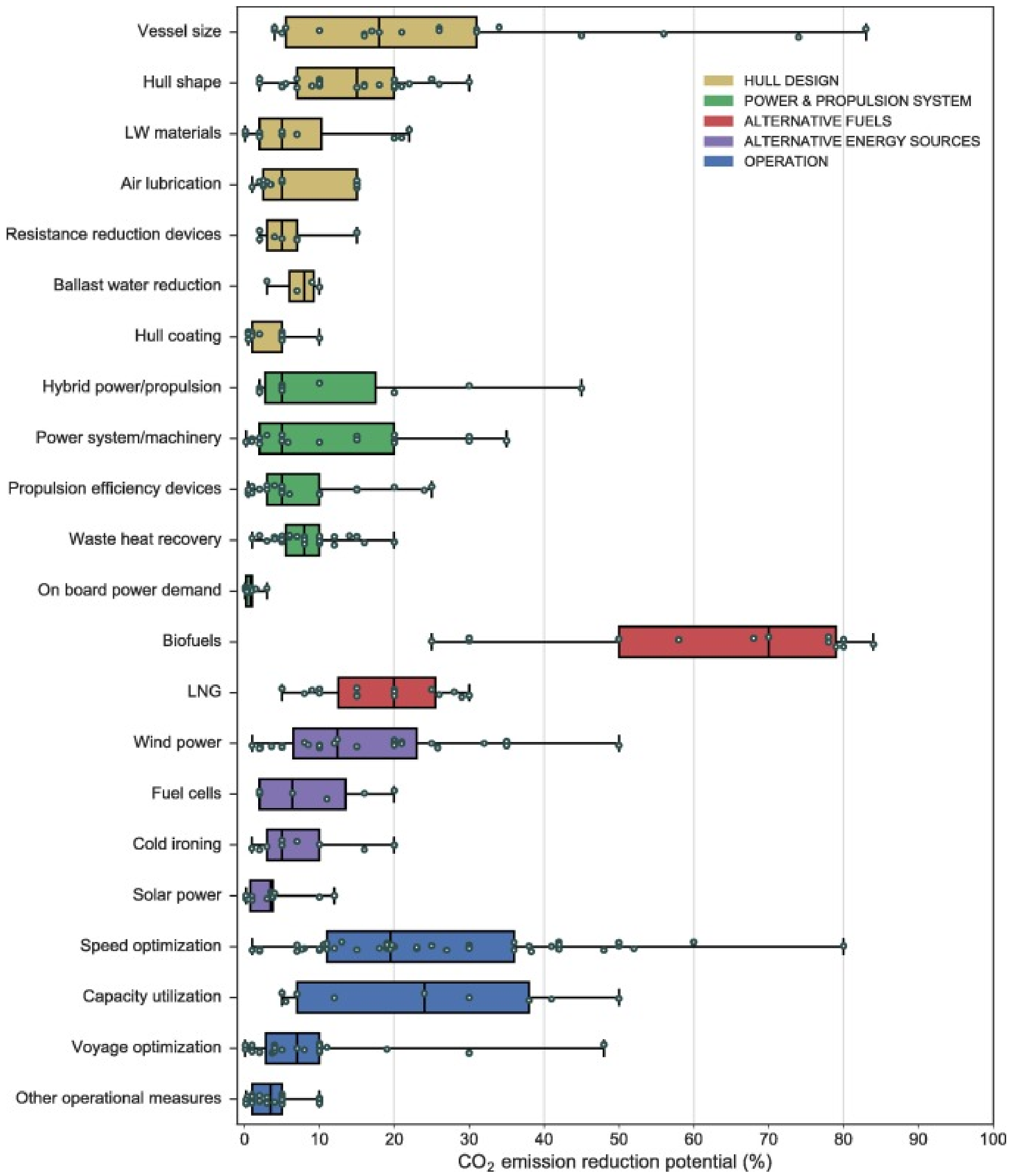


Figure 1.1: CO2 emission reduction potential from individual measures. Taken from Bouman et al. (2017)

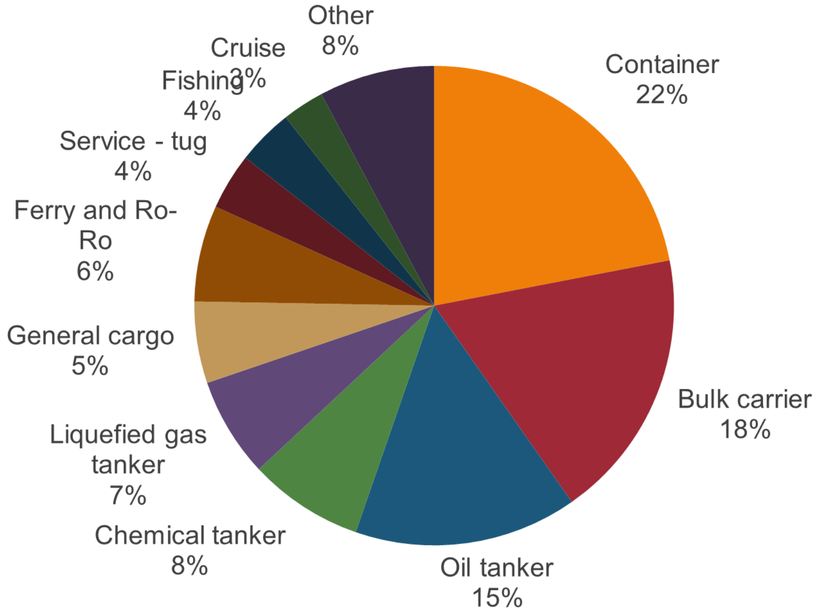


Figure 1.2: Shipping GHG emissions by segment (calculated from Faber et al. (2020))

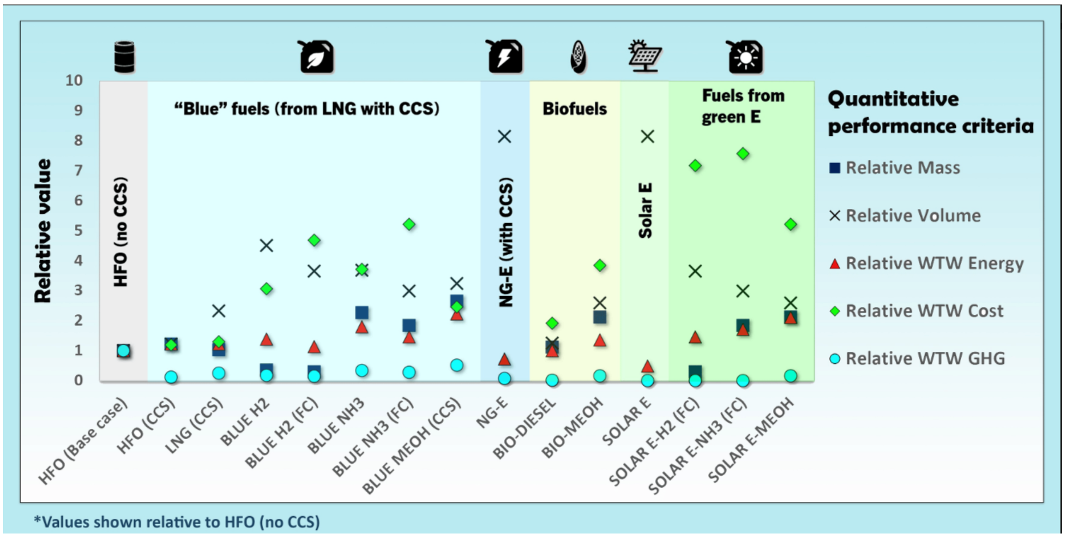


Figure 1.3: Energy, cost and emissions from various marine fuels, relative to HFO. Taken from Law et al. (2021)

(a) CCS: Carbon Capture and Storage; E: electricity; FC: fuel cell; GHG: greenhouse gas; HFO: Heavy Fuel Oil; H2: Hydrogen; LNG: Liquefied Natural Gas; MEOH: Methanol; NG: natural gas; NH3: ammonia; WTW: Well-to-Wake tion through systems such as the EU MRV and the IMO Data Collection System (DCS) means that an increasing amount of data on GHG emissions and energy efficiency is now available. This development paves the way for measures aimed directly at reducing GHG emissions from ships (Adamowicz, 2022). Discussions about introducing a market-based mechanism at the IMO level have been ongoing since 2010 and despite limited progress until 2023 (Psaraftis, 2019), a basket of measures – including a marine fuel standard and a GHG pricing mechanism – are being developed to deliver the 2023 IMO Strategy (IMO MEPC, 2023) and could potentially take effect as soon as 2027 (Comer and Carvalho, 2023). Meanwhile, regional-level action, particularly through the European Union's European Green Deal and its plan to integrate the shipping sector into its carbon market framework between 2024 and 2026 (Commission, 2023), is likely to lead to regulatory changes (Rayner, 2021). Similarly, partnership initiatives led by more progressive segments of the industry, such as the Getting to Zero and Poseidon Principles (Rayner, 2021), could also play a progressive role.

In parallel, the influence of shipping customers is on the rise (Garcia et al., 2021; Jameson et al., 2022; Serra and Fancello, 2020), demonstrated by initiatives such as Sea Cargo Charter. Charterers who signed up for this initiative commit to reporting their GHG emissions related to shipping compared to a decarbonisation trajectory. Additionally, initiatives such as the Cargo Owners for Zero Emission Vessels underline growing pressures, with major container customers like Amazon and IKEA pledging to only use zero-/low-emission shipping from 2025 onwards (Cargo Owners for Zero Emission Vessels, 2022).

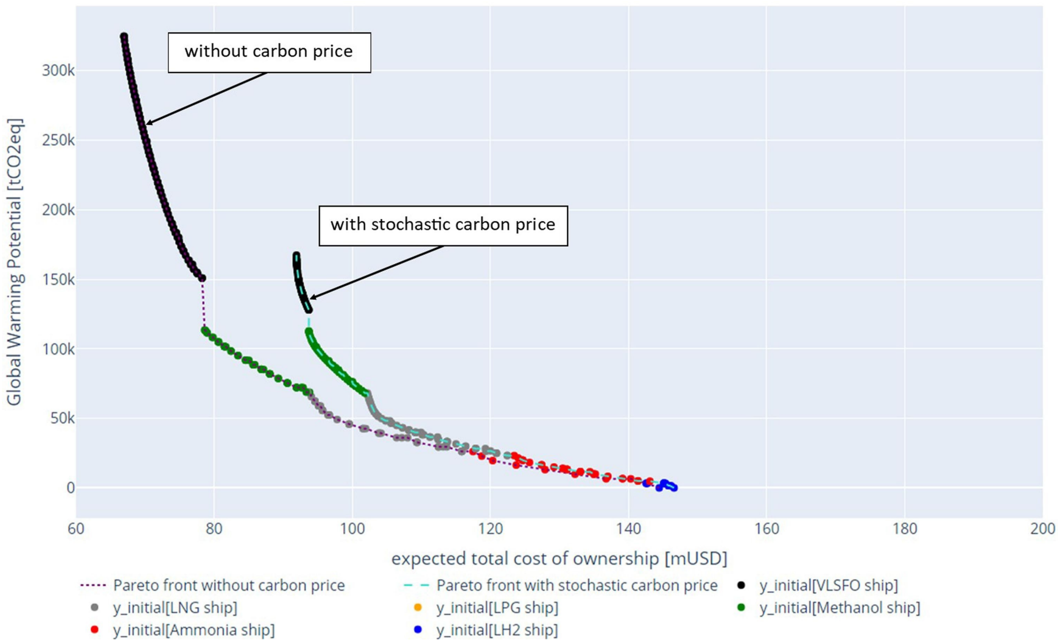


Figure 1.4: Most cost-efficient ship design, depending on the level of emissions. Taken from Lagemann et al. (2023)

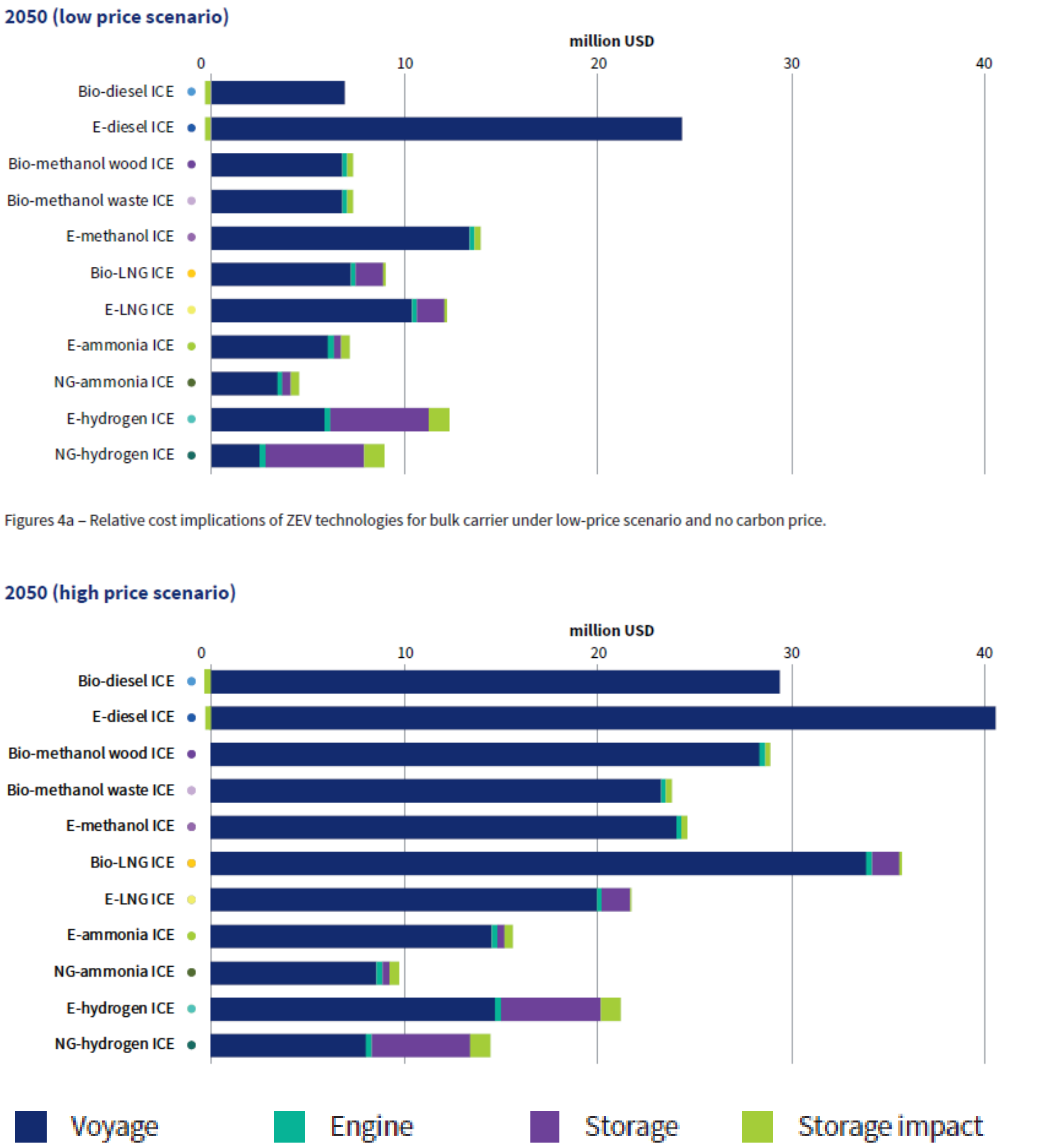


Figure 1.5: Voyage cost with various alternative marine fuels. Taken from Lloyd's Register and UMAS (2020)

1.1.2 Transition away from fossil transportation

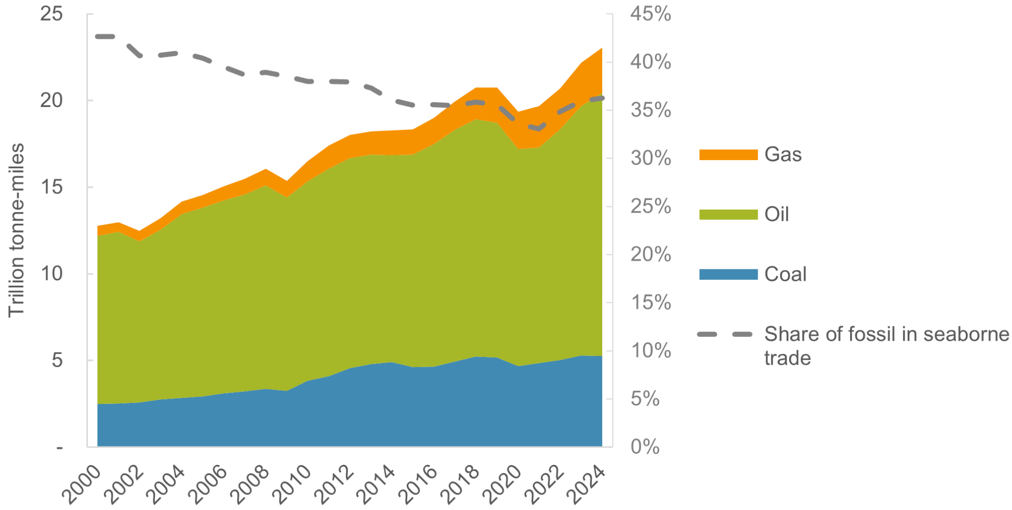


Figure 1.6: Fossil seaborne trade (calculated from Clarksons Research (2022b))

Apart from this transition to zero/low-carbon shipping, shipping is also affected by the use of fossil fuels in other sectors. World trade is largely driven by long-term GDP growth, but it is also impacted by the energy pathway of the onshore sectors and their consumption of fossil fuels (Sharmina et al., 2017; Walsh et al., 2019). Fossil fuels represent around 35% of the world's trade (figure 1.6), so a decrease in fossil use and therefore transportation would have a significant impact on seaborne trade. Most fossil transportation concerns crude oil and oil products; but for coal, and even more so gas, transportation have increased significantly over the last two decades (figure 1.6).

Not all shipping segments would be affected equally. Coal is mostly transported by bulk carriers; but, because it only represents 17% of dry bulk trade (based on Clarksons Research (2022b)), dry bulk shipping is less sensitive to the decarbonisation of land economies (Walsh et al., 2019). However, some ship sizes might be significantly impacted, as larger bulk carriers have been traditionally more focused on iron ore and coal (MSI, 2019). On the other hand, oil and gas tankers, because they are almost entirely dedicated to carrying fossil fuels, are particularly sensitive to the decarbonisation pathway of land economies. Although many studies consider that fossil gas will be used at least up to 2050, it is likely to be necessary to move away from oil to remain within a 1.5°C carbon budget, unless a very large amount of carbon removal becomes available through bioenergy (MSI, 2019; Müller-Casseres, Edelenbosch, et al., 2021; Walsh et al., 2019). Thus, oil tankers appear particularly at risk.

The transportation of new energy commodities, such as hydrogen, ammonia or biofuels; and the maintenance of offshore wind farms also create opportunities for shipping, but those are unlikely to offset the overall decline in energy transportation (Jones et al., 2022). However, Jones et al. (2022), similarly to all studies that rely on IPCC and similar scenarios, are technology optimistic in their treatment of negative emission technologies that significantly influences outcomes in terms of continued use of fossil fuels, particularly gas (Deprez et al., 2024).

1.2 Elements of context: shipping finance

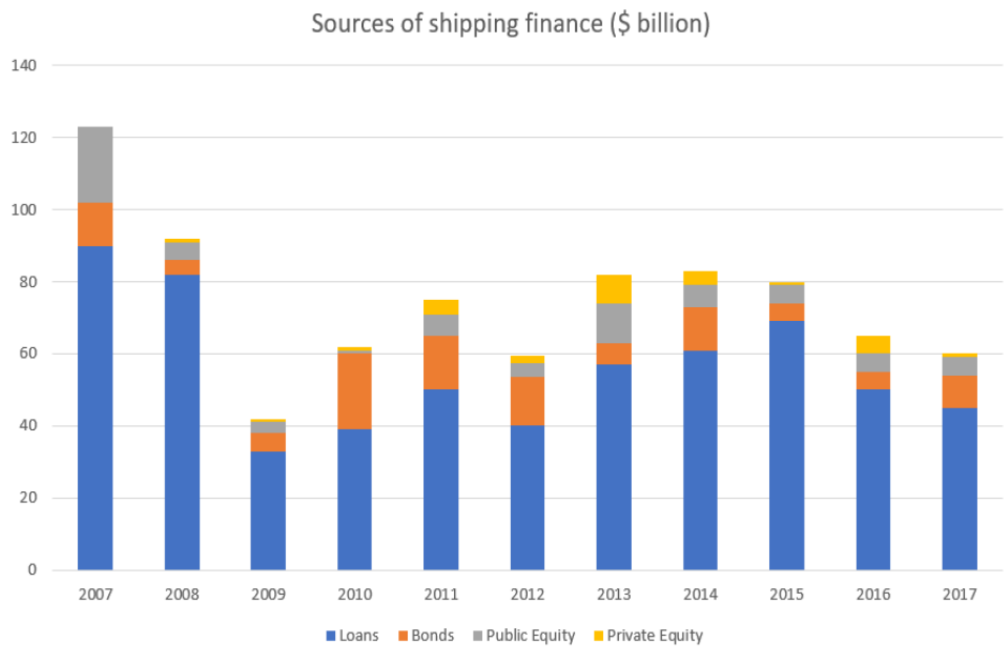


Figure 1.7: Sources of shipping finance (from Tsianakidis, 2019).

The[1] majority of ship finance historically comes from shipowners' balance sheet and debt provided by commercial banks, and more recently by Asian leasing

[1]This section is directly taken from the article "Exploring financiers' beliefs and behaviours at the outset of low-carbon transitions: a case study on shipping", section 3, whom I am the main author of. I have written the first draft of this section and it has been reviewed by the co-authors.

agencies (Figure 1.7). The shipping debt market exhibits concentration, with the top 10 shipping financiers accounting for approximately 45% of the banks' shipping debt portfolio (Petropoulos, 2021). This implies that a small group of external financiers could have significant influence on financing decisions.

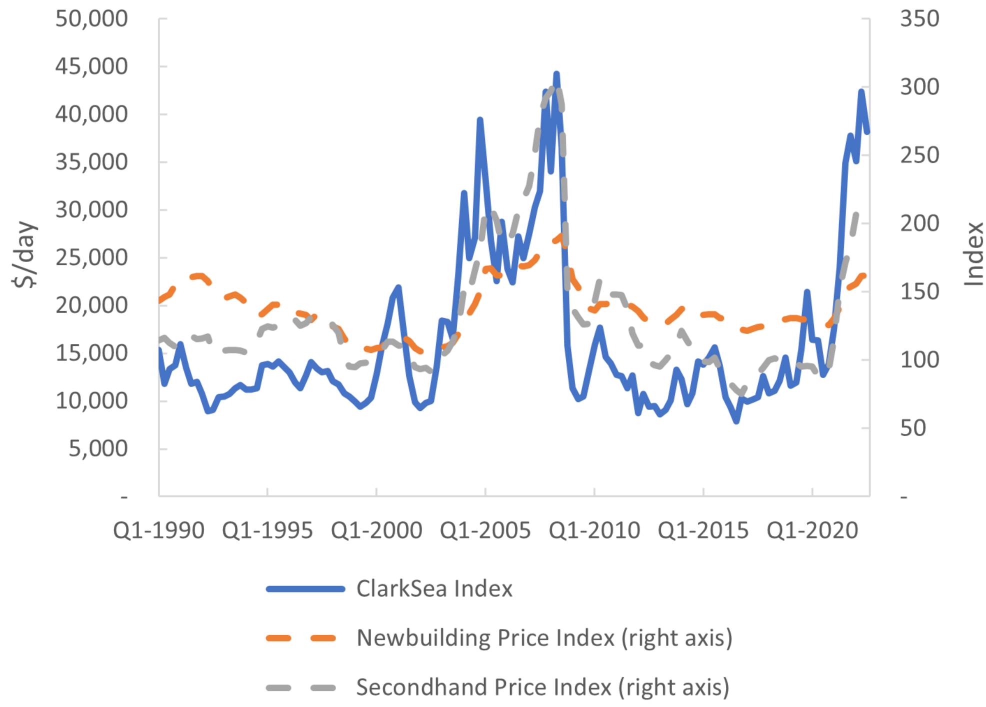


Figure 1.8: Prices on shipping markets, 1990–2022 (Clarksons Research, 2023).

Debt issued by banks has tenors typically ranging from 5 to 12 years. Loan profiles are longer due to the economic lifetime of ships; so that shipping loans often include a balloon payment and are refinanced, often by the same bank. The Global Financial Crisis and the subsequent banking regulations changed the shipping financial regime, as they led European commercial banks to reduce their exposure from the sector because of the large scale of non-performing loans in shipping, in particular in Germany. In a sector characterised by a high volatility of revenues and asset values (see Figure 1.8; see Alexandridis et al. (2018)) for an in-depth review of the literature on the topic), remaining banks now focus on the largest and top-tier shipowners, which are perceived to be safer, resulting in intense competition in this segment.

1.3 Defining transition risks, stranded assets and financiers' expectations

After setting the context of the analysis, let us discuss the main concepts used in this thesis.

Climate change creates a variety of economic and financial risks. *Physical risks* encompass climate-related damages (P. Bolton and Kacperczyk, 2021; Carney, 2015). *Liability risks* correspond to potential claims for compensation from certain entities and countries following climate-related damage (Carney, 2015; Lamperti et al., 2021). The primary focus of this thesis, *transition risks*, are broadly defined as "the threats, possibly systemic, posed by the transition to a low-carbon economy to financial stability" (Carney, 2015).

The drivers of transition risks can be classified into three main categories (Campiglio and van der Ploeg, 2022). First, the introduction of climate mitigation policies may not be anticipated by economic actors, which could result in a sudden reassessment of the profitability of fossil fuel extraction and other carbon-intensive industries (*policy risk*) (Campiglio and van der Ploeg, 2022; Monasterolo, 2020; Monasterolo and Raberto, 2018). Even when mitigation policies are expected, very stringent measures could induce similar consequences (Campiglio and van der Ploeg, 2022). For example, if the emission reduction targets mandated by policies exceed the expected lifespan of existing productive assets, certain assets may need to be idled, potentially impacting the overall market value of the firm. The second factor contributing to transition risks involves unexpected or very rapid technological advances (Campiglio and van der Ploeg, 2022; Monasterolo, 2020). Such developments can prematurely render existing capital investments obsolete and cause abrupt declines in the stock prices of carbon-intensive firms (*technology risk*) (Campiglio and van der Ploeg, 2022). Third, rapid changes in preferences, convictions, and anticipations of consumers, entrepreneurs, and financiers have the potential to impact the profitability of businesses and the prices of financial assets (*preference risk*) (Campiglio and van der Ploeg, 2022).

The concept of stranded assets is tightly linked to transition risks and is defined as assets ”which have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities” (Caldecott and McDaniels, 2014). Daumas (2023) and van der Ploeg and Rezai (2020a) further describe stranded assets through three categories, shown in figure 1.9. *Stranded resources* represent the economic losses associated with untapped fossil resources (Daumas, 2023; van der Ploeg and Rezai, 2020a). *Stranded capital* refers to production assets that are projected to lose value or require costly conversion (Daumas, 2023; van der Ploeg and Rezai, 2020a). Finally, losses related to stranded resources and capital result in what can be termed *stranded paper*, i.e. the losses which are passed onto the external financiers. These, for example, can take the form of devaluation of equity values and increased defaults on loans of carbon-intensive firms (Campiglio and van der Ploeg, 2022; Curtin et al., 2019; Daumas, 2023; van der Ploeg and Rezai, 2020a). The prospect of paper stranding could exacerbate capital or resource stranding if the financial sector rapidly withdraws from associated activities (Monasterolo, 2020; van der Ploeg and Rezai, 2020b). The two last categories of stranded asset risks are relevant to shipping and are the focus of this thesis.

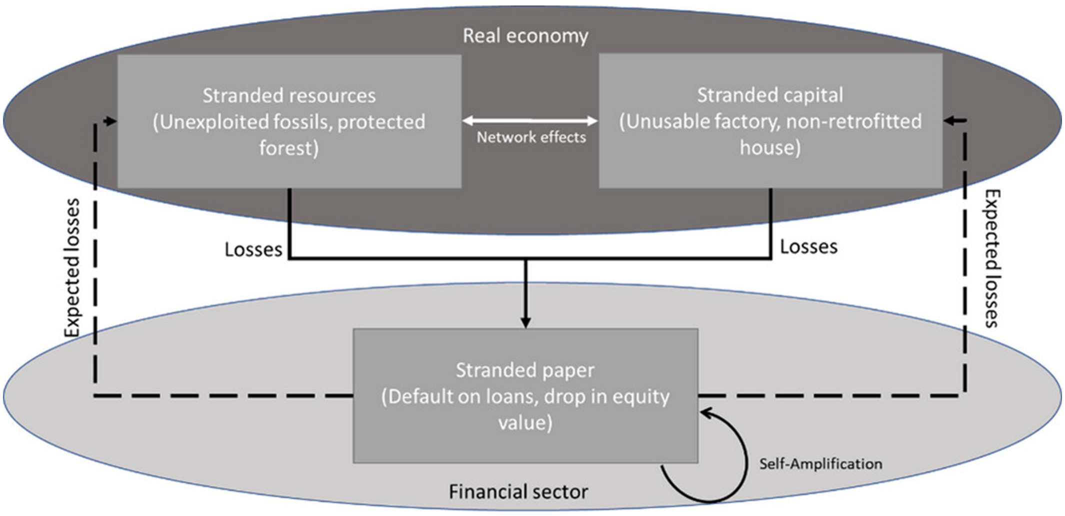


Figure 1.9: Types of stranded assets and their interactions (taken from Daumas (2023))

In the shipping industry, the risk of stranded assets can be further classified into two main types: *demand-side risk*, which involves the potential loss of seaborne fossil fuel cargo as offshore sectors transition to zero / low carbon alternatives, and *supply-side risks* associated with the propulsion of ships transitioning from fossil fuel to alternative low / zero carbon solutions (Smith et al., 2015). These demand- and supply-side risks can result in unforeseen devaluations of ship assets, which subsequently affect the profitability of shipping financiers. For example, in the case of a traditional bank loan, if the shipowner defaults, the financier would take ownership of the asset and recover the value of the ship at the time of default.

Financiers' expectations towards an upcoming low-carbon transition have been coined as "climate sentiments" (Daumas, 2023; Dunz et al., 2021) or "beliefs / a priori beliefs" (Campiglio and van der Ploeg, 2022; Masini and Menichetti, 2012, 2013). This concept stems from the notion of disorderly transition and the assumption that the transition is not fully anticipated by economic actors (Battiston et al., 2017), so that they form expectations about the drivers of future climate mitigation (e.g. future policy, future technology availability and adequacy) which are not necessarily perfect. The concept of stranded assets implies that financiers and asset owners had imperfect expectations on an upcoming low-carbon transition at the time of investment, otherwise the subsequent losses would not be "unexpected". Those expectations are adaptive, that is, they adjust when mitigation becomes clearer or when transition risks materialise (Campiglio and van der Ploeg, 2022; Giglio et al., 2021).

1.4 Rationale for investigating the role of financiers

A large share of ship finance comes from external financiers which shape the financing terms offered to shipowners and the types of assets eligible for financing. Financier decisions have an impact not only on their profitability, but also on their ability to transition to low/zero-carbon ships in the future. For example, funding a stable regime of polluting ships could boost technology lock-in and make the transition to low/zero-carbon shipping more difficult. As a result, investigating the role of financiers in creating or preventing stranded assets matters. To begin with, if those risks are not properly priced in, disruption is likely to translate into stranded paper. In addition to this, limited access to capital is a barrier to the uptake of low/zero-carbon technologies. This section explains those two rationales.

The potential risks associated with transitioning ship assets can affect lenders in two ways. First, as in other industries, the declining profitability of firms exposed to transition risks can have a cascading impact on their lenders. This can manifest itself as an increased default rate, which may be exacerbated by the interconnectedness of lenders (Battiston et al., 2017; Lamperti et al., 2019; Semieniuk et al., 2021). This link has proven to have a significant impact on shipping lenders in the past. For instance, following the 2008 economic crisis, an oversupply of ship capacity and reduced shipping earnings resulted in a non-performing loan ratio of 40% for German banks' shipping portfolios (Damyanova, 2018a). Second, the transition risk could lead to an unforeseen devaluation of ship assets due to regulatory changes, technological changes, or changes in consumer demand, as discussed above. In the event of a borrower's insolvency, this would impact lenders, as the ship's value might be the only means of recovering the initial loan amount[2]. Despite these potential consequences, it remains an open question whether external financiers are actively considering and integrating transition risks into their decision-making processes.

Investigating the role of financiers in transition risk matters also because the lack of access and high cost of capital appears to be a market barrier to the uptake of emission abatement technologies in the shipping industries through various channels reviewed in Ghaforian Masodzadeh et al. (2022). First, many of these technologies have a high initial investment cost (Acciaro, 2014; Balcombe et al., 2019; Fitzpatrick et al., 2019; Longarela-Ares et al., 2020) while there is a lack of internal and external financial resources for shipowners, particularly for smaller shipowners, especially since the 2008 financial crisis, which saw shipping banks reducing their involvement in the sector (Rehmatulla, Parker, et al., 2017; Rojon and Dieperink, 2014; Stulgis et al., 2014). Furthermore, bankers often are unwilling to finance new technologies with which they are unfamiliar (Ghaforian Masodzadeh et al., 2022).

Although access to capital is listed as one of the barriers to energy efficiency and low-carbon investments in the shipping industry by most of the literature on

[2]However, it is important to note that ship arrests, while theoretically possible, are typically considered a last resort in practice (Drobetz et al., 2016; Franks et al., 2015; Girvin, 2019).

market barriers (for example Dewan et al. (2018), Fitzpatrick et al. (2019), Halim et al. (2018), Jafarzadeh and Utne (2014), H. Johnson and Andersson (2016), Longarela-Ares et al. (2020), and Rehmatulla and Smith (2015a); see an extensive review in Ghaforian Masodzadeh et al. (2022)), very few studies actually focus on this barrier (exceptions include Mitchell and Rehmatulla (2015) and Stulgis et al. (2014)). The literature has focused more on other major barriers such as negative externality, the principal-agent split incentive between the charterer and the shipowners, and the lack of existing infrastructure (Dewan et al., 2018; Longarela-Ares et al., 2020; Rehmatulla, Calleya, and Smith, 2017; Rehmatulla and Smith, 2015a, 2015b; see an extensive review in Ghaforian Masodzadeh et al. (2022)). This relative lack of understanding of the role of capital access could arise because there are mixed views on whether access and capital cost are a low or a medium barrier (Dewan et al., 2018; Fitzpatrick et al., 2019; Jafarzadeh and Utne, 2014; Rehmatulla and Smith, 2015a) or a major barrier (Rojon and Dieperink, 2014; Stulgis et al., 2014). This lack of consensus in the literature might also come from the difference in scope: while Dewan et al. (2018), Jafarzadeh and Utne (2014), and Rehmatulla and Smith (2015a) look at operational energy efficiency (e.g. routing, speed, power utilisation) which requires low initial capital investments and no external financial needs, Rojon and Dieperink (2014) and Stulgis et al. (2014) look at emission abatement measures with high upfront investment (e.g. sails, propeller cap fins, rudder modifications, retrofit to LNG). The relatively limited exploration of these barriers compared to the market failures listed above could also be due to the fact that policy options to address market barriers such as financial risk and capital are less obvious (Ghaforian Masodzadeh et al., 2022).

Although there is a growing but conflicting body of evidence in the econometric literature on the incorporation of climate risks into financial instruments in various industries (Bingler, 2022; Degryse et al., 2021; Delis et al., 2019; Fatica et al., 2021; Hachenberg and Schiereck, 2018; Seltzer et al., 2020; details in Section 2.1.4), there is a notable lack of research on the role of financiers in the shipping industry during low-carbon transitions. This includes their perspectives on climate risk, the underlying factors that influence their financing decisions, and their adaptation strategies in terms of financial tools and instruments. Because this issue is largely understudied, there are fewer recommendations available to policy makers. This thesis aims to address this and investigates the interplay between the risk of stranded assets in the shipping industry and the expectations regarding low-carbon transitions by external financiers.

1.5 Thesis overview

This thesis is organised as follows:

- Chapter 2 - Literature review: this chapter provides a literature review of the theoretical background, empirical evidence and modelling approaches to study the role of financiers during low-carbon transitions and stranded assets. It highlights the literature gaps and sets out the research questions of the thesis.

- Chapter 3 - Research approach: This chapter discusses the research design and the relevant methods to answer the research questions and explains the choice of research approach.

- Chapter 4 - Existing sunk capital and emissions in shipping: in this chapter, the current capital already invested in the fleet and the consequences in terms of future emissions and shipping supply are described and compared to the limits imposed by a 1.5°C-aligned world

- Chapter 5 - Financiers during socio-technical transitions; a proposal of theoretical framework: in this chapter, the insights derived from the empirical evidence examined in Chapter 2 are leveraged to characterise the behaviours of financiers within a conceptual framework that extends the Multi-Level Perspective.

- Chapter 6 - Exploring shipping financiers' expectations and behaviours at the outset of low-carbon transitions: this chapter elucidates the views held by financiers regarding shipping low-carbon transitions, with the aim of understanding their behaviour.

- Chapter 7 - Modelling financiers' expectations and stranded assets: this chapter formalises the findings from the previous chapters into a model of shipping financiers, investment decisions, and stranded assets. It examines the impact of financiers on the potential unfolding of a shipping supply-side low-carbon transition and the resulting stranded assets.

- Chapter 8 - Discussion and conclusions

Chapter 2

Literature review

This literature review follows the progression from empirical evidence, theory and modelling approach. The first section reviews empirical evidence on the behaviour and the role that external financiers have played in past technological transitions. The second section reviews how various economic schools of thought view technological transitions and the role of finance during the transitions. Finally, the third section reviews how different modelling approaches incorporate finance, investment decisions, and stranded assets.

2.1 Empirical evidence: finance and low-carbon transitions

This section reviews empirical evidence on finance and stranded assets during low-carbon transitions. First, it reviews the literature related to the role of finance in the shipping industry. Second, it looks at the past shipping transitions in the Multi-Level perspective Literature. It then summarises the evidence on the role of financiers during past socio-technical transitions in other sectors which have already undergone a transition. Finally, the literature on measuring current financiers' belief of transition risks is reviewed.

2.1.1 The role of external finance in shipping

The existing literature[1] [2] on shipping finance covers a large range of topics including the sources of finance and capital structure, valuation methods and risk management. An in-depth review of shipping finance is available in Alexandridis et al. (2018), but only the topics of the role and source of external finance in shipping are covered here, as they are the focus of this thesis.

Due to the reliance of the shipping industry on high value assets, access to substantial capital is essential to replace the ageing fleet and to fund the second-hand ship market (Alexandridis et al., 2018). The longevity of shipping firms has been historically closely tied to their ability to secure financing with favourable terms, particularly low interest rates (Stopford, 2009). Traditional banks have limited their exposure to the shipping industry and now request more secure loan conditions (lower loan-to-value ratio, higher level of syndication (S. X. Gong et al., 2013), stronger legal guarantees to be able to enforce mortgages (Girvin, 2019)) due to weak market conditions and stricter BASEL III capital requirements imposed by the Basel Committee on Banking Supervision following the 2007 financial crisis (Girvin, 2019; S. X. Gong et al., 2013). Despite this trend, lending remains the main source of external (i.e. not shipowners) shipping finance (Del Gaudio, 2018; Drobetz et al., 2013; Girvin, 2019; Paun and Topan, 2016) and the literature on alternative sources of capital (bonds, public equity, shipping funds) is limited (Alexandridis et al., 2018). However, some studies have argued that an alternative model of finance is necessary for the uptake of zero/low-carbon technologies (Schinas and Metzger, 2019; Schinas et al., 2018). Although those proposed in this literature have not gained traction yet, new financial instruments such as green loans or sustainability-linked loans have started to be emitted for shipping in recent years,

[1] This section is based on subsection 2.1 of the study ”Exploring financiers’ beliefs and behaviours at the outset of low-carbon transitions: a case study on shipping”. I am the main author of the paper and have drafted the first version of the section, which has been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

[2] This section builds on the extensive literature review of ship finance conducted by Alexandridis et al. (2018) completed by a research on Web of Science with keyword (”shipping”, ”marine” OR ”maritime”) AND (”financ*” OR ”bank*).

with bank loans remaining the preferred instruments of ”green” finance (Morchio et al., 2024)

As a consequence, banks lending to shipping (called ”shipping banks” in the following, although they are not necessarily specialised in shipping only), despite their partial retraction from the sector, still play a major role in supporting ship investments and providing some shipowners with a cheap and reliable source of capital. Pangalos (2023) argues that because larger shipowners have stronger bargaining power with fuel providers and clients; higher technical management capacity; and better access to sources of capital, they may be better placed to acquire zero/low-carbon ships. Drobetz et al. (2016), however, show that banks have continued to support healthy firms. During the 2007 financial crisis, and even despite when covenants were breached, banks avoided foreclosing on ships and selling them at a discount. They also provided increased financial support while rationing the credit to financially weak shipowners. Xiao (2020) studies the positive causal relationship between loan growth and marine economy growth in Hong Kong, while Akgül and Çetin (2019)’s interviews of shipping practitioners shows that the price of debt and the availability of capital are factors that restrict investment of Turkish ship firms, although the main driver remains market conditions.

The popularity of bank borrowing among ship-owning firms can be attributed to several factors listed by Alexandridis et al. (2018):

- Lower cost and availability: compared to other types of finance;
- Ownership conservation: the ownership of the business remains concentrated and unaffected, which is important to many family-oriented shipping companies which are reluctant to change this structure;
- Confidentiality: raising funds through bank loans does not necessitate public disclosure of strategic, financial, and operational information, unlike methods like IPOs and corporate bond issues (Kavussanos and Tsouknidis, 2014, 2016).
- Relationship banking: historically, shipping bank loans have been granted

based on relationship banking principles. This fosters long-term relationships, amicable trust, and information sharing between the borrowing firm and the bank (Alexandridis et al., 2018; Gavalas and Syriopoulos, 2015; Mitroussi et al., 2016).

The focus of the literature on shipping has been on shipowners rather than the sources of finance itself. Even then, the focus has been on a default risk assessment of financial instruments (for example Kavussanos and Tsouknidis (2016) and Mitroussi et al. (2016); see Alexandridis et al. (2018) for a review), which does not consider the agency of the finance providers. Fewer studies have looked directly at the behaviour and beliefs of finance providers. Exceptions include S. X. Gong et al. (2013)'s survey on banks reducing from the shipping sector after 2009; Mitchell and Rehmatulla (2015)'s interviews with debt and equity providers on the topic of energy efficiency and stranded assets; and Gavalas and Syriopoulos (2015) and K. R. Lee and Pak (2018)'s studies of banks' decision-making drivers. From these, it appears that the borrower's financial strength; historical track record; and past relationship with the bank are the main drivers of lenders' investment decisions (Gavalas and Syriopoulos, 2015; K. R. Lee and Pak, 2018), while ship asset characteristics, in particular energy efficiency (Mitchell and Rehmatulla, 2015), are overlooked or not the main focus (Gavalas and Syriopoulos, 2015; K. R. Lee and Pak, 2018).

This section has attempted to provide a brief summary of the empirical literature relating to shipping finance. Overall, there is a large amount of evidence of the source and role of external financiers in shipping, but there is a very limited amount of evidence on whether external shipping financiers are expect transition risks and opportunities and whether this has translated into their behaviour. However, such evidence exists in other sectors that have already undergone a socio-technical transition. They are reviewed in the next subsection.

2.1.2 Shipping in the Multi-Level Perspective

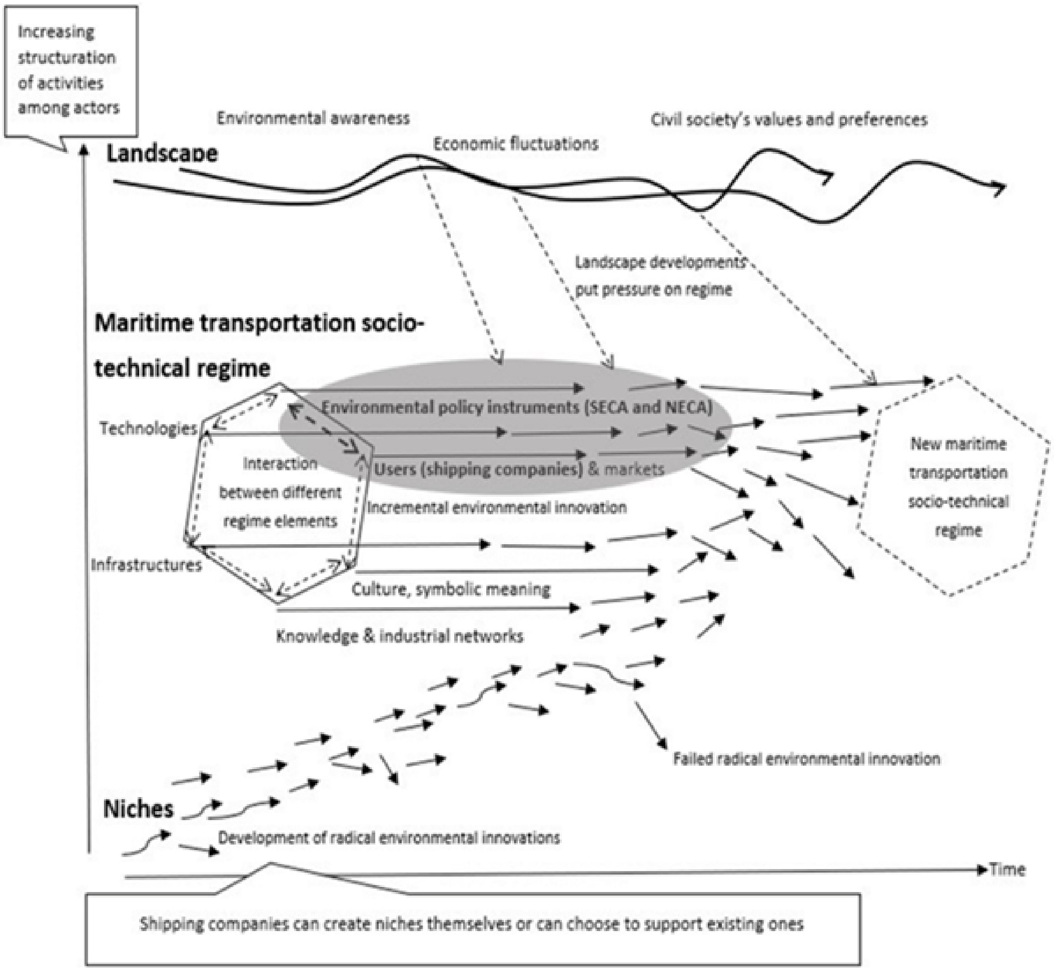


Figure 2.1: MLP of shipping low/zero-carbon transitions. Taken from Stalmokaite and Yliskylä-Peuralahti (2019)

This[3] thesis builds on the multi-level perspective (MLP) framework, derived from transition theories. The MLP explains the uptake of technological innovations in markets that are associated with key societal and economic functions such as energy or transport (Geels, 2002; Geels and Schot, 2007; Markard and Truffer, 2008; Markard et al., 2012). According to the MLP framework, there are three layers that interact: exogenous landscape pressure, the socio-technical regime, and niches. Ex-

[3]This section is directly taken from the article "Exploring financiers' beliefs and behaviours at the outset of low-carbon transitions: a case study on shipping", section 2.2, whom I am the main author of. I have written the first draft of this section and it has been reviewed by the co-authors.

ogenous landscape pressure represents a change in civil society's awareness about an issue (e.g. environmental) which exerts pressure on the socio-technical regime (e.g. incumbent industry) (Geels, 2002; Geels and Schot, 2007; Markard and Truffer, 2008; Markard et al., 2012). Socio-technical regimes are stable economic and social configurations, however they can be destabilised if exogenous pressure, such as the growing public pressure to decarbonize industry sectors including the shipping industry, create opportunities for niche innovations to break through (Geels, 2002; Geels and Schot, 2007; Markard and Truffer, 2008; Markard et al., 2012). The third layer are niches which develop in protected spaces and can provide innovations. If these niches are successful, they are taken up by incumbents and can replace the previous socio-technical regime (Geels, 2002; Geels and Schot, 2007; Markard and Truffer, 2008; Markard et al., 2012).

Pettit et al. (2018) and Stalmokaite and Yliskylä-Peuralahti (2019) both use the MLP framework to describe the shipping industry. They describe the shipping regime as comprised of a large range of industry incumbents including shipowners, charterers and customers, ports and fuel providers and regulators (see Figure 2-1) (Pettit et al., 2018; Stalmokaite and Yliskylä-Peuralahti, 2019). Shipping case studies include electric or hydrogen-fuelled coastal shipping in Norway (Bach et al., 2020; Bergek et al., 2021)

Socio-technical transitions can evolve differently depending on the nature of the innovations and landscape pressures (Geels and Schot, 2007; Geels et al., 2016). In some cases, incumbents are replaced by niche entrants who introduce *competitive* innovations, i.e. innovations which aim at replacing the existing regime technology (Geels and Schot, 2007) (e.g. the uptake of small-scale renewables in Germany by entrants such as citizens, cooperatives and farmers (Geels et al., 2016). In others, *symbiotic* innovations, i.e. innovations that enhance the current system technology by enabling it to address issues and improve its performance (Geels and Schot, 2007), are adopted by regime incumbents who then adapt to the new socio-technical regime (e.g. the uptake of large-scale onshore and offshore wind by incumbent utilities in the UK (Geels et al., 2016). Baresic (2020a) and Pettit et al. (2018)

suggest that because shipping assets are capital intensive and have long lifespans, the industry is conservative to radical innovations and has a strong path dependency. Baresic (2020a), who bases his argument on the transition to LNG as a marine fuel, argues that the involvement of industry incumbents, in particular shipowners, and the development of symbiotic innovations (e.g. dual-fuel engines or drop-in fuels) are likely to be necessary conditions for a successful shipping transition to take place.

2.1.3 The role finance in historical technological and low-carbon transitions

While[4] the transition literature has focused mainly on the behaviour of industry incumbents such as utilities or shipowners, there is increasing empirical evidence on the behaviour of financiers during transitions (R. Bolton and Foxon, 2015; Falcone et al., 2018; Geddes and Schmidt, 2020; Geddes et al., 2018; S. Hall et al., 2016; Hughes and Downie, 2021; Monk and Perkins, 2020; Seyfang and Gilbert-Squires, 2019; Urban and Wójcik, 2019; Yip and Bocken, 2018; F. Zhang, 2020). This section and the next largely build on transitions which have happened in other sectors than shipping, there is limited empirical evidence of financiers' role in shipping transitions. Although the behaviour of shipping financiers might differ from those, this review might still give some useful insight on the range of possible behaviours that financiers, in general, can take during transitions. Furthermore, many of the below case studies share similarities with shipping, as they concern carbon- and capital-intensive industries with long-lived assets such as electricity generation, and are also concerned by the issue of stranded assets. Finally, the fact, that shipping financiers also tend to be involved in other sectors than just shipping, suggests that those findings might be applicable to shipping as well (this is tested in Chapter 6).

Some financiers, like most industry incumbents, are found to ignore the risks

[4]This section is directly taken from the article "Exploring financiers' beliefs and behaviours at the outset of low-carbon transitions: a case study on shipping", section 2.3, whom I am the main author of. I have written the first draft of this section and it has been reviewed by the co-authors. It has been slightly altered to fit the format of the thesis.

and opportunities arising from the growing transition and therefore continue financing the incumbent technology. The Royal Bank of Canada or the China Construction Bank continue to finance the extraction of fossil fuels (Urban and Wójcik, 2019), while Japanese bilateral banks continue to finance coal power plants in South East Asia because they perceive the stranding of their assets unlikely and do not include transition risk assessments (Hughes and Downie, 2021). Most German banks and institutional investors initially, and UK banks until the date of the article at least (2018), were reluctant to finance small-scale renewables projects due to lack of knowledge of the technology; inadequate existing financial tools and instruments for the size and type of project; and perceived riskiness of the projects (Geddes et al., 2018).

In some cases, not only are financiers not expecting of the upcoming socio-technical transition, but they encourage their clients to grow their incumbent technologies. For example, (Ferguson-Cradler, 2022; Kungl and Geels, 2018) document how the shareholders of German power utilities exerted pressure from 2005 to 2010 on the firm management to invest ambitiously in carbon-intensive assets and utilities; and in some cases prevented the move away from coal to protect their regional coal industry (Geels et al., 2016).

In many cases, however, financiers are found to support the transition when they realise the threat and/or opportunity brought by the technology innovation. While this support might be a driver of the uptake of the new technology, it is not argued here that it is the only one, nor that it is sufficient to drive the transition alone. In particular, the design of the government support has also played a large role in shaping the transition to large-scale or small-scale decentralised renewables in the UK and Germany, respectively (Geddes et al., 2018; Geels et al., 2016). Alternatively, the absence of government financial support and the divestment from private investors has hampered the transition to low-carbon steel in the UK (Geels and Gregory, 2023).

In some cases, regime financiers finance industry incumbents in leading the transition. An example of this behaviour is the early support of commercial banks in the development of combined cycle power plants by UK electricity utilities (R. Bolton et al., 2015; Kern, 2012) and of large-scale offshore and onshore wind projects since the 1990s (R. Bolton et al., 2015; Geddes et al., 2018), both of which are symbiotic innovations[5]. Commercial banks have, however, refrained from investing in small-scale renewables in the UK promoted by small niche entrants due to the perceived risk of the investment and the inadequacy of their financing instruments to these actors (Geddes et al., 2018; Stenzel and Frenzel, 2008).

However, there are also examples in the literature of financiers supporting industry niche entrants. This suggests that regime financiers are not intrinsically loyal to industry incumbents. Examples include the support of the UK Green Investment Bank, which was formerly owned by the UK government, and later commercial banks for the uptake of bioenergy in the UK (Geddes et al., 2018). In Germany, there was support from KfW, and later on the German Savings and Cooperative Banks, for small-scale solar photovoltaic and onshore wind (Geddes et al., 2018; F. Zhang, 2020).

The development of financial innovations is often necessary for financiers to support the new technology. Examples of symbiotic financial innovations include the creation and uptake of green bonds since 2006 and of Environmental, Social and Governance (ESG) metrics in the last few decades to evaluate firms, developed by a few incumbent financiers as a response to landscape pressure from a reputation crisis and shift in customer preferences (Monk and Perkins, 2020; Seyfang and Gilbert-Squires, 2019; Urban and Wójcik, 2019), or the uptake of wealthtech and Insurtech in Iran (Ghazinoory et al., 2023). Alternatively, financial innovations can be competitive and carried out by financial entrants, leading, if successful, to a substitution of the financial regime in favour of financial entrants. Examples of potentially competitive financial innovations include the creation of value-based banks such as GSL, Triodos, Ecology (Falcone et al., 2018; Seyfang and Gilbert-Squires, 2019; Urban and Wójcik, 2019; Yip and Bocken, 2018); of new banks replicating

[5] In the MLP framework, symbiotic innovation refers to an innovation that aligns with and supports the existing socio-technical regime, facilitating gradual transitions and integration within established systems (Geels and Schot, 2007)

the example of local German banks in the UK to support small-scale investments in renewables (Abundance, Pure Leapfrog, Hampshire community bank) (S. Hall et al., 2016; F. Zhang, 2020) and of Fintech (Ghazinoory et al., 2023; Sánchez, 2022). None of them has so far been successful in substituting the entire financial regime Evidence from Cairns et al. (2023) on the community energy in the UK suggests that those banks are more likely to finance niche competition innovations (in that case, small-scale renewables developed by energy cooperatives) than most commercial banks. Similarly, Braunholtz-Speight et al. (2020) and Cairns et al. (2023) show that community energy largely tap into community shares, which have low liquidity; are long term; and are characterised by the principle of ”one shareholder, one vote,” and therefore ill-adapted to traditional equity holders such as pension funds, who consequently do not invest in them.

This section has shown that financiers can adopt a large variety of behaviours during transitions: they can hamper or enable a transition and express preference for certain technologies. By grouping the findings into similar behaviours in the above paragraphs (2nd to 5th paragraph of this section), one can identify 5 archetypes : an Inert behaviour, a Creative-self destruction, Loyal enabler who support the transition led by regime incumbents taking on the niche technology, Redirecting enablers which support the transition led by niche new entrants which take on the niche innovation, and winding down when they partially or fully retrieve from the sector. Those archetypes are used in Chapter 5 to propose a novel theoretical framework.

A few literature gaps are worth highlighting, however. First, the evidence has focused so far on electricity transitions; while the evidence in other sectors, and in particular shipping, is scarce. It is also unclear to what extent shipping financiers price in the risk of ships being stranded in the cost of capital, as few empirical studies have addressed this issue for the shipping industry. Qualitative insights from interviews with shipping financiers and shipowners (Mitchell and Rehmatulla, 2015) suggest, however, that they seldom take transition risks into account. There is, however, much denser evidence in other industries,which may inform the situation in the shipping industry as well. They are reviewed in the next section.

2.1.4 Past and current expectations of financiers of upcoming low-carbon transition

The literature has found contradictory evidence on whether transition risks affect the prices of financial instruments and in particular the cost of debt (see in-depth literature reviews in Campiglio and van der Ploeg (2022), Daumas (2023), and Q. Wang (2023)). While some studies find that transition risks have no effect on bond yields (Bingler, 2022; Hachenberg and Schiereck, 2018), others suggest that some financial actors have started to incorporate them into bond and loan margins, although insufficiently (Degryse et al., 2021; Fatica et al., 2021; Kleimeier and Viehs, 2016; Seltzer et al., 2020. Findings on the stock markets are equally mixed: while Alessi et al. (2021) and Rojo-Suárez and Alonso-Conde (2024) finds evidence of a positive premium on stock returns, Görgen et al. (2020) does not find any significant result while Oberndorfer et al. (2013) finds a negative premium.

Several reasons might explain this discrepancy. One is methodological: the reviewed studies use different measures of transition risk exposure (Q. Wang, 2023) such as GHG emissions, emission intensity or emission scores/carbon performance ratings. Those contradictory results could further arise from the fact that climate pricing is time dependent (Daumas, 2023; Rojo-Suárez and Alonso-Conde, 2024) and geography dependent (P. Bolton and Kacperczyk, 2021). Given that these studies look at different periods and/or different regions, they might find different results because financial markets do not expect transition risks consistently across time and space. In particular, there is now increasing evidence of the time-dependency of financiers' expectations. El Ghoul et al. (2018) show that equity premiums have been reduced for firms with better environmental risk management before the 2007 financial crisis and after 2009, but was insignificant between. Various studies report increased, although insufficient, expectations of transition risk after the Paris Agreement (Monasterolo and de Angelis (2020) looking at beta of stocks, P. Bolton and Kacperczyk (2021) and Mukanjari and Sterner (2018) at stocks returns, Mathiesen (2018) at credit agencies, Seltzer et al. (2020) at bond yields and Delis et al. (2019) at the loan spreads).

There is evidence that financiers react to policy and political events (Huang et al., 2019; Ramelli et al., 2018; Sen and von Schickfus, 2020) and technology announcements (Byrd and Cooperman, 2018). The election of Donald Trump as the president of the United States in 2016, and the consequent withdrawal from the Paris Agreement, led to an increase in stock returns (Ramelli et al., 2021) and a decrease in the bond yields of carbon-intensive industries (Seltzer et al., 2020). Sen and von Schickfus (2020) shows that equity investors were fully expecting the risk of stranded assets carried by German coal power plants in 2015, but that they expected to be compensated for them. Huang et al. (2019) shows that banks did not price transition risks into loan spreads before the implementation of the Clean Air Action in China; and that they priced them in, although not sufficiently, after the implementation of the policy. Byrd and Cooperman (2018) finds that equity investors are expecting that the coal industry is threatened by climate mitigation, but they expect improvements in Carbon Capture and Storage (CCS) technology to enable the sector to continue operating; only at the end of the study period do they find that equity investors update their expectations and no longer expect the industry to be saved by CCS. Finally, Ramelli et al. (2021) shows that climate strikes have increased the expectations of equity investors on transition risks; which not only suggests that transition risks were not fully priced in beforehand; but also that equity investors are perceiving of the landscape pressure they are under and are readjusting their pricing when they perceive that the pressure is increasing.

Therefore, the existing body of literature supports the idea that financiers' responses to transition risk drivers in the short term are heavily influenced by fluctuations in their attention given to climate change and notable events (Daumas, 2023).

Finally, it should be noted that most current evidence has looked at how margins vary depending on borrowers' characteristics; such as, the participation of firms in the Carbon Disclosure Project (Degryse et al., 2021; Kleimeier and Viehs, 2016), ownership of fossil fuel reserves by borrowers (Delis et al., 2019) and reported corporate emissions (Seltzer et al., 2020). However, the interest rate applied should be tied to the type of assets financed, as lower margins should be demanded for low-carbon assets, and vice versa. This inconsistency could be due to the lack of sufficiently granular data on physical assets and their links to financiers (Campiglio and van der Ploeg, 2022). Looking at assets, and not only corporate level when studying transition risks, is crucial for a more realistic assessment of how such considerations translate into investment decision and stranding effects. In fact, companies with a high environmental ESG score might not necessarily invest in low-carbon assets and anecdotal evidence suggests that firms with high ESG environmental scores are not more likely to emit green bonds than less environmentally-friendly firms (Immel et al., 2021)– firms that boast strong ESG scores pollute as much as their lower-rated competitors (Amenc et al., 2023).

This section has reviewed the existing empirical literature on the expectations of financiers to upcoming low-carbon transitions in various sectors. Given the contradictory evidence from the literature, it is difficult to draw definitive conclusions about whether financiers are now pricing transition risks. Many, but not all, of the reviewed studies have seen an increase in the last decade. However, if financiers do price transition risks, it is likely to be timid (Delis et al., 2019; Krueger et al., 2020; Monasterolo and de Angelis, 2020) and dependent on the attention of financiers to short-term events (Giglio et al., 2021). Furthermore, although financiers have started to implement mitigation strategies (Krueger et al., 2020), financiers do not always believe that the economic losses from the low-carbon transition will translate into financial losses for themselves, as they expect to be compensated by the government (Ameli et al., 2020; Sen and von Schickfus, 2020) or saved by technological progress (Byrd and Cooperman, 2018). Two notable literature gaps are however worth highlighting: first, there is a lack of evidence of the expectations of financiers to shipping transition risks; second, the literature has focused on the pricing of transition risks at the firms' level rather than the asset level.

2.2 Finance and energy systems in the different economic schools of thought

This section presents an overview of the economic schools of thought and justifies the choice of the theoretical framework used in this thesis. To do so, it first identifies the theoretical features that are necessary to study the topic of this thesis, i.e. expectations and stranded assets (Section 2.2.1). After providing a quick overview of the existing schools of thought (Section 2.2.2), Section 2.2.3 describes whether and how those address the desired theoretical features previously identified. Based on this, the last section justifies the choice of theoretical frameworks used in this thesis.

2.2.1 Identifying the desired features to study expectations and stranded assets

Studying the interplay between financiers' expectations and stranded assets requires an understanding of several features:

- **Path-dependency** and sunk capital: stranded assets supposes that the capital shipowners have invested in is long-lasting and can not be repurposed freely.

- **Limited rationality**: in this thesis, rationality is understood in a neoclassical sense, and as defined by Hafner, Jones, Anger-Kraavi, and Pohl (2020) as the fact that a rational agent optimises its utility using perfect information about the future (e.g., the temperature trajectory). This supposes a near perfect foresight and the capacity to proceed all available information. The assumption of rationality is incompatible with stranded assets because, if shipowners and their financiers had perfect knowledge at the time of investment about future shipping demand and mitigation policies, no asset would be stranded because no loss of value would be unanticipated. Studying stranded assets requires the assumption that those actors have imperfect information about the future (Semieniuk et al., 2021; Svartzman et al., 2020). Note that, assuming that shipowners are not rational with this definition of rationality does not necessarily mean that they are irrational, in the more common meaning of the term. On the contrary, in the situation where the 1.5°C transition is not a certainty, financiers are not irrational if they are not fully pricing in transition risk, nor from their own strictly commercial point of view "should" they be doing so.

Several authors argue that this is because transitions, and therefore low-carbon transition risks, are characterised by deep uncertainty which economic actors cannot fully anticipate and quantify (Bachner et al., 2020; Battiston, Dafermos, and Monasterolo, 2021; Lavoie, 2022; Mercure et al., 2016, 2019; Monasterolo, 2020). Deep uncertainty in low-carbon transitions arises from the unpredictable dynamics of technology adoption and diffusion and its unpredictable implementation and effectiveness (Mercure et al., 2016; Svartzman et al., 2020): when credible commitment to future policy is not made, no probability can be assigned to this risk and investors make investments that are deemed to be stranded (Kalkuhl et al., 2020). Policy-related transition risks arise from the fact that climate policies are not time-consistent (Kalkuhl et al., 2020), credible (Bretschger and Soretz, 2018; van der Ploeg and Rezai, 2020b) or properly anticipated (Rozenberg et al., 2020). This deep uncertainty could occur in the shipping sector, as the IMO has pledged to implement climate policies to meet its 2018 and 2023 Strategies, but the concrete implementation and the date of implementation are uncertain and subject to lobbying forces (Bach and Hansen, 2023; Psaraftis, 2019; Psaraftis and Kontovas, 2020). Although the ambition of the Initial Strategy has recently increased each net-zero GHG emission by 2050 and support the uptake of zero/low-carbon technologies, as yet, the policy measures remain insufficient to support the ambition (Bach and Hansen, 2023). This disconnect between ambition and action, if it closes at some point, can cause significant stranding if it happens too late or too quickly. In addition, because investment occurs under deep uncertainty, it is difficult for agents to accurately gauge the potential returns of their investments (Lavoie, 2022; Mercure et al., 2019; Monasterolo, 2020). As a consequence, Battiston, Dafermos, and Monasterolo (2021) argues that it is necessary to understand the forward-looking expectations of agents about climate change scenarios and how these expectations affect the realisation of those scenarios.

- **Role of finance**: the impact that external financiers have on investment decisions, i.e., the interplay between industry (shipowners) and financial (e.g. shipping banks) systems.

Before discussing whether and how these three features are covered in different schools of thought, let us first briefly describe the existing schools of thought.

2.2.2 Overview of the various schools of thought

The economic schools of thought are divided by Hafner, Anger-Kraavi, et al. (2020), Lavoie (2022), and Mercure et al. (2019) between the equilibrium and non-equilibrium approaches[6]. In the equilibrium approach, a representative agent seeks to maximise utility by efficiently allocating fixed resources among various potential applications. This approach is closely related to constrained optimisation, where each point in time is considered optimal and exists within a stable state relative to its context (Lavoie, 2022; Lund et al., 2017; Mercure et al., 2019). Equilibrium economics is based on a range of assumptions that are used in equilibrium models, including, but are not restricted to, perfect rationality; the presence of representative agents and firms; the concept of constant returns to scale; and the idea of market equilibrium in the long term (Hafner, Anger-Kraavi, et al., 2020; Lavoie, 2022).

[6] Also called neo-classical versus new economics, heterodox economics

	School name			Focus	Use in shipping	Innovation and technology	Growth	Typical research method
Equilibrium	Neoclassical	Solow		Long-term economic growth, driven by capital accumulation, labor force growth, technological progress, and productivity changes		Exogenous	Capital accumulation	Optimization
		Endogenous growth		Long-term economic growth, driven by technological progress and human capital accumulation		Knowledge in production function	Capital & knowledge accumulation	
		General Equilibrium		Interrelationships and interactions among various markets in an economy, e.g. how prices, quantities, and allocations are determined across all markets simultaneously	Eide et al (2011, 2013), Ben Brahim et al (2019), Larkin et al (2017)	Knowledge in production functions, learning curve, knowledge spillovers	Capital & knowledge accumulation	
Non-equilibrium	Post-Schumpeterian	Evolutionary Economics		Evolution of industries and economic structure as they respond to changes in market demand, technological advancements, and regulatory environments	Engelen et al (2007)	Knowledge networks, diffusion, learning	Entrepreneur, innovation clustering, creative destruction	Dynamic systems, historical approach, case study
		Transition Theories	Multi-Level Perspective	How transitions from one socio-technical system to another occur, by explaining the dynamics of innovation and change across different levels of a society, including niche innovations, dominant regimes, and the broader landscape of societal norms, regulations, and practices.	Stalmokaite & Yliskyla-Peuralahti (2019), Pettit et al (2018), Karlsen et al (2019), Domagoj (2020)	Historical		
			Technology Innovation Systems	Systemic nature of innovation, viewing it as a collaborative and evolving process that involves not just individual firms or researchers, but also government agencies, universities, suppliers, consumers, and other stakeholders	Bach & al (2020, 2021), Rojon & Dieperink (2014), Baresic (2020)	Case studies		
			Strategic Niche Management	Role of small-scale, innovative initiatives or "niches" in driving and shaping transitions to more sustainable practices or technologies and the importance of nurturing them	Baresic (2020)	Case studies		
	Post-Keynesian			Impact of real-world complexities of the economy (e.g. uncertainty, historical time, institutions, imperfect markets, power relationships) onto financial instability, income distribution, and effective demand.		Sectoral technological progress functions	Cumulative causation of knowledge accumulation	Econometrics, stock-flow consistent models
	Behavioural			How psychological, cognitive, emotional, and social factors influence individuals' economic decisions and behavior		-		Empirical
	Institutional economics			Influence of various social, legal, and cultural institutions on economic behavior and outcomes	Xue & Lai (2023)	-	Institutional framework	Historical approach, case study, empirical

Figure 2.2: Overview of the schools of economic thought (adapted from Mercure et al. (2019) and authors own ideas)

The development of a non-equilibrium approach answers calls to consider the following characteristics of economies and energy systems (Hafner, Anger-Kraavi, et al., 2020):

- Complexity, non-linearity, non-ergodicity (one cannot rely on past data to predict the future) and deep uncertainty: *deep uncertainty* is not measurable, either because one cannot assess the probability that an event occurs or because even the realm of possibility is not known (Bachner et al., 2020; Battiston, Dafermos, and Monasterolo, 2021; Lavoie, 2022; Mercure et al., 2019). It is defined as opposed to *risk*, which can be hedged against by looking at the probability that an event occurs based on historical data.

- *Path-dependency, lock-in and irreversibility*: past decisions and events have long-lasting effects on the future state of the economic systems.

- Agents' heterogeneity

- Behavioural effects: agents do not have perfect information on the future but take decisions according to *heuristics*, i.e. cognitive rules which allow them to make decisions under limited information and cognitive capacity (Lavoie, 2022; Nelson and Winter, 1982) (e.g. agenda, search heuristics, expectations, technical models (Geels, 2019)). Another example of path-dependency is *learning* effects: technology uptake usually adopts an S-shape pattern, as the adoption of an innovation increases the chance that it will be adopted again (Mercure et al., 2016).

- Interdisciplinary: integrate insights from various fields such as psychology, ethics, history, engineering, evolutionary theory, etc.

- Role of institutions and social context: how institutions and social context leads to inertia and power relationships (Hafner, Anger-Kraavi, et al., 2020).

- Inclusion of financial flows explicitly

- Multiple equilibrium or disequilibrium.

A further description of the individual schools of thought, based on the classification of Mercure et al. (2019), is presented in Table 2.2.

2.2.3 The desired features in the various schools of thought

After an overview of the various schools of thought in the previous section, this section describes how they address the three features of energy systems identified in Section 2.2.1; that is: Path-dependency, Rationality, and the Role of finance. The results are summarised in Table 2.3 and are discussed in successive sections below.

	School name			Corresponding financial theory	Path-dependency	Rationality	Role of finance
Equilibrium	Neoclassical	Solow		Efficiency Market Hypothesis	-	Rational expectations and representative agent	Commodity in a finite quantity
		Endogenous growth			-		
		General Equilibrium			None in the purest form, but some can be introduced (sunk investments, learning effects)		
Non-equilibrium	Post-Schumpeterian	Evolutionary Economics		Adaptive Market Hypothesis	Simulation parameters accumulate over simulation time	Evolutionary and collective, behavioural, heterogenous agents	Credit creation
		Transition theories	Multi-Level Perspective	-	Historical: heuristics, learning, actors, institutions, infrastructure		
			Technology Innovation Systems	-			
			Strategic Niche Management	-			
	Post-Keynesian			-	Economic and financial stocks and flows accumulate over simulation time		Endogenous credit creation which is necessary for any economic activity to take place
	Behavioural			Behavioural finance	-	Behavioural, heterogenous and numerous agents	-
	Institutional economics			-	Institutional	Collective	-

Figure 2.3: Schools of economic thought and desired theoretical features (adapted from S. Hall et al. (2017) and Mercure et al. (2019) and authors own ideas)

(a) The darker colours, the more adapted the school of thoughts is to the desired features of this thesis. The justification for those colours can be found in the text.

2.2.3.1 Path-dependency and sunk capital

Path-dependency is often ignored in neoclassical economics, although limited insights have been introduced recently in the form of sunk investments (e.g. in Kalkuhl et al. (2020)) and learning effects (e.g. in Rezai and van der Ploeg (2017)). However, these are more ad hoc additions in larger frameworks which mostly ignore this feature; generally ignore softer factors of path-dependency such as beliefs and institutions; and largely ignore deep uncertainty (Hafner, Anger-Kraavi, et al., 2020). Behavioural economics also ignores path-dependency, although for a different reason: this stream of literature focuses on the identification of bias at any point in time (Simon, 1955; Sorrell et al., 2011), while ignoring the evolution of such biases over time (S. Hall et al., 2017), so it ignores the path-dependent factors of behavioural biases. Therefore, none of these schools are adapted to look at this feature and they are not chosen as a framework of analysis.

The different strands of evolutionary economics are concerned with how path-dependency leads to stickiness in physical capital (sunk investment), but also in institutions and heuristics (feature ”Rationality”). Transition studies, which directly builds on evolutionary economics (Geels, 2002; Markard and Truffer, 2008; Mercure et al., 2019; Safarzyńska et al., 2012) – the Multi-Level Perspective (MLP), the Technological Innovation Systems and the Strategic Niche Management – all look at the levers and unfolding of technological transitions. The latter two are mainly concerned with the emergence of new innovations rather than existing assets (Geels, 2018; Markard and Truffer, 2008) and are therefore less relevant to the study of stranded assets.

The MLP framework, on the other hand, allows us to study the evolution of the incumbent regime during the transitions. In particular, this framework enables an understanding of regime stability and inertia despite the pressure to transition, e.g. need for decarbonising the economy (Geels, 2014; Geels and Schot, 2007) by conceptualising the regime as a self-sustaining set of actors, institutions, beliefs, knowledge, network and infrastructure (Geels, 2011, 2021). This approach to understanding incumbent and investment decisions seems therefore helpful in understanding why certain incumbent actors (regime incumbents, in this framework) would invest in assets which are incompatible with a certain temperature trajectory. Although no study using the MLP framework has explicitly focused on stranded assets to my knowledge, the increasingly rich literature using this framework has proved it to be a particularly helpful theory for looking at the behaviour of incumbents (and sometimes their financiers, see the literature in Section 2.1.3) at the outset and during socio-technical transitions. It has also proved to be particularly helpful in understanding how new technologies and behaviours emerge and destabilise this regime; either through support or resistance by incumbent actors, or by creating risks for the actors and assets. This literature includes studies on the role of the incumbent in transitions in road transport (Berggren et al., 2015; Budde et al., 2012; Penna and Geels, 2015; Späth et al., 2016; Trencher et al., 2021), electricity generation (R. Bolton et al., 2015; Brauers et al., 2020; Fathoni and Boer, 2021; Geels et al., 2017; Kattirtzi et al., 2021; Kungl and Geels, 2018; Saleh and Upham, 2022; Vögele et al., 2018), petro-chemical (Geels, 2022; Nykamp et al., 2023), steel, (Geels and Gregory, 2023), shipping, (Baresic, 2020a; Nykamp et al., 2023; Stalmokaite and Yliskylä-Peuralahti, 2019) egg industries (Hoerisch, 2018), fossil extraction (Morgunova, 2021) and biofuels (Smink et al., 2015; Strøm-andersen, 2019).

2.2.3.2 Limited rationality

Let us now turn to the second desired feature of the theoretical framework identified in section 2.2.1, that is, limited rationality. Equilibrium theory assumes that demand is predictable, at least probabilistically (measurable *risk*) (Lavoie, 2022; Mercure et al., 2019). As a result, capital is optimally allocated and used (Mercure et al., 2019). Regarding financiers' rationality, neoclassical economics views finance through the lens of the Efficient Market Hypothesis (S. Hall et al., 2017). In this framework, financial markets are efficient in incorporating and reflecting all available information (Fama, 1970; Lucas, 1978). This framework is not helpful in understanding that some decisions might lead to stranded assets as, in this framework, transition risks are fully priced into the financial markets and does not help in understanding why certain events would be unexpected (Chenet et al., 2020). Therefore, it is not chosen as a framework for analysis.

On the other hand, investment decisions under deep uncertainty are covered by all non-equilibrium schools of thought, but are only explicitly covered in the case of external finance in the Adaptive Market Hypothesis (the financial pendant of evolutionary economics, S. Hall et al. (2017) and Lo (2004)) and behavioural finance (Masini and Menichetti, 2012, 2013; Shiller, 2003; Wüstenhagen and Menichetti, 2012).

Behavioural finance, which is the pendant of behavioural economics (S. Hall et al., 2017), focuses on the behavioural biases of financiers (Shiller, 2003), and Masini and Menichetti (2012, 2013) studies how a priori beliefs and preference affect investments in renewables. However, behavioural finance ignores the collective and evolving nature of those biases (S. Hall et al., 2017) that are relevant for the topic of stranded assets; financiers' expectations of the upcoming transition and niche technologies are characterised by collecting learning, herding behaviour (Rickman, Larosa, and Ameli, 2022) and potential sudden shifts (as previously discussed in Section 2.1.4). Therefore, behavioural economics is not chosen as a theoretical framework.

Some work in evolutionary economics, on the other hand, has focused on the evolutionary characteristic of finance and expectations. In particular, the concept of heuristics seems very useful in understanding the expectations of the upcoming transition and stranded assets as it allows us to understand how expectations of a transition form and can evolve. It is used both in the AMH and in the MLP literature, as they are both grounded in evolutionary literature. The MLP literature views heuristics as cognitive rules which are socially constructed and shared by members of a socio-technical regime (Geddes and Schmidt, 2020; Geels and Raven, 2006; Geels and Schot, 2007; Safarzyńska et al., 2012). This work builds on both of these strands of literature and defines *heuristics* as an adaptive set of tools, rules and beliefs which are socially constructed and shared among the members of a socio-technical regime who use them to make decisions under deep uncertainty. As in S. Hall et al. (2017) and Lo (2004), those heuristics are sticky and evolving, i.e., they are fairly stable and cannot be changed overnight, but they can evolve with time under landscape pressure.

Although the MLP is helpful for understanding sticky beliefs and expectations (Geels, 2018), its focus on finance has been limited until recently; there are now several attempts to conceptualise finance within the MLP framework. For Geddes and Schmidt (2020), finance sits at the level of the regime, along with others such as the technology regime or the energy regime. Urban and Wójcik (2019) characterise finance as a composition of the three levels (financial landscape, financial regime, and financial niche where financial innovations develop) and where the financial regime can undergo a transition. Geddes and Schmidt (2020) and Geels and Gregory (2023) propose that finance is situated at the level of the regime, alongside others such as the technology regime or the energy regime, while Cairns et al. (2023) assumes that it is located between the landscape and the regime levels which they call a ”meta-regime”. However, these framings fail to address certain limitations in the depiction of finance within the MLP, which frames finance as a passive and neutral resource without agency. Naidoo (2019, 2020) demonstrates that finance is not neutral but should be analysed through a behavioural lens. As a consequence, Steffen and Schmidt (2021) call for a better conceptualisation of finance in transition studies, in particular in the MLP. The MLP is however a relevant framework to understand the role of agency and heuristics, given the importance of those concepts in the MLP literature. The conceptualisation of agency in the MLP literature assumes that actors are self-interested, strategic, and aim to optimise their actions to achieve their goals, albeit within the limits of bounded rationality. Actors rely on cognitive rules and shared heuristics, and their decisions are influenced by formal rules, role relationships, and normative ties within regulatory structures and social networks (Geels and Schot, 2007).

The AMH, on the other hand, largely covers those issues; it assumes that the investment environment and the behaviour of financiers change over time. In this framework, during times of stability, the investment decision process of financiers ("heuristics") is adapted to their environment and near-optimal so that the Efficient Market Hypothesis holds true. However, these heuristics become ill-suited when the environment changes, in which case 'behavioural biases' can be observed. Eventually, financiers adapt themselves to new realities in periods of turbulence or change, such as the global financial crisis, which forces financiers heuristics and behaviours to evolve gradually. Therefore, the AMH seems is the most suitable of the approaches reviewed to understanding the formation of financiers' expectations.

2.2.3.3 Impact of finance on the real economy

Let us finally consider how the third desired feature of the theoretical framework, namely the impact of finance on the real economy, is covered by various schools of thought. This feature is not well covered in the economic literature, and in none of the schools of thought considered above, apart from Post-Keynesian economics (Hafner, Anger-Kraavi, et al., 2020) where the banking sector is considered central to the development of the economy (Lavoie, 2022). In this framework, firms depend on credit creation to finance the capital necessary for production, which is constrained by the credit worthiness of potential borrowers– that is, the (lack of) confidence by banks in the ability of firms to repay loans. This confidence is a direct consequence of deep uncertainty: banks cannot perfectly know the probability that a firm will pay back its loan (Lavoie, 2022). As a consequence, banks rely on heuristics (e.g. past liquidity ratio, collateral, historical relationship of the bank with the borrower) to evaluate the credit worthiness of the loan. Furthermore, the bank can lose trust and confidence in times of financial uncertainty and demand higher margins from borrowers and tighten credit-rationing restrictions, which puts further pressure on firms in difficult times (Lavoie, 2022). The conceptualisation of confidence of banks and deep uncertainty appears helpful in understanding the role of finance in creating/avoiding and reacting to transition risks.

2.2.4 Choice of theoretical framework

The MLP is chosen as the basis theoretical framework for this thesis, for the reasons developed in the previous subsections and summarised as follows:

- Evolutionary economics is the best-suited overarching framework to look at path-dependency, due to its focus on time and path-dependency.
- Within evolutionary economics, the MLP is the most suited framework to understand expectations and stranded assets because it looks at the incumbent regime and at technology lock-in not only in terms of capital invested, but also in terms of beliefs and rationality (heuristics); the interactions of its component actors (sometimes including financial actors); and the institutions. It is also well-suited to look at how niche technologies and transitions disrupt this regime, creating risks including stranded assets.
- The MLP has also proved to be a rich framework for looking at beliefs and heuristics (although it is not the only one), building on institutional economics and conceptualising heuristics.

However, it has several limitations regarding the topic of this thesis:

1. Finance is under-represented in MLP studies and often regarded as a passive resource which lacks agencies, so that financiers' beliefs and expectations have not been studied.
2. As a consequence, the interactions between the finance sector and the industry regime have been neglected, although recent literature has attempted to fill this gap.
3. It is typically well adapted for qualitative studies, but its use for quantitative– and in particular modelling– methods is scarce (discussion on the topic can be found in Geels (2011), Geels et al. (2020a), and van Sluisveld et al. (2020)). In particular, it is not clear from this theory how to model the interactions between finance and industry (shipowners).

The first limitation can be addressed by combining insights from the AMH. The second and third limitations can be addressed by the insights from post-Keynesian economics, which focuses on the interactions between the financial and the industry sectors. Therefore, this thesis builds on these two strands of literature, in addition to the MLP (see Figure 2.4).

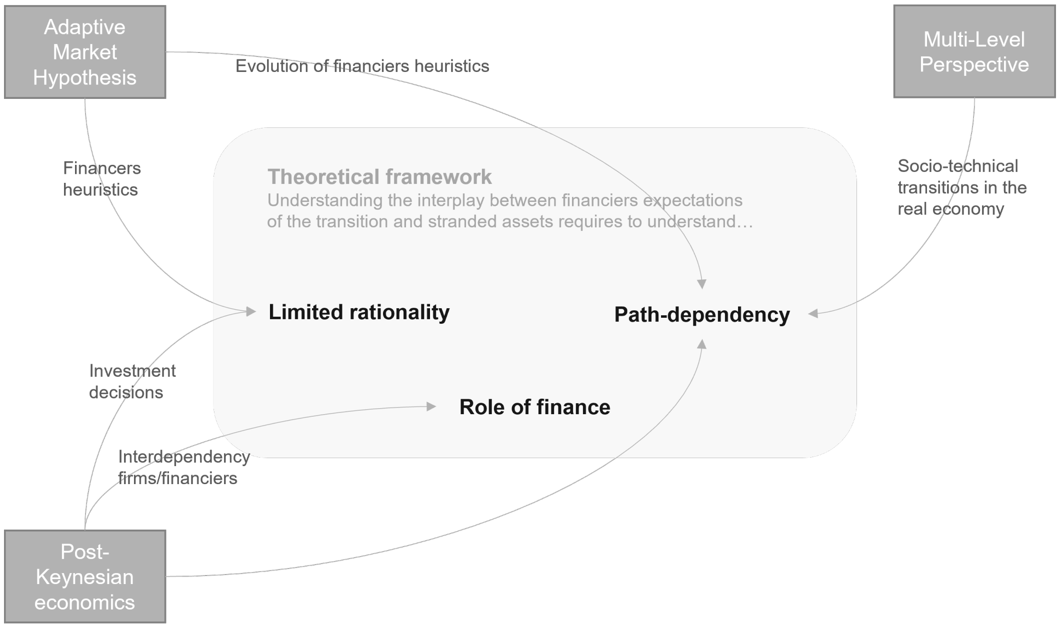


Figure 2.4: Overall theoretical framework

2.3 Modelling financiers' expectations and stranded assets

Having discussed the desired features which are needed to study expectations of the transition and stranded assets in the shipping industry, let us now turn to the approaches to model them. This section reviews how both the shipping fleet evolution and shipping stranded assets can be modelled, with a particular focus on the role of external financiers. There are many models already in place to describe investment decisions and fleet evolution in shipping. They use similar techniques and algorithms as energy systems or sectoral energy systems, so the existing approaches to model energy systems are first reviewed in order to provide a description and evaluation of modelling approaches in shipping (Section 2.3.1). Using this classification, a review of existing shipping models is then conducted (Section 2.3.2). How asset stranding and finance can be modelled are reviewed in Sections 2.3.3 and 2.3.4 respectively.

2.3.1 Classification of modelling approaches

Many attempts to classify energy models into categories exist (Hafner, Anger-Kraavi, et al., 2020; L. M. Hall and Buckley, 2016; Lund et al., 2017; Mercure et al., 2019; Prina et al., 2020; van Vuuren et al., 2009), which this section builds on.

Most classifications divide energy system models between *top-down* ”macro models” and *bottom-up* models (L. M. Hall and Buckley, 2016; Prina et al., 2020; van Vuuren et al., 2009). Top-down models focus on the links between the energy system and the broader macroeconomic sectors. They feature a simplified portrayal of the energy system's components (Prina et al., 2020; van Vuuren et al., 2009): in shipping, they would typically feature a markets interactions based on historical bunker sales and trade. This lack of detail (speed, ship-specific technical information) means that the estimate of emissions can lack accuracy (Nunes et al., 2017). Bottom-up models, on the other hand, analyse in socio-economic detail the components within various energy sectors. These comprehensive models enable users to compare the effects of various technologies on the energy system and assess the optimal pathways to achieve a reduction in GHG emissions (Prina et al., 2020; Smith et al., 2023; van Vuuren et al., 2009). In shipping, they can cover the ship-specific technical information (e.g. installed power) and how they are being operated (e.g. speed), which they tend to aggregate under representative ship specifications. A major limitation of the bottom-up approach, especially in the context of this thesis, is that it overlooks the connections between the energy system and broader macroeconomic sectors (Prina et al., 2020), including the financial system. Many models are now designed as hybrids, combining top-down and bottom-up modules (L. M. Hall and Buckley, 2016; Prina et al., 2020)

Many classifications further divide models between those that adopt an optimisation methodology and those that do not (Hafner, Anger-Kraavi, et al., 2020;

Lund et al., 2017; Mercure et al., 2019), a division that is justified by a difference in the underlying school of thought that underpins them. Mercure et al. (2019) and Hafner, Anger-Kraavi, et al. (2020) implicitly focus on top-down models[7] and categorise them between optimisation/supply-led models, which are linked to equilibrium schools of thought described in the previous section, and simulation/demand-led models, which are linked to non-equilibrium schools of thought. Mercure et al. (2019) argues that a similar divide between demand-led/supply-led models can be found in the bottom-up literature between partial cost-optimisation and simulation models. This classification is also adopted by Lund et al. (2017), who implicitly focus on bottom-up models and argues that optimisation models are linked to the neoclassical school of thought, while simulation models are grounded on institutional economics (a branch of non-equilibrium economics).

Typical equilibrium models include Optimal Growth (RICE/DICE from Nordhaus (2017)), General Equilibrium (GEM-E3, e.g. in Polzin et al. (2021)), Partial Equilibrium and other bottom-up optimisation models (MARKAL and adaptations, e.g. TIMES McGlade and Ekins (2014), McGlade et al. (2018), and Muttitt et al. (2023)). They are frequently employed as policy instruments for evaluating economic and climate-related policies; for example, Hafner, Anger-Kraavi, et al. (2020) notes that 30 out of the 31 models used by the Intergovernmental Panel on Climate Change (IPCC) report are equilibrium models.

Concrete applications of the non-equilibrium school of thought include:

- Econometric models : the energy system is determined by linear relationships estimated using real-world data and econometric techniques (Hafner, Anger-Kraavi, et al., 2020; e.g. the E3ME/E3MG model)

- System Dynamics Models: an energy system is determined by non-linear relationships (differential equations) and various feedback controls (Hafner, Anger-Kraavi, et al., 2020; e.g. IMAGE-TIMER)

- Agent-Based Models: the energy system is made of agents which are diverse

[7]The models they review mostly are top-down models, although some optimisation bottom-up models are also included.

by their types (consumer, firms) and/or by their behaviours and which interact following rules (Hafner, Anger-Kraavi, et al., 2020; e.g. MATISSE)

- Stock-Flow Consistent (SFC) models: focus on the interactions between the financial and economic systems. Post-Keynesian assumptions, especially those related to the role of monetary and banks, have been formalised by Godley in Post-Keynesian stock-consistent models with Godley and Lavoie (2007) serving as a reference. The basis assumption of SFC models is the accounting consistency for all monetary stocks and transactions: that every monetary flow comes and goes somewhere (i.e., there is no "black hole" in the economy) and every asset of an agent is a liability of another (Godley and Lavoie, 2007; Lavoie, 2022). For example, any debt granted by a bank to a company represents a liability on the company's side, and an asset on the bank's side. This allows for an accurate portrayal of financial assets and debts.

- Bottom-up simulation model: generates a system by simulating and predicting the actions of a system given exogenous assumptions. Investment decisions made by these simulation models are often guided by a basic heuristic method; for example, all new ships built from 2018 are methanol-fuelled. The primary purpose of simulation models is to anticipate the operation of a particular system based on specific assumptions, without ensuring the identification of the optimal allocation (Lund et al., 2017; Prina et al., 2020) (e.g. EnergyPlan, LEAP)

Figure 2.1d describes how non-equilibrium models address the desired features of the non-equilibrium approach described in section 2.2.2.

In practice, many models are a hybrid between those different approaches (Mercure et al., 2019). Notably, equilibrium models can incorporate elements that remain fixed despite optimal changes resulting in 'sub-optimal' solutions (Mercure et al., 2019); for example, accounting for sunk capital or myopic foresight, firms only know future development of variables critical for investment (price, policy,

Table 2.1: Overview on evaluated features compared to the potential of different modelling approaches to capture them (taken from Hafner, Anger-Kraavi, et al. (2020))

No.	Desired features of a 'new approach in economics'	E	SD	ABM	SFC	Relevance for the understanding of energy transitions
1	Complexity, non-linearity, non-ergocity and deep uncertainty	✓	✓✓	✓✓		• Impacts model results and policy implications (see section 3); • Energy transitions are influenced by, and impact, other areas such as consumption, production or labour market (e.g. changes in skills requirements) and include delays (e.g. changes in regulations, in skills etc.) and are thus characterised by complexity. • Non-ergocity relevant is relevant as in sustainability transitions future changes are likely to be different to past data patterns.
2	Importance of time, path-dependency, lock-in and irreversibility	✓	✓✓	✓		• Representation of infrastructure lock-in or cost decreases due to learning effects; • Technical potential for different energy sources or availability of resources required for equipment; • Changes in actor behaviour over time.
3	Agents' heterogeneity and behavioural elements	✓	✓	✓✓	*	• Investigation of consumer, energy producer, financial investor and government interactions; • Understanding renewable energy technology innovation or adoption from a bottom-up perspective; • Representation of the different skill requirements; • Evaluation of distributional effects of policy interventions.
4	Interdisciplinary	✓	✓✓	✓✓		• Simulation of the relevant political, social, institutional, technical, organisational or economic aspects on energy transitions
5	Role of institutions and social context	✓	✓✓	✓✓		• Representation of institutional influences on regulations or frameworks (e.g. climate related risk disclosures); • Influences of syndicates or other interest groups on wage formation process; • Representation of lobbying on political processes, regulations or frameworks.
6	Ethical and moral philosophical aspects	✓	✓✓	✓✓		• Relevant to understand how different policy objectives should or could be prioritised when there are trade-offs between them; • Understanding of what does a 'just energy transition' mean; • Ethics might be relevant for actor's behaviour.
7	Finance	✓	✓	✓	✓✓	• How can the energy transition be financed? • What are the implications of a (very quick or very slow) energy transition on the stability of the financial system? • What are the effects of increased investments on GDP? (see section 3)
8	Multiple equilibria/disequilibrium	✓✓	✓✓	✓✓	✓✓	• Impacts model results and policy implications (see section 3);
						• Energy-transitions involve deep structural non-marginal changes and are therefore likely out-of-equilibrium transitions'.

(a) * Depends on what modelling approach the SFC is combined with

(b) E: econometrics; SD: Systems dynamics; ABM: Agent-based modelling; SFC: stock-flow consistent modelling

(c) Non-equilibrium models, in their purest form, do not address those features

(d) It is the understanding of the author that two ticks means, in the original article, that the feature is particularly well covered in those modelling approaches; while one tick means it's partly covered.

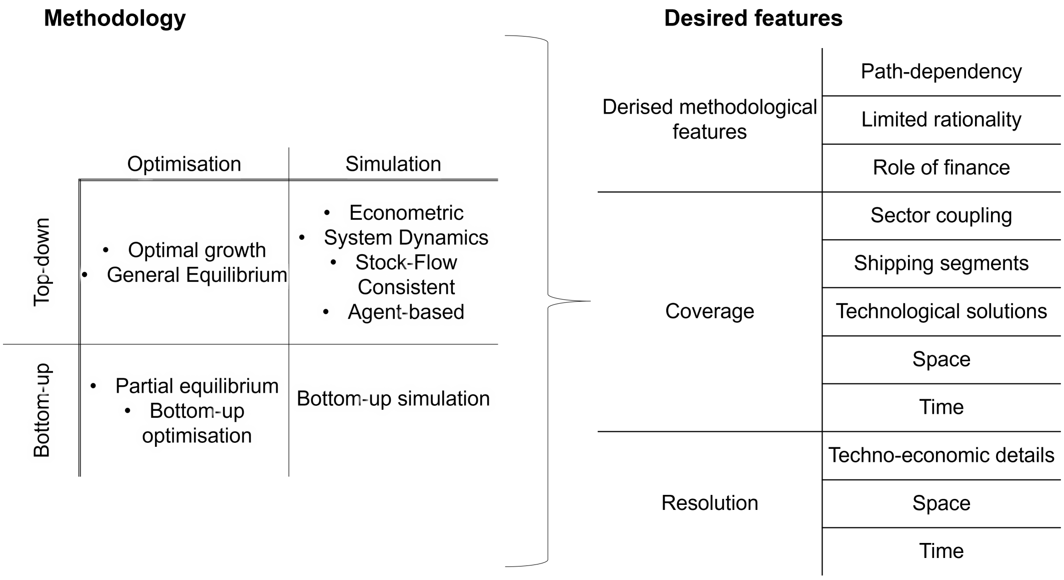


Figure 2.5: Classification of energy models

technology available) one or a few modelling time steps (generally years) in advance, while ignoring long-term evolutions (Prina et al., 2020). The use of myopic foresight, as opposed to perfect foresight by which firms and policy makers optimise investments across all time steps (usually years) simultaneously (Prina et al., 2020), allows for the relaxation of rational expectations by optimising at each time step (Mercure et al., 2019), although the other assumptions underpinning the rational agent (optimisation behaviour, capacity to process all available information) are not relaxed. Furthermore, there have been recent efforts to develop energy models that can take advantage of top-down and bottom-up approaches; hybrid models fuse top-down macro-economic models with at least one bottom-up model for each ultimate sector (Prina et al., 2020). This fusion can be achieved by manually transferring data and parameters from one model to another (*soft-linking*) or by employing automated routines for the same purpose (*hard-linking*) (Prina et al., 2020). Perhaps the most widely used of these hybrid models is the Integrated Assessment Model (IAM), which hard-link climate, economy, and energy models and whose top-down components are equilibrium models.

The classification of energy models presented in figure 2.5 is a summary of the classifications discussed above, and is used later in this thesis to assess the modelling approach chosen for this thesis.

Regarding methodology, the models are classified along the divides top-down/bottom-up, optimisation/simulation. The models are evaluated based on: 1) the desired methodological features defined in Section 2.2 that are necessary for the aim of this thesis; 2) their coverage; and 3) their resolution, as suggested by Prina et al. (2020). Regarding the former, as discussed in section 2.2.2, the role of finance, rationality, and time-dependency are particularly critical to this thesis. They are best covered by stock-flow consistent, agent-based models and system dynamics respectively. Those models therefore appear to be relevant to the study of the research topic (the choice of the exact model is discussed in the next Chapter).

Coverage refers to how large the model is (e.g. all ships in the world) while resolution refers to how detailed the components are within this coverage (divided by ship segment, size, or even individual ship, as opposed to one broad category). Prina et al. (2020) in their classification consider time, space, and techno-economic details (divided between segments and technological solutions available) as well as the coupling of shipping with other sectors. A granular resolution and a wide coverage of time and techno-economic details are particularly critical for the aim of this thesis because they are directly linked with the potential for stranded assets: the model needs to cover a period long enough to include the timing of the transition, i.e. several decades, and the granularity of the technical-economic details must be sufficient to model the alignment or misalignment of sunk investments with the transition. Furthermore, having a large coverage of shipping segments is further important to assess stranded assets in the shipping industry, otherwise results might only cover part of the issue and not be necessarily applicable to the whole fleet. Those 5 elements (good coverage and resolution of techno-economic details and time, and good coverage of shipping segments) are therefore used as critical evaluation criteria in the remainder of this thesis. Finally, a granular space resolution and the coverage sector coupling are secondary although they are not irrelevant so they are also reported; for example, some routes/regions might be more at risk than others to be stranded and/or the limited availability of some energy sources, e.g.

biofuels, might make some alternatively-fuelled ships uneconomic.

This section has reviewed the key modelling approaches of energy systems and, using the theoretical insights from section 2.2, identified a list of desired features that a model needs to have in order to represent the predicted interactions between the expectations of an upcoming shipping transition and stranded assets. The classification and list of desired features (summarised in Figure 2.5) are used as follows in the remainder of the thesis:

- Classify and judge the appropriateness of existing shipping models to study the topics of this thesis - expectations of upcoming transition and stranded assets in the next subsections.
- Select a modelling approach to be used in the thesis in the methodology chapter (Chapter 3).
- Critically evaluate the methods and results and highlight their limitations in the modelling results Chapter (Chapter 7).

2.3.2 Review of approaches to model shipping investment decisions and systems

This section reviews and evaluates the existing shipping models within the classification described above. To select shipping models, a search on Web of Science was conducted on 10/08/2023 using the search words "(shipping OR seaborne transport* OR maritime) AND (simulat* OR model*) AND (decarbon* OR climate change OR green OR carbon emissions OR CO2 emissions)" in topics for all sources published after 2015.

Several filtering criteria on the initial selection of studies (2800) were applied. First, because this thesis is concerned with investment decisions in high- and zero/low-carbon ships, only the models which derive ship investment decisions in at least two technologies linked to different emission profiles were included (e.g. scrubber, size, use of energy efficiency device, alternative fuels). This excludes several types of models:

- This excludes white, grey and black-box models. White-box models enable an understanding of how on-board energy is used in various design specifications and operational scenarios, allowing the assessment of ship performance; fuel consumption; and emissions. Grey and black-box ship prediction models rely on data from continuous monitoring systems, noon reports, and/or weather data. Although these modelling approaches offer valuable insights into the performance and emissions of individual vessels, they often face challenges in terms of scalability, computational costs, and reliance on data availability; and the inability to quantify the effects of policies, market dynamics, and financial measures on the global fleet. Those models are therefore excluded as they do not allow one to model the evolution of the fleet.

- This also excludes models focused only on ship routing and speed optimisation (e.g., Cheaitou and Cariou (2019), J. Lu et al. (2023), Qiu et al. (2018), H. Wang et al. (2021), and K. Wang et al. (2015)) and models that look at the fuel switch in Emission Control Areas (ECA) (W. Gong et al., 2018) without considering investment decisions. The literature of operational optimisation is prolific and uses a wide range of bottom-up static optimisation techniques to minimise the cost and sometimes the emissions from an existing fleet in a set of routes. However, this literature is static and excludes investment and fleet evolution, which are the focus of this thesis.

- This finally excludes models of fleet deployment and mix, when those only consider one type of ship technology (i.e., conventional) and do not consider the possibility for a shipowner to invest in ships with differentiated emission profiles such as scrubbers, alternative fuels, and energy efficiency (e.g., Bakkehaug et al. (2014)). However, the models which only look at differentiated ship sizes were included when the authors made the link between ship size and energy intensity clear, as ship size is linked with improved energy efficiency and consequently emission reduction.

The studies which focus on seaborne ship assets are only further filtered, i.e.

this excludes barges; port investments; and studies whose algorithms are not clear, as they are not helpful to inform the difference in modelling approaches. However, some models which are not fully public, but whose methodology is transparent, were included. Further models referenced in the selected studies were investigated in cascade effect. The final sample includes 21 shipping models, summarised in Tables 2.3 and 2.2.

Table 2.2: Review of the existing shipping models: modelling approach

	Methodology		Desired methodological features		
Reference	**Top-down/bottom-up**	**Optimisation approach**	**Path-dependency**	**Rationality**	**Role of finance**
4th GHG study	Hybrid: - trade flows: top-down - fleet evolution and emissions: bottom-up	Hybrid: - trade flows: non-equilibrium (macroeconomic)	High: sunk investment, exogenous learning	Low: exogenous	Low: uniform cost of capital
Al-Enazi et al (2022)	Bottom-up	Optimisation	Low: none	Low: perfect foresight	Low: none
Ankathi et al (2022)	Bottom-up	Hybrid: - fuel production: simulation - fuel mix: optimisation (IEA ETP)	Low: none	Low: perfect foresight	Low: none
Bas et al (2017)	Top-down	Non-equilibrium (agent-based)	High: sunk investment, learning effects	High: endogenous preference	Low: none
ben Brahim et al (2019)	Bottom-up	Optimisation	Medium: sunk investment	Low: perfect foresight	Low: none
Bullock et al (2020)	Bottom-up	Simulation	Medium: sunk investment, stranded assets	Low: exogenous	Low: none
Chica et al (2023)	Top-down	Non-equilibrium (agent-based)	High: sunk investment, learning effects	High: endogenous preference	Low: none
Dettner & Hilpert (2023)	Bottom-up	Simulation	Medium: sunk investment	Low: exogenous	Low: none
DNV GL Maritime Forecast (2022), Eide et al (2013, 2011)	Bottom-up	Optimisation	High: sunk investment, learning effects	Medium: myopic foresight	Low: uniform cost of capital
Halim et al (2018)	Hybrid: - trade flows: top-down - transport work: top-down - technology mix : bottom-up	Hybrid: - trade flows: equilibrium (general equilibrium) - transport work: non-equilibrium (macroeconomics)	Low: none	Low: exogenous	Low: none
IEA Technology Perspectives	Bottom-up	Optimisation	Low: none	Low: perfect foresight	Low: none
Karslen et al (2019)	Top-down	Non-equilibrium (agent-based)	Medium: learning effects	High: endogenous preference	Low: uniform cost of capital
Mueller-Casseres et al (2021)	Bottom-up (fuel production, fleet evolution and emissions)	Optimisation	Medium: sunk investment	Low: perfect foresight	Low: none
Nelissen et al (2016)	Hybrid: - fleet growth: hybrid (4GHG) - technology uptake: bottom-up	Hybrid: - fleet growth: hybrid (see 4GHG) - technology choice: optimisation	High: sunk investment, learning effects	Medium: myopic foresight (technology choice)	Low: uniform cost of capital
Patricksson et al (2015)	Bottom-up	Optimisation	Low: none	Medium: myopic foresight	Low: none
Randrianarisoa & Gillen (2022)	Top-down	Non-equilibrium (econometric)	Low: none	Medium: historical	Low: none
Schinas & Bergmann (2021)	Bottom-up	Simulation	High: sunk investment, exogenous learning	Low: exogenous	Low: none
Schwartz et al (2020)	Bottom-up	Simulation	Medium: sunk investment	Low: exogenous	Low: uniform cost of capital
Smith et al (2019, 2016, 2022), Raucci et al (2017)	Bottom-up	Optimisation	High: sunk investment, exogenous learning	Medium: myopic foresight	Low: none
Taljegard et al (2014)	Bottom-up	Optimisation	Low: none	Low: perfect foresight	Low: uniform cost of capital
Zhen et al (2020)	Bottom-up	Optimisation	Low: none	Low: perfect foresight	Low: none
Zhu et al (2018)	Bottom-up	Optimisation	Low: none	Low: perfect foresight	Low: uniform cost of capital

(a) When a model is linked to another existing model, including when only the input are used and the existing model is not described in the article, the model was classified as "hybrid" and the approach was separately described for both models. However, only the part of the model which deals with ship investments and fleet evolution is relevant for this thesis and is discussed below. The colours correspond to the classification of the ship investment part.

(b) The three last columns correspond to the methodological desired features identified in Figure 2.5. Darker green corresponds to a better assessment on those criteria

Table 2.3: Review of the existing shipping models: coverage and resolution

		Coverage				Resolution		
Reference	**Sector coupling**	**Shipping segments**	**Technological solutions**	**Space**	**Time**	**Techno-economic details**	**Space**	**Time**
4th GHG study	Demand drivers	High (all)	High (Alternative fuels, renewable energy, energy efficiency, size)	High (World)	High (2018-2050)	High	Low	Low (decarbonization scenario), High (BAU)
Al-Enazi et al (2022)	Fuel suppliers	Low (LNG, hydrogen and ammonia carriers)	Low (Alternative fuels)	Low (set of international routes from Qatar)	Low (1 theoretical time step)	Medium	High	Low
Ankathi et al (2022)	Demand driver, fuel supplier	Low (Tanker)	Medium (Alternative fuels, energy efficiency (basic))	High (World)	High (2018-2050)	Medium	High	Low
Bas et al (2017)	Fuel suppliers	High (all)	Low (Alternative fuels)	High (World)	Medium (20 years)	Medium	Medium	High
ben Brahim et al (2019)	None	Medium (Bulk carriers,	Low (Alternative fuels)	Low (Denmark)	High (2016-2050)	Medium	Low	High
Bullock et al (2020)	None	High (all)	High (Alternative fuels, renewable energy,	Low (Europe)	High (2019-2050)	Medium	Low	High
Chica et al (2023)	None	High (all)	Low (Renewable energy (wind))	High (World)	High (30 years)	High	Low	High
Dettner & Hilpert (2023)	None	High (all)	Low (Alternative fuel (e-	Low (Northern Europe)	Medium (2015-2040)	Low	High	Low
DNV GL Maritime Forecast (2022), Eide et al (2013, 2011)	Demand driver, fuel supplier	High (all)	High (Alternative fuels, renewable energy,	High (World)	High (2020-2050)	High	Medium	High
Halim et al (2018)	Alternative transport modes	High (all)	High (Alternative fuels, renewable energy, energy efficiency)	High (World)	Medium (2015-2035)	High	Low	High
IEA Technology Perspectives	Fuel providers, alternative transport modes	High (Tankers, bulk carriers, containers, general cargo, other ships)	High (Alternative fuels, renewable energy, energy efficiency)	High (World)	High (2010-2050)	Low	Low	High
Karslen et al (2019)	Shipyard	Low (Bulk carriers)	Low (Renewable energy (wind))	Low (stylized)	High (2020-2050)	Low	Low	High
Mueller-Casseres et al (2021)	Demand drivers, fuel suppliers	Medium (Bulk carriers, tankers and containers)	Medium (Alternative fuels, energy efficiency (basic))	Low (Brazil)	High (2010-2050)	Medium	Low	Low
Nelissen et al (2016)	Demand drivers	Medium (Tankers, bulk carriers, containers)	Low (Renewable energy (wind))	High (World)	High (2020-2050)	Low	High	High
Patricksson et al (2015)	None	Low (Ro-Ro)	Low (Scrubber, low-	Low (12 routes in the	Low (1 theoretical time	Low	High	Low
Randrianarisoa & Gillen (2022)	None	Low (Container)	Low (Size)	High (World)	Low (1 theoretical time	Low	Low	Low
Schinas & Bergmann (2021)	None	High (all)	Low (Renewable energy (wind))	High (World)	Low (2021-2026)	Low	Low	High
Schwartz et al (2020)	None	Low (General cargo)	High (Renewable	Low (Baltic sea)	High (2020-2050)	High	Low	High
Smith et al (2019, 2016, 2022), Raucci et al (2017)	Demand driver, fuel supplier	High (all)	High (Alternative fuels, renewable energy,	High (World)	High (2018-2050)	High	Low	Medium
Taljegard et al (2014)	Demand drivers, fuel	High (short sea, deep	Medium (Alternative	High (World)	High (2020-2050)	Medium	Medium	Medium
Zhen et al (2020)	None	Low (Container)	Low (scrubber and shore	Low (Four routes in	Low (1 theoretical time	Low	High	Low
Zhu et al (2018)	None	Low (Container)	Low (Size)	Low (stylized)	Low (1 theoretical time	Low	Low	Low

(a) Only technological solutions are reviewed because they have a significant capital investment cost and are the focus of this thesis, as opposed to operational solutions.

(b) The columns correspond to the criteria of evaluation identified in Figure 2.5 under coverage and resolution. Darker green corresponds to a better assessment on those criteria

Table 2.2 shows a clear preference for bottom-up models. This is not surprising, since this approach allows one to include more techno-economic details and is therefore generally preferred for sectoral models. They therefore tend to perform well against the evaluation criteria under resolution (Table 2.3). Besides, one can argue that shipping is too small in and of itself to represent a meaningful impact on macroeconomic dynamics such as prices and financial stability, so those are simply considered exogenous. Several models are hybrid between top-down and bottom-up models, but the former approach is used to model the drivers of the shipping demand and/or the fuel production pathways; as opposed to the shipping systems themselves, which are modelled in a bottom-up approach (for example, in Faber et al. (2020), Halim et al. (2018), and Müller-Casseres, Edelenbosch, et al. (2021)). Bottom-up models typically study all or a subset of shipping segments by aggregating them under representative ship specifications (e.g. ship type, size) (ben Brahim et al., 2019; Dettner and Hilpert, 2023; Eide et al., 2011, 2013; Longva et al., 2020; Müller-Casseres, Carvalho, et al., 2021; Smith et al., 2016, 2019b, 2022, 2023; Taljegard et al., 2014) and/or on representative routes (Al-Enazi et al., 2022; Dettner and Hilpert, 2023; Zhen et al., 2020; Zhu et al., 2018).

Some noteworthy exceptions adopt a top-down non-equilibrium approach: Bas et al. (2017) models the uptake of alternative fuels using an agent-based model; Karslen et al. (2019) proposes an agent-based model between technology providers and shipowners to study the uptake of wind technologies on board of ships; Chica et al. (2023) studies the effect of interactions between shipowners on the uptake of wind technologies by also using agent-based models; and Randrianarisoa and Gillen (2022) conduct an econometric analysis of the effect of supply chains on, among others, ship size. They deduce from their estimated parameters, in a small macroeconomic model, the consequences in terms of GHG emissions. These models tend to have, by construction, a much less granular resolution and less wide coverage in terms of techno-economic details (Table 2.3) : Chica et al. (2023), Karslen et al. (2019), and Randrianarisoa and Gillen (2022) only focus on one type of technical solution (although Chica et al. (2023) includes several competing wind technologies); Bas et al. (2017) on the other hand, includes four technologies (heavy fuel oil, HFO, marine gas oil, LNG and scrubber) and a large amount of detail on the geography and ship specifications, and therefore shows a fairly detailed technical resolution.

From this review, there does not seem to be a consensus between optimisation versus non-optimisation approaches for modelling shipping, with the sample of modelling approaches being fairly balanced between the methodologies. Bottom-up optimisation models constitute the single preferred approach of the sample (Al-Enazi et al., 2022; ben Brahim et al., 2019; Eide et al., 2011, 2013; IEA, 2020; Longva et al., 2020; Müller-Casseres, Carvalho, et al., 2021; Smith et al., 2016, 2019b, 2022, 2023; Taljegard et al., 2014; Zhen et al., 2020; Zhu et al., 2018), and most of them would use perfect foresight (Al-Enazi et al., 2022; ben Brahim et al., 2019; IEA, 2020; Müller-Casseres, Carvalho, et al., 2021; Taljegard et al., 2014; Zhen et al., 2020; Zhu et al., 2018). Those studies typically minimise a cost function across one or several time steps to choose the cost optimal technologies onboard ships.

There is an agreement in the literature of optimisation models that investment decisions are made by optimising a measure of profits. In contrary, for non-optimisations models, there is no agreement in the literature on how to model the choice of technology by asset investors in non-equilibrium top-down models. Dafermos (2012), Dafermos and Nikolaidi (2021, 2022), Dafermos and Papatheodorou (2015), Dafermos et al. (2017, 2018), and Dunz et al. (2021) models the choice of technology as a linear function of the comparative costs of technologies (to my knowledge, there is no such approach for shipping). Bas et al. (2017) for shipping and Monasterolo and Raberto (2018) and Ponta et al. (2018) assume that asset owners simply choose the least costly option at the time of investment, usually using the Net Present Value. Finally, Lamperti et al. (2018) and Mercure, Pollitt, Viñuales, et al. (2018) and Chica et al. (2023), Karslen et al. (2019), and Rehmatulla et al. (2015) for shipping models consider that past experience and imitation dynamics largely determine the choice of technology, so that even if a technology is more cost effective, lack of awareness of its existence and / or benefits means that it will not represent 100% of investments right away so that technology uptake follows an S-curve. It is worth noting that Chica et al. (2023), Karslen et al. (2019), and Mercure, Pollitt, Viñuales, et al. (2018) all include elements of cost optimisation as well, as once asset owners are aware of the existence of a technology, they choose the most cost-effective one, so that the second approach (e.g. Bas et al. (2017)) is simply a special case of this third approach where awareness of a technology spreads immediately and perfectly.

Finally, several studies have proposed bottom-up simulations to represent the evolution of the fleet (Dettner and Hilpert, 2023; Faber et al., 2020; Halim et al., 2018; Schwartz et al., 2020). These studies adopt a simple heuristic and derive the consequences for the fleet evolution: Dettner and Hilpert (2023) assume that an exogenous share of new ships are replaced with e-methanol-fuelled ships; Halim et al. (2018) exogenously imposes the adoption of technological, operational, and alternative fuels onto all ships in 2035; Schwartz et al. (2020) imposes all ships, all new ships, or all ships after dry docking (depending on the technology) to adopt an emission-reduction solution; Schinas and Bergmann (2021) assumes that an exogenous share of the fleet is retrofitted to wind technologies. These studies do not attempt to find the "best" pathway towards decarbonisation, but are helpful to understand the consequence of a technological pathway onto other variables, such as emissions or investment needs.

Let us now compare how the different models perform against the 16 desired features set in Figure 2.5. Those performances are summarised in Table 2.2. Let us start with the desired methodological features (path dependency, limited rationality and role of finance): most of the models include to some extent elements of path dependency, mostly in the form of sunk investments, by explicitly modelling capital invested, retrofitted, and retired (Bas et al., 2017; ben Brahim et al., 2019; Bullock et al., 2020; Dettner and Hilpert, 2023; Eide et al., 2011, 2013; Faber et al., 2016; Longva et al., 2020; Müller-Casseres, Carvalho, et al., 2021; Nelissen et al., 2016; Raucci et al., 2017; Schinas and Bergmann, 2021; Schwartz et al., 2020; Smith et al., 2016, 2019b, 2022, 2023, as summarised on Table 2.2). Only one study computes an estimate of stranded assets from those sunk investments (Bullock et al., 2020), which shows that this topic has not been widely investigated in the literature. It is worth noting that many models also include learning effects (Bas et al., 2017; Eide et al., 2011, 2013; Karslen et al., 2019; Nelissen et al., 2016; Raucci et al., 2017; Schinas and Bergmann, 2021; Smith et al., 2016, 2019b, 2022, 2023), i.e., that past investment / experience in one technology reduces the cost of investing in this technology in the future. This is relevant to some extent to study stranded assets, as learning effects might create lock-in into a technology, but this feature is less critical than the physical lock-in in the form of sunk investments, to the aim of this thesis.

Of those 22 modelling approaches, only the three agent-based models (Bas et al., 2017; Chica et al., 2023; Karslen et al., 2019) and the four bottom-up optimisation with myopic foresight (Eide et al., 2011, 2013; Raucci et al., 2017; Smith et al., 2016, 2022, 2023) allow theoretically to look at the role of expectations and behaviour of shipowners during the unfolding of the low-carbon transition (desired feature "rationality" in Table 2.2). Note however that the bottom-up optimisation models with myopic foresight would only be able to relax some aspect of neoclassical rationality (perfect foresight), while maintaining the other assumptions underpinning the neoclassical rational agent - capacity to process all available information and agent optimising its utility - therefore ignoring further behavioural elements (heuristics, beliefs, behavioural bias for example). Furthermore, to my knowledge, the four bottom-up models have not been used to investigate the issue of limited rationality and behaviour, apart from the notable exception of Raucci et al. (2017) which looks at the effects of varying the time horizon for investment. However, even this study does not look at actual foresight, that is, the quality of the knowledge of shipowners on future carbon and fuel prices. Furthermore, because the investment horizon was not the variable that varied between the included scenarios, it is not possible to disentangle what is due to the foresight of the shipowners from what is not. The feature "limited rationality" therefore remains largely under-researched in the shipping modelling literature.

Furthermore, finance is never endogenously included in these models (desired feature "role of finance" in Table 2.2). In some, it is implicitly included through the use of discount rates and cost of capital (Eide et al., 2011, 2013; Karslen et al., 2019; Nelissen et al., 2016; Schwartz et al., 2020; Smith et al., 2016, 2019b, 2022, 2023; Taljegard et al., 2014; Zhu et al., 2018), but those are uniform across technologies, geography, and actors. This implicitly assumes that financiers are passive catalysts of investments and do not take a view on the relative riskiness of technology and actors over others. As a consequence, none of the reviewed models performs well on the three desired methodological features, although Bas et al. (2017) and Chica et al. (2023) performs well on two out of three (path dependency and rationality).

Let us now look at the performance of the models against the desired features of resolution and coverage, summarised in Table 2.3, keeping in mind that techno-economic details, time and shipping segments were argued to be the most critical in the previous section. None of the two best performing models against the desired methodological features (Bas et al., 2017; Chica et al., 2023) performs well against those criteria. On the other hand, four models perform particularly well in the time and techno-economic coverage and resolution: the model used in the 4th GHG study to project fleet evolution, the GHG Pathway Model from DNV GL (Eide et al., 2011, 2013; Longva et al., 2020), GloTraM (Smith et al., 2016, 2019b, 2022, 2023) and the model proposed in Halim et al. (2018) (Table 2.3). These three models cover most of the shipping segments, a large range of technological solutions (energy efficiency devices, renewable energy and alternative fuels), and at least 20 years of fleet evolution. Of those four models, two (GloTraM and the GHG Pathway Model from DNV GL) perform somewhat better in terms of desired methodological features, although insufficiently (Table 2.2). They generally perform poorly in terms of space resolution, apart from the latest version of the DNV model, which includes some geographic information (Table 2.3), but this criterion is considered less critical for the assessment of stranded assets. This is because, for an early overall assessment of stranded assets, it is assumed that the stock of ships is perfectly mobile through the globe (e.g. some ships are not "locked" to some routes) and that countries of ownership do not matter. While this a simplification and both of those assumptions could be released in future work, for a first assessment, other details were deemed more critical - e.g. technologies, time.

This section has reviewed the existing models of shipping investment decision and fleet. Here are some key takeaways from this review:

- There is a wide range of approaches to model shipping, with none making a consensus

- No existing approach covers all desired features for this thesis identified in Figure 2.5, with some models performing well in terms of methodological features path-dependency and rationality but poorly in terms of coverage and resolution, while others perform well in terms of resolution but poorly in terms of those methodological features (Table 2.2 and 2.3). This means that no existing model alone is sufficient in its current stage to model the shipping transition and the materialisation of stranded assets.

- Four models perform better than the others and are taken for consideration in the choice of methods detailed in the next Chapter. The models covered in Bas et al. (2017) and Chica et al. (2023) cover best the methodological features of path-dependency and rationality, which is maybe not surprising given their non-equilibrium nature. However, they perform poorly in terms of coverage and resolution. GloTraM and the GHG Pathway Model from DNV GL perform particularly well in terms of resolution and coverage, but are limited in terms of their representation of rationality.

- None of the models sufficiently represent the role of finance, and few have explicitly considered stranded assets. Given that those aspects are poorly covered by the shipping modelling literature, further insights from modelling in other sectors are reviewed in the next two subsections.

2.3.3 Review of approaches to model stranded assets

The previous section showed that only a couple of studies examine the risk of asset stranding in shipping (Bullock et al., 2020; Raucci et al., 2017). This section provides a broader overview of the existing approaches available to model this issue. Several articles have already provided an extensive literature review on how stranded assets have been modelled (Campiglio and van der Ploeg, 2022; Curtin et al., 2019; Daumas, 2023), which this section builds on. This literature review is mostly based on the study of stranded assets in other sectors, such as electricity generation, with the notable exception of Bullock et al. (2020). Their empirical results are not applicable for shipping, but their methodological approaches might be helpful as ships, like power plants, fossil fuel reserves or buildings, have long lifespans, large initial investments, are possible but costly to retrofit, and emit large amount of carbon over their lifespans.

Many studies have primarily used model-based forward-looking approaches, in which they compare a baseline projection (representing business-as-usual or unambitious policies) with a policy scenario or an externally imposed carbon budget constraint (Curtin et al., 2019; Daumas, 2023). These estimates serve as indicators of the vulnerability of a sector's capital stock to stranding within a given projection. These studies, often reliant on extensive models, do not explicitly describe the specific drivers of asset stranding, so they consider climate policies, technological displacements, and shifts in demand collectively. Much of the literature has attempted to quantify the stranded physical assets required to achieve a specific temperature target, such as fossil fuel reserves that cannot be extracted (McGlade and Ekins, 2014, 2015; Welsby et al., 2021) or committed emissions embedded in existing fixed assets (Bullock et al., 2020; Löffler et al., 2019; Y. Lu et al., 2022; Pfeiffer et al., 2016). However, this literature has focused primarily on quantifying these physical asset strandings and has not dived into how stranded assets can impact the financial sector.

Daumas, 2023 divides studies which have provided monetary estimates of stranded assets between :

- Book loss: the economic value of existing carbon intensive assets forced to be for decommissioned/unexploited before their projected economic lifespan (Edwards et al., 2022; Hauenstein, 2023; N. Johnson et al., 2015; Löffler et al., 2019; Saygin et al., 2019; W. Zhang et al., 2021).

- Foregone streams: the continuous reduction in financial income that firms exposed to transition risks may need to endure during the low-carbon transition (Chen et al., 2023; Mercure, Pollitt, Viñuales, et al., 2018; Muldoon-Smith and Greenhalgh, 2019).

Some of this literature has allocated which specific assets would be stranded using criteria such as cost (N. Johnson et al., 2015; Löffler et al., 2019; McGlade and Ekins, 2014, 2015; Welsby et al., 2021), age (Saygin et al., 2019), equity considerations (Pye et al., 2020 or a composite score (W. Zhang et al., 2021). Most studies (Y. Lu et al., 2022; McGlade and Ekins, 2014, 2015; Pfeiffer et al., 2016; Saygin et al., 2019; Welsby et al., 2021; W. Zhang et al., 2021) are static in nature because they only look at the existing assets stock to calculate the risk of assets becoming stranded. Their analyses implicitly assumes that no new power plant will be built nor no new fossil fuel reserves be discovered, i.e., that the decarbonisation will start at the time of analysis and will be gradual. However, risk of asset stranding might be greater if climate mitigation is delayed. However, a few (Bullock et al., 2020; N. Johnson et al., 2015; Löffler et al., 2019; Mercure, Pollitt, Viñuales, et al., 2018; van der Ploeg and Rezai, 2020b) use energy models to project future additions to the existing stock of assets, by modelling future investments before the transition risk materialises.

The body of research on asset stranding frequently concentrates on specific sectors at high risk of stranding; notably fossil fuel extraction and electricity generation (Campiglio and van der Ploeg, 2022; Curtin et al., 2019; Daumas, 2023). Shipping has been largely ignored, apart from the notable exception of Bullock et al. (2020), which only covers European emissions. Furthermore, although the link between physical stranded assets and financial instability has been understudied (Campiglio and van der Ploeg, 2022; Daumas, 2023), an increasing number of studies (Battiston et al., 2017; Caldecott et al., 2016; Semieniuk et al., 2022) now map physical assets to the chains of ownership and financing to study the cascade effects on the financial sector.

2.3.4 Review of approaches to model finance

As discussed in section 2.3.2, none of the shipping models incorporates the role of finance. Therefore, the existing approaches to modelling finance and capital investments in other sectors are reviewed here, to inform how such approaches could be applied to the shipping industry.

Although historically very few models have considered the role of finance (Mercure et al., 2019), there has been an increased interest in the last five years in integrating the role of finance and cost of capital into transition and energy models. Lonergan et al. (2023) shows that most energy models do not take the cost of capital into account at all, which is consistent with the findings of the literature review presented in Section 2.3.2. Those which do insufficiently justify the choice of value applied and a third of the models reviewed assume a uniform cost of capital (Lonergan et al., 2023). Lonergan et al. (2023) stresses the importance of considering the impact of geography, basis interest rates set by central banks, and the riskiness of technologies on the cost of capital (Lonergan et al., 2023). In addition, the impact of the expectations of the financiers of transition risks / stranded assets could have a significant effect on the availability and price of finance (Battiston, Monasterolo, et al., 2021). Let us successively discuss these four factors.

2.3.4.1 General interest rate

Accounting for base levels of cost of capital, typically as a consequence of the basis interest rate set by the Central Banks, is relevant when technologies show a different level of capital intensity, such as renewables (high capital investment per amount of electricity, low operating costs) and fossil-fuelled electricity generation (low capital investment per amount of electricity, high operating cost) (Lonergan et al., 2023). Egli et al. (2018) and Hansen et al. (2024) shows that wind and solar investments have largely benefited from low general interest rates after 2010. This effect is less likely to be important for shipping, as alternative-fuelled and more efficient ships are only marginally more expensive than conventional ones, while the difference in cost of fuel is very large. In some SFC models, the evolution of the basis interest rate is an endogenous product of central banks trying to control for inflation (Bovari et al., 2020; Lamperti et al., 2021; Monasterolo and Raberto, 2018) while in some bottom-up optimisation models it is set as an exogenous factor. For example, Hirth and Steckel (2016) and Schmidt et al. (2019) show that a higher uniform cost of capital penalises renewables rather than fossil fuels, so that their uptake is lower when assuming high interest base rates.

2.3.4.2 Geography

Countries in which investments into new technologies have happened benefit from self-sustaining learning effects, as countries with better macroeconomic policies and background have better access to capital. This creates a renewable investment trap that excludes poor and vulnerable countries from financing in renewable energy (Ameli et al., 2023; Rickman, Kothari, et al., 2022). As a consequence, there is now solid evidence that models using uniform cost of capital generally overestimate the transition costs in developed economies and underestimate them in developing economies (Egli et al., 2019a). Ameli, Dessens, et al. (2021), Schyska and Kies (2020), and Sweerts et al. (2019) adapt bottom-up optimisation models by including differentiated cost of capital by country, and shows that lower access to finance in developing economies means that they face higher decarbonisation costs (climate investment trap). The differences in cost of capital are not only due to the difference in the cost of equity and cost of debt by country, but also to the different levels of leverage. This bias might concern shipping if shipowners and fuel producers from high-income countries are better placed to invest in zero/low-emission ships and the fuel production chain; if they have better access to finance; and a lower cost of capital than those in developing countries. However, this hypothesis has not been investigated to my knowledge in the literature.

2.3.4.3 Technology riskiness

The cost of capital of various technologies has historically evolved significantly over time during socio-technical transitions (Egli et al., 2018; Zhou et al., 2021). Initially, low-carbon technologies may face higher costs of capital if they are less profitable and less mature than conventional ones, but also if they are perceived to be riskier because of financiers' lack of knowledge and experience. Egli et al. (2018, 2019b), Masini and Menichetti (2012, 2013), and Wüstenhagen and Menichetti (2012) argue that this penalty reduces with the learning effects of financiers: initially, low-carbon technologies are considered less mature and riskier, but as financier providers accumulate experience in financing renewable technology, their perception of risk and the spreads associated with the loans are reduced. Rickman, Larosa, and Ameli (2022) further shows that, in the wind generation industry, learning processes are driven mainly by a few private banks, creating a herding effect. Bachner et al. (2019), Halstead et al. (2019), Polzin et al. (2021), and Sweerts et al. (2019) show that including differentiating capital cost by technology reduces largely the cost of the transitions and/or facilitates the uptake of renewables, especially when renewables are de-risked by a public policy (Bachner et al., 2019; Sweerts et al., 2019).

In bottom-up optimisation models that attempt to incorporate the technology-differentiated cost of capital, the initial difference in the cost of capital is usually set exogenously and can be calibrated using existing empirical data (Lonergan et al., 2023). Evolution can be setup exogenously in a scenario analysis (Bachner et al., 2019; Sweerts et al., 2019), or learning effects can be integrated into energy models by including endogenous learning effects of external capital providers in the cost of capital (Polzin et al., 2021).

Non-equilibrium models give more freedom to make those effects endogenous. In some SFC models, financiers evaluate the financial risk of a potential borrower by looking at their past financial performance (non-performing loan ratio, debt-to-equity ratio, illiquidity, for example) (Bovari et al., 2020; Dafermos and Nikolaidi, 2021, 2022; Dafermos et al., 2017, 2018; Dunz et al., 2018, 2021; Monasterolo and

Raberto, 2018; Ponta et al., 2018). When different technologies are used by separate firms, carrying low-carbon technologies that are typically less profitable at the beginning of the period would receive less advantageous financing conditions; however, those financing conditions improve as the investment cost and the efficiency of low-carbon technologies improves (Dunz et al., 2021). How this perceived riskiness is translated into action differs among models. In some, financiers then price this perceived riskiness in the interest rate or equity yield they request– requesting a higher yield for riskier firms (Dunz et al., 2018, 2021). In other, financiers ration credit to firms, i.e., they refuse to provide some or all of the finance requested by perceived riskier firms (Bovari et al., 2020; Dafermos and Nikolaidi, 2021, 2022; Dafermos et al., 2017, 2018; Monasterolo and Raberto, 2018; Ponta et al., 2018). Furthermore, in such models, the implementation of a climate policy such as a carbon tax or dirty penalising factors, because it deteriorates the balance sheets of carbon intensive firms, leads to an increase in the cost of capital or a reduced access to capital of carbon intensive firms. This further deteriorates their profits so that the materialisation of transition risks is amplified by the reaction of the financial sector. This effect is relatively mild when policies are implemented progressively (Bovari et al., 2020; Dafermos et al., 2018) but can be fairly brutal when the implementation is strong and sudden (Dafermos and Nikolaidi, 2022; Dunz et al., 2018, 2021).

Differentiating by technology seems of paramount importance as several of the shipping zero/low-carbon solutions are not mature (wind propulsion, alternative fuels), and the technology for conventional ships has historically evolved very slowly, so the impact of the perceived technology riskiness on the cost of capital is likely to be important. This is therefore helpful in understanding how finance reacts to changes in the economic environment - in particular transition risks - and feedbacks from the financial to the economic system as a consequence.

2.3.4.4 Expectation of transition risks

Carbon intensive technologies, although considered less risky, could face a higher cost of capital if they become less competitive due to the rapid decline in the cost of renewables (Bachner et al., 2019) or as a consequence of divestment due to fear of stranded assets (Bachner et al., 2019). Battiston, Monasterolo, et al. (2021) argues forward-looking expectations of financiers regarding conventional technologies are fundamental in understanding whether the financial system will play an enabling or hampering role in the low-carbon transitions, as opposed to being a reactive backward-looking catalyst of investments.

To my knowledge, only Bachner et al. (2019) and Dunz et al. (2018, 2021) account for the role of forward-looking expectations of financiers. In Dunz et al. (2018), equity investors discount the equity returns of brown equities with an exogenously higher rate of return if they anticipate that the government will apply a carbon tax. In Dunz et al. (2021), the interest rate that banks request not only reacts to the base interest rate of the central bank and the past financial strength of firms, but also to the expected future profits of the firm and the expectations of the bank on future climate policy. This adjustment involves reducing the interest rate for low-carbon firms while increasing it for high-carbon firms in anticipation of an upcoming rise in the carbon tax. Their analysis indicates that banks can mitigate the negative economic effects of climate policy by adjusting their lending practices and the cost of debt earlier than the transition shock (Dunz et al., 2018, 2021). Finally, Bachner et al. (2019) models the expectations of stranded assets into an increased cost of capital for fossil fuelled generation; those expectations are modelled exogenously in a scenario approach.

2.3.4.5 Modelling finance in equilibrium and non-equilibrium approaches

It is worth highlighting the difference in how equilibrium and non-equilibrium studies have attempted to include the role of finance in energy transitions. Some bottom-up equilibrium models have focused on the cost of capital by setting exogenously different costs of capital on a different country and/or technology (e.g. Ameli, Dessens, et al. (2021), Halstead et al. (2019), Hirth and Steckel (2016), Polzin et al. (2021), Schinko et al. (2019), and Sweerts et al. (2019) see Lonergan et al. (2023) for a systemic review, who does not explicitly focus on optimisation models but who in practice ignores all non-equilibrium models). The cost of capital can be highly disaggregated and calibrated onto empirical data because the models themselves show a high level of detail on technology and/or geography. However, because the cost of capital is exogenous, there are no feedback loops between the financial and the economic sectors. This is partly because the role of finance is not the focus of such models, and it is largely considered as a catalyst of investments that does not have agency on its own. This might also be due to the nature of equilibrium models which, because they rely on the assumption of actors' rationality and the existence of an equilibrium, are ill-equipped to look at the interconnectedness of financial and economic systems (Battiston, Dafermos, and Monasterolo, 2021).

There has been an increased adoption in recent years for top-down non-equilibrium evaluations of climate-related financial issues (Bovari et al., 2020; Dafermos and Nikolaidi, 2021, 2022; Dafermos et al., 2017, 2018; Dunz et al., 2018, 2021; Lamperti et al., 2021; Monasterolo and Raberto, 2018; Ponta et al., 2018). These models build on the Post-Keynesian tradition to integrate finance into energy models (Bovari et al., 2020; Dafermos and Nikolaidi, 2021, 2022; Dafermos et al., 2017, 2018; Dunz et al., 2021; Lamperti et al., 2021; Monasterolo and Raberto, 2018; Ponta et al., 2018) and describe finance as an endogenous actor that facilitates or impedes investment in different technologies, either by credit rationing or by price of capital. Particularly important for this thesis, non-equilibrium models are better-equipped to capture how forward-looking expectations of climate scenarios form and impact their actualisation, and therefore the endogenous nature that defines transition risks (Battiston, Dafermos, and Monasterolo, 2021; Battiston, Monasterolo, et al., 2021).

2.4 Summary of research gaps

The first section has highlighted two empirical gaps. First, although there is increasing knowledge surrounding financiers' expectations of transition risks in the energy and electricity generation sectors, it is unclear how shipping financiers view transition risks in shipping and whether they are willing to support the transition to zero/low-carbon shipping (e.g. their perception of transition risks, the underlying factors steering their financing behaviours, and the adaptations they are making in their tools and strategies) (second research gap in Table 2.4). Furthermore, there is limited evidence in any sector on whether financiers take into consideration the carbon intensity of the asset/project finance itself, as opposed to the history of the borrower. Given how controversial the tools to measure ”greenness” at the corporate level are (F. Berg et al., 2022), and given that there is no evidence that firms with better ESG environmental performance invest in greener assets/projects (Amenc et al., 2023), it appears necessary to look at whether financiers take into account what they finance, not only who they finance (third research gap in Table 2.4).

The second section has shown that the MLP, although it can be used as a theoretical framework to describe and understand energy transitions and the roles taken by various stakeholders, views financiers solely as providers of resources and neglects their active agency (Naidoo, 2020) – like most of the economic schools of thought and energy models (first research gap in Table 2.4). In line with the MLP and AMH literature, this agency refers to the capacity of financiers' actors to act in their self-interest and strategically, to reach their own goals, where cognitive capabilities and time are limited (bounded rationality) (Geels and Schot, 2007). This limited perspective fails to describe the diverse array of behaviours documented in the empirical literature on energy transitions reviewed in the second section. There is therefore a need to theorise the agency of financiers and their influence on firms.

The last section has highlighted that there is both a large range of modelling approaches available to estimate the risk for stranded assets on the current stock of assets as well as modelling approaches to estimate the evolution of the fleet in the coming decades as the shipping low-carbon transition unfolds. However, there is a need to include the role of finance when modelling fleet evolution and emissions. More generally, energy models fail to incorporate the learning effects of financiers toward new technologies and their forward-looking expectations regarding the upcoming low-carbon transitions. The lack of an energy modelling approach to incorporate, 1) the perceived riskiness of new zero/low-carbon technologies and 2) their expectations of future transition risks constitutes a methodological gap (fourth research gap on Table 2.4). It is therefore unclear how those expectations influence the realisation of low-carbon transitions (last research gap on Table 2.4).

2.5 Research questions

This thesis aims at filling those literature gaps and at studying the interplay between:

- Financiers' expectations of the upcoming transition in shipping;
- The investment decisions by shipowners; and
- The materialisation of the risk of stranded asset.

More precisely, this thesis aims to answer the following research questions:
Research question 1: What share of the existing capital in ships is incompatible with land and shipping carbon budgets?
Research question 2: What are the current expectations of financiers regarding the upcoming shipping low-carbon transition?
Research question 3: How could the expectations of financiers of upcoming low-carbon transition in shipping evolve during this transition?
Research question 4: How do those expectations affect the amount of stranded assets?

The way in which the research gaps identified in the previous section are covered by the research questions is summarised in table 2.4.

Table 2.4: Overview of research gaps and research questions

Literature gap	**Type of gap**	**Research question**
Theoretical understanding of financiers' agency during socio-technical transitions	Theoretical	RQ3
Understanding of financiers' expectations of the upcoming shipping low-carbon transition	Empirical	RQ2
Understanding of financiers' pricing of transition risks at the asset level	Empirical	
Inclusion of financiers' expectations of an upcoming transition into energy modelling	Methodological	RQ4
Understanding of how financiers' expectations of an upcoming socio-technical transition impacts its realisation	Empirical	

The research questions are answered in several steps, described in Figures 2.6 and 2.7. The first step, conducted in Chapter 4, consists of describing the current state of the shipping fleet (that is, the sunk capital today) compared to the limits imposed by the necessity to limit the temperature increase to 1.5°C and avoid the catastrophic effects of climate change. This step answers RQ1. The second step, already partially covered in this chapter and completed in Chapter 5, aims to identify archetypal behaviours of financiers, depending on their expectations of an upcoming transition. This step partly answers RQ3. This gives a framework to understand where shipping financiers expectations are and how they could evolve in the coming decade, as the transition unfolds. Then, Chapter 6 conducts an empirical assessment of shipping financiers' current expectations of the upcoming low-carbon transitions and behaviour, and answers RQ2 and RQ3. Chapter 7 covers three steps that aim to answer RQ4. By building on the outputs from Q2 and Q3, Chapter 7 looks at the evolution of financiers' expectations and consequent behaviours, along with the evolution of the fleet. Finally, it looks at the consequent stranded assets that arise if shipping is to respect the temperature target of 1.5°C increase.

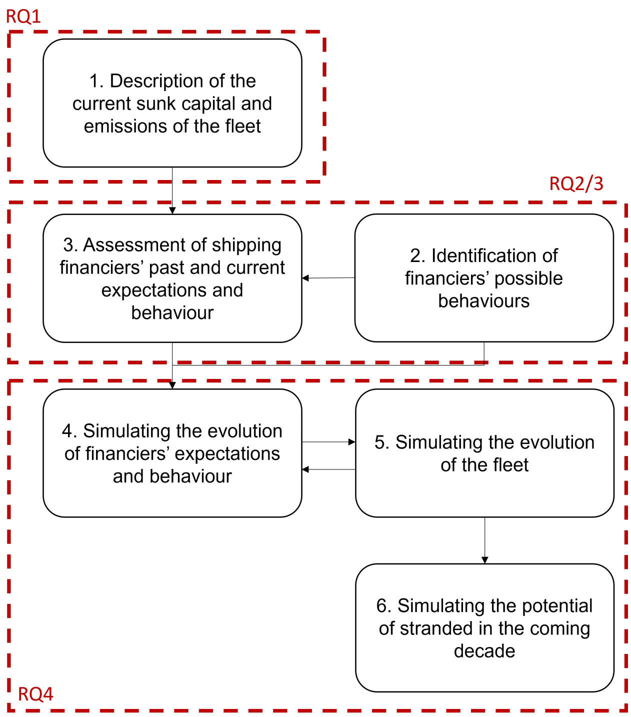


Figure 2.6: Overview of research questions

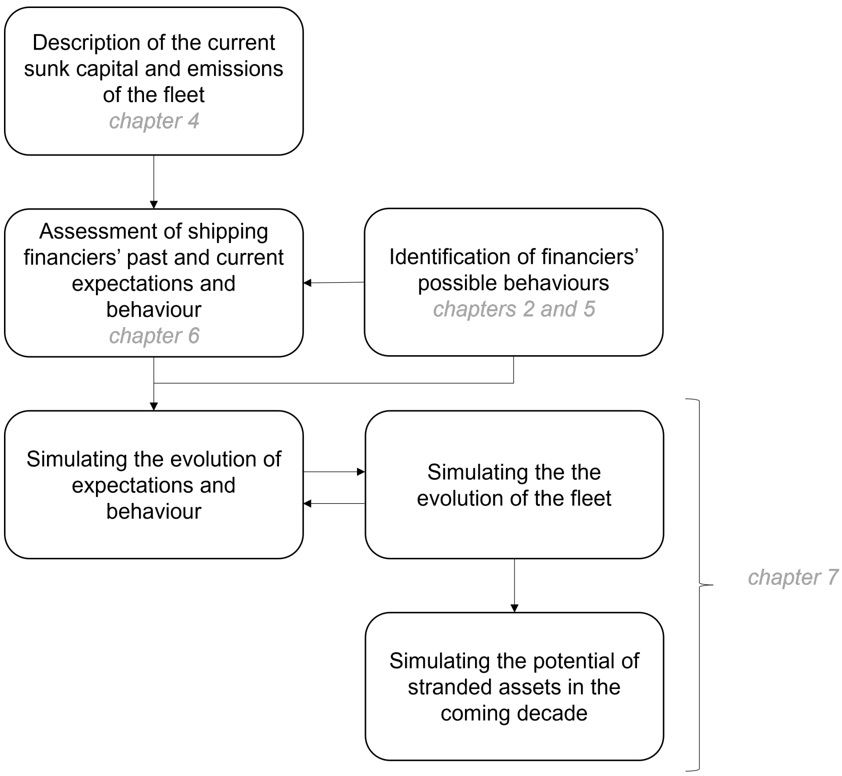


Figure 2.7: Research framework and structure of the thesis

Chapter 3

Research approach

This section explains the chosen research approach used to answer the four research questions stated above. To do so, the model proposed by Creswell, W. John & Creswell (2018) is used, which stipulates that a research approach is made of three elements:

- Ontological background: which philosophical ideas underline the research;
- Research design: procedures/strategy of enquiry, offering guidance for the procedures of the study;
- Research methods: how data is collected, analysed and interpreted.

The choices related to the ontological approach, the research design, and the research methods taken in this thesis are discussed in the following three subsections.

3.1 Ontological approach

Creswell, W. John & Creswell, 2018 classifies the ontological approaches into four broad categories and defines them as follows:

- **Postpositivist** assumptions have historically represented the conventional paradigm of research. Postpositivists adhere to a deterministic philosophy where causes determine effects or results. Consequently, the issues examined by postpositivists revolve around the need to identify and evaluate the factors that impact outcomes, and tend to use an experimental setting. Additionally, postpositivism tends to be reductionistic, aiming to reduce complex concepts into a concise, discrete set that can be tested, such as the variables that constitute hypotheses and research questions.

- Social **constructivists** maintain that people actively create an understanding of their surrounding world and their professional environments. People build subjective interpretations of their encounters. These interpretations are diverse and manifold, leading researchers to explore the complexities of perspectives rather than simplify them into a limited number of categories or concepts.

- **Transformative**: while there is no singular body of literature that defines this perspective, it encompasses various communities of researchers who align with critical theory; participatory action research; Marxism; feminism; racial and ethnic minority perspectives; individuals with disabilities; indigenous and postcolonial groups; as well as members of LGBTQ+ communities.

- **Pragmatism**: rather than focusing on methodologies, researchers prioritise the research problem and question, employing a variety of available approaches to gain a comprehensive understanding of the issue.

Table 3.1: Ontological approaches (adapted from Creswell, W. John & Creswell (2018))

Postpositivism	**Constructivist**	**Transformative**	**Pragmatism**
Determination	Understanding	Political	Consequences of actions
Reductionism	Multiple participant meanings	Power and justice oriented	Problem-centered
Empirical observation and measurement	Social and historical construction	Collaborative	Pluralistic
Theory verification	Theory generation	Change oriented	Real-world practice oriented

The ontological approach of this research is pragmatic. This is both a personal preference and guided by the research questions: because they are diverse and call for various approaches, a single type of method is not apt at answering all of them, as discussed further in the following section, which justifies the choice of research design.

3.2 Research design

There exists a wide range of research designs, which Creswell, W. John & Creswell (2018) divides between quantitative, qualitative, and mixed methods.

Table 3.2: Research designs (adapted from Creswell, W. John & Creswell (2018))

Quantitative	Qualitative	Mixed methods
Survey	Narrative research	Convergent
Experiment	Phenomenology	Explanatory
Modelling	Grounded theory	Exploratory
	Ethnography	
	Case study	

The main types of designs are summarised in Table 3.2 and are as follows:

- **Survey research** offers a numerical representation of trends, attitudes, or opinions within a population through the examination of a representative sample from that population. This method includes both cross-sectional and longitudinal studies that use questionnaires or structured interviews to collect data (Creswell, W. John & Creswell, 2018).

- **Experimental research** aims to identify whether a particular treatment has an impact on a specific outcome. Researchers achieve this by administering treatment to one group while withholding it from another group, subsequently analysing and comparing the outcomes of both groups (Creswell, W. John & Creswell, 2018).

- **Modelling** is a type of quantitative design which was not included in Creswell, W. John & Creswell (2018)'s original list; it consists of mathematical structures or a set of procedures which can be described by equations, computer code, pictures or words (Gräbner, 2018; Weisberg, 2013).

- **Narrative research** is rooted in the humanities and focuses on the examination of individuals' lives and the collection of personal narratives from one or more individuals.

- **Phenomenological research** delves into the firsthand experiences of individuals with respect to a specific phenomenon, as recounted by the participants themselves (Clarke and Braun, 2013; Creswell, W. John & Creswell, 2018).

- **Grounded theory** originates from sociology and aims to formulate a comprehensive and abstract theory based directly on the perspectives and insights of the participants (Clarke and Braun, 2013; Creswell, W. John & Creswell, 2018).

- **Ethnography** involves the extensive study of the shared behaviours, language, and actions of a cultural group in their natural environment over an extended period.

- **Case studies** involve a thorough examination and analysis, typically of a programme; event; activity; process; or one or more individuals, with the objective of providing an in-depth understanding of the subject under investigation (Creswell, W. John & Creswell, 2018).

Mixed research approaches involve the collection of both qualitative and quantitative data, using quantitative and qualitative methods and a procedure to integrate them (Creswell, W. John & Creswell, 2018). There are three types of procedures according to Creswell, W. John & Creswell (2018), summarised in figure 3.1:

- **Convergent mixed methods** represent a mixed research approach where the researcher combines quantitative and qualitative data to offer a holistic examination of the research issue. In this design, the researcher generally collects both types of data concurrently and subsequently integrates them when interpreting the overall findings.

- **Explanatory sequential mixed methods** involve a research approach where the initial phase consists of quantitative research with subsequent analysis and a follow-up qualitative research phase to provide a more detailed explanation of the quantitative findings.

- In the **exploratory sequential approach**, the research process starts with a qualitative research phase, during which the researcher explores the perspectives of the participants. After analysing the data collected, this information is then used to inform and build a subsequent quantitative phase.

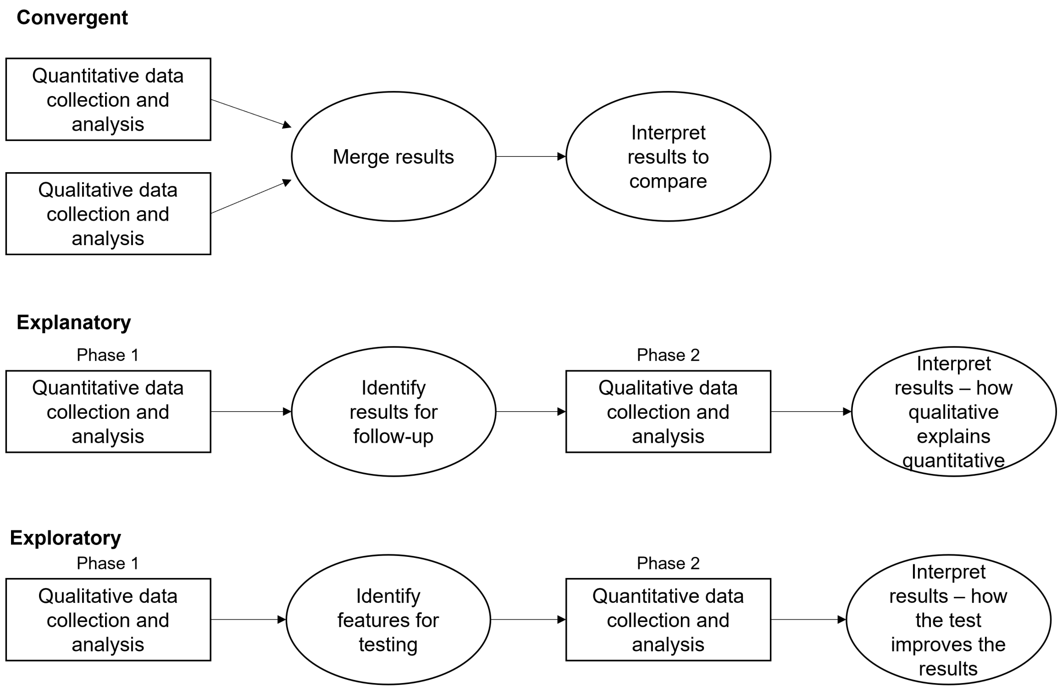


Figure 3.1: Mixed methods approaches (adapted from Creswell, W. John & Creswell (2018))

The research design is summarised in figure 3.2.

Research questions (RQ) two and three are empirical questions. RQ2 can be investigated for shipping directly, as it concerns the current state of the financiers' expectations. On the other hand, RQ3 can only partly be investigated for shipping, as the transition has already started to unfold, so the expectations of financiers might have already started to evolve, but expectations in the later phases are unknown. RQ3 can also be investigated by looking at how financiers' expectations have evolved in other sectors which are more advanced or have already undergone a socio-technical transition, which has already been carried out in the literature review.

Various research designs reviewed above are helpful to answer RQ2 and RQ3. A survey design can provide a numeric description of the trends in opinion or actions of financiers. The results of such a design would be reliable and replicable, but they would not provide any description of the detailed meaning of low-carbon transitions to financiers. Given that the object of this study, i.e. expectations, is complex and subjective by nature, such a design would likely miss important aspects. This is why Campiglio and van der Ploeg (2022) calls for research to directly elicit financiers' expectations. Qualitative designs such as case studies, e.g. ethnography or phenomenology, are well suited for this. However, those methods typically focus on a small sample of individuals, so that results might be hard to generalise to the entire shipping finance. Given those limitations, an explanatory mixed methods approach is chosen for several reasons (see the second row of Figure 3.1 for a description of this design). First, it draws on the strengths of both qualitative and quantitative designs and minimises their limitations. Second, it allows for a more complete understanding of the research questions, by explaining the quantitative results with subsequent qualitative data collection and analysis. In a first step, the evolution of financiers' expectations over the last decade is first researched quantitatively by using a dataset of shipping loans (survey research design). In the second step, the results are explained in a case study that covers a small sample of shipping financiers.

RQ4 investigates the causality of one variable (expectations) onto the other (stranded assets)– a type of question which is typically answered by a quantitative research design (Creswell, W. John & Creswell, 2018). In such a design, the concept of causality means that variable X is expected to have a causal effect on variable Y (Creswell, W. John & Creswell, 2018), and this is the definition which is taken here. Because the transition to zero-/low-carbon shipping has not yet unfolded, neither a survey nor real-life experiments are possible, and only a modelling design is possible. A computer model is not understood here as a faithful reproduction of reality or as a predictive instrument: as Poitras (2021) argues, because the results cannot be confirmed by real-life experiments or observations, this design is rhetoric rather than scientific. This does not mean that modelling is not helpful per se: the design of this step is based on the view that models are tools to explore how properties are related (Peace and Weyant, 2008), that is, the "investigation of deductive relationships and conditions" (Godfrey-Smith, 2009, p114). The modeller defines (imagines, in Godfrey-Smith (2009)'s vocabulary) the set-up and the links between the variables, and the model derives the consequences of the configurations that were imagined (what would happen to Y given X). Causality can be deduced by comparing it with a counterfactual, similar to an experimental design (Weisberg, 2013): where a control variable of interest is changed to observe the effects on the dependent variable.

In the context of this thesis, the dependent variable of interest is the amount of stranded assets which would occur in this transition, and the control variable of interest is the expectations of shipping financiers of an upcoming low-carbon transition. Its evolution is parameterised ("imagined") using the empirical results of research questions two and three. This integration between qualitative findings from other disciplines, in particular socio-technical transition studies, and quantitative modelling approaches has been demanded by several authors on the ground that transitions are subject to deep uncertainty, subjective expectations, and complex evolutions that quantitative research designs alone cannot grasp (Hafner, Anger-Kraavi, et al., 2020; Semieniuk et al., 2021; Svartzman et al., 2020). On the other hand, very few studies have used a formal modelling approach to understand the unfolding of socio-technical transitions (Walrave and Raven, 2016). To my knowledge, very few studies have attempted to combine the two research designs (Geels et al., 2020b; McDowall, 2014; van Sluisveld et al., 2020 are exceptions) and never attempted to understand the role of finance.

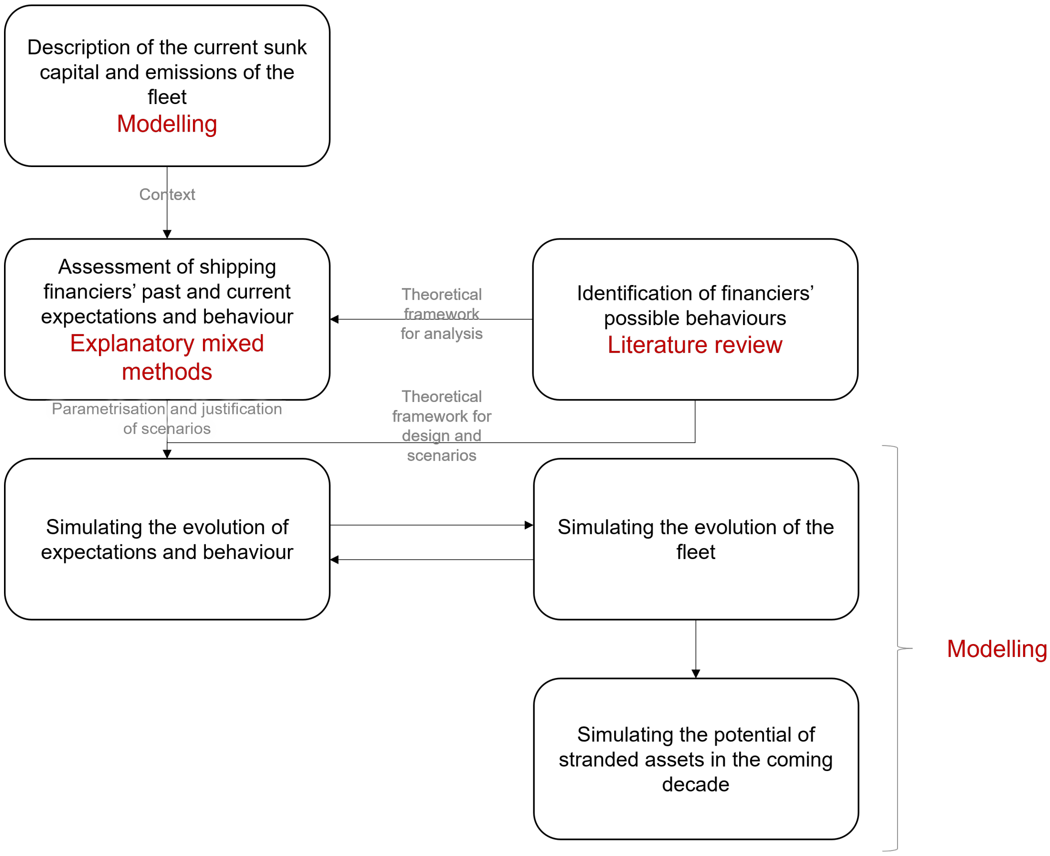


Figure 3.2: Overview of the research design

3.3 Research methods

This section justifies the choice of research methods under the various elements of the research design, summarised in Figure 3.3. It provides an overview of the research methods, but the research methods for each step of the analysis are explained in more detail in chapters 4 to 7.

First, a simple bottom-up simulation model is used to describe the current state of the fleet in terms of sunk capital and committed emission, i.e., emissions that would produce the current fleet if it operated until the end of its lifetime. This step is descriptive and simply provides some context in order to measure the materiality of the risk of stranded assets. The amount of committed emissions is compared to the carbon budget for shipping aligned with a 1.5°C scenario. This method is bottom-up to allow for a detailed description of the fleet, and a simulation because it uses a simple rule, i.e. that ships continue to emit as they have in the past - in practice, as reported in 2018 in the IMO 4th GHG study (Faber et al., 2020).

Second, using the literature review of Section 2.1, a theoretical framework is derived that explains the possible evolution of financier behaviour depending on their expectations of the upcoming transition.

The third step consists of an explanatory mixed methods approach. First, a regression analysis is performed using a shipping loan data set to quantify whether shipping lenders are expecting stranded assets identified in the step 1 (see Figure 3.3). The results are then explained by a case study, using semi-structured interviews with some of the shipping lenders of the dataset, and analysis of further documents. These data are analysed and interpreted using the theoretical framework developed in step 2. Other methods could have been used for the qualitative part, such as ethnography. However, this method was chosen due to time constraints – a mixed-method approach is already time consuming given the need to collect both quantitative and qualitative data – and the practical considerations of access to interviewees and documents. This third step provides empirical evidence on the current expectations and behaviour of shipping financiers and on their evolution over the last decade.

The choice of modelling approach to perform steps four, five and six is based on the literature review carried out in Section 2.3. This section identified several desired characteristics that are necessary to understand the interaction between financiers' expectations and stranded assets, as summarised in Figure 2.5. This section showed that non-equilibrium models, in particular those building on Post-Keynesian and evolutionary economics, are best suited to represent the role of finance, path-dependency and limited rationality, which are the three central concepts of the theoretical framework of this thesis. However, those models are high-level by construction and do not perform well in terms of coverage and resolution. On the other hand, existing shipping bottom-up optimisation models provide a detailed description of the fleet and its evolution in terms of socio-technical details. Bottom-up optimisation models have already been adapted to differentiate exogenously in the cost of capital, but they are not able to generate the difference in cost of capital by themselves.

Given these strengths and weaknesses, the two approaches are combined, so that RQ4 is answered by using two models, a non-equilibrium top-down model and a bottom-up optimisation model.

Regarding the former, two existing shipping non-equilibrium models were identified in the previous chapter (Section 2.3.2) as performing better than the others against the features of rationality and path-dependency (Bas et al., 2017; Chica et al., 2023), but did not represent the role of finance, while SFC-models were found to be best placed to represent all those features, in particular the role of finance. The two shipping models mentioned above are therefore not used directly (although they are used to inform the choice of specific equations, as will be described in Chapter 7), and a new SFC model is built from scratch to best integrate the three desired methodological features identified in figure 2.1d, i.e. path dependency, rationality and role of finance, but with a separate shipping sector covering a wider range of techno-economic details than usually covered by SFC models. This model builds on the previous post-Keynesian work from Dafermos and Nikolaidi (2021, 2022), Dunz et al. (2021), and Godley and Lavoie (2007) on the interactions between the financial and the goods production systems, and on the work from Chica et al. (2023), Karslen et al. (2019), and Rehmatulla et al. (2015) on the representation of shipping in nonequilibrium top-down models.

Regarding bottom-up optimisation, the previous chapter (Section 2.3.2) found that two models were performing particularly well in terms of coverage and resolution, and somewhat better than the others along the 3 methodological desired features: GloTraM and the GHG Pathway Model from DNV GL. For convenience, because GloTraM was available to the writer, it was used and adapted to allow for the differentiated cost of capital and explicitly models fleet value and stranded value, using its detailed output. GloTraM is a prominent global model designed to forecast fleet development from the base year of 2018, with projections made at four-year intervals. These projections assume that new ships are commissioned with the goal of optimising shipowners' profits. This model has found application in several institutions, including the Danish Shipowners Association (Smith et al., 2016), DG CLIMA (as mentioned in Lonsdale et al. (2019)), and the UK Department of Transport (as mentioned in Smith et al. (2019b)).

The interaction of the two models is twofold:

- The exogenous input of each model are derived of the output of the other, using a soft link. In particular, technical parameters such as the carbon intensity of shipping and the carbon price are derived from GloTraM and used in the land-shipping SFC model. The cost of capital of each technology is an output of the land-shipping SFC model, which is used exogenously in GloTraM.

- The models both produce estimates of the fleet evolution and of stranded assets, which are compared to each other. This is important first because there is no consensus on the "best" modelling method and second because they might produce significantly different results, which Bachner et al. (2020) and Sanstad (2015) describe as epistemic uncertainty. Comparing the results of the two models addresses this epistemic uncertainty and allows for more robust results, an approach which is suggested by Bachner et al. (2020). However, it is worth stressing the points made in the previous section, that none of the models can predict the future, but are only used to answer RQ4, i.e. to look at the influence of a set of assumptions (in the context of RQ4, the expectations of stranded assets by financiers) onto a variable, here the realisation of stranded assets. This is because, in addition to the limitations already highlighted related to the desired methodological features, the outcomes are influenced by the input provided to these models. From this point of view, the difference between the results in the scenarios with and without expectations of stranded assets are more relevant to this thesis than the actual range of stranded assets, which are evaluated under RQ1.

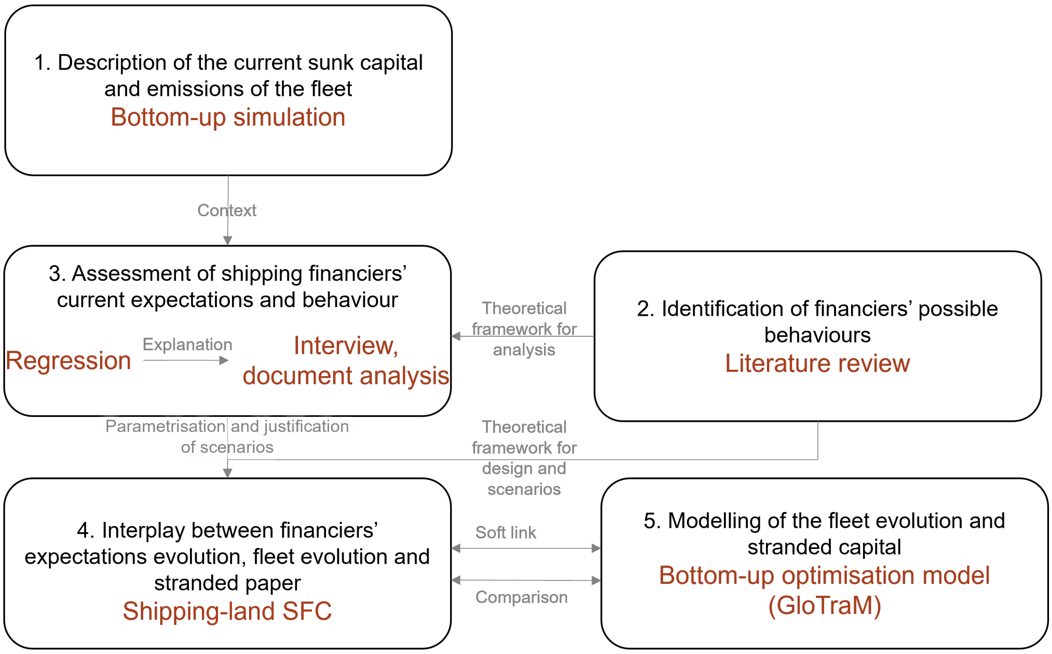


Figure 3.3: Overview of the research methods

Chapter 4

Existing sunk capital and the risk of stranded assets in shipping

This chapter aims to answer the first research question, namely: What share of the existing sunk capital in ships is incompatible with land and shipping carbon budgets? To do so, it looks at the current state of the shipping fleet in terms of sunk capital and future emissions and transport work, which can be expected throughout the remaining lifetime of the existing ships. The chapter that follows, which fits into the analysis of this thesis as shown in Figure 4.1, provides an analytical description of the current sunk capital and how it compares with the limits imposed by the need to limit climate change. The next section presents the research methods used in this chapter. The next two sections then describe the main findings and discuss the results.

This Chapter builds on the work of Bullock et al. (2020), which estimates the European shipping committed emissions and carbon budgets in 2019, and consequently assesses the amount of stranded assets in physical terms (emissions above budget). This Chapter uses the same approach to estimate supply-side stranded assets - committed emissions and carbon budget - but extends the results to the whole world fleet and updates them to the year of analysis, i.e. 2023. This Chapter further proposes however two methodological extensions. First, it proposes a method to cover demand-side risks as well, by proposing the concept of ”committed demand”, which is the mirror of committed emissions for demand-side risks (details in Section 4.1.3). Second, it proposes an approach to monetise the stranded assets estimated (see Section 4.1.1), which is also used in Chapter 7.

Bullock et al. (2020) further looks at the possible evolution of the fleet beyond the date of the analysis, which this Chapter ignores. This is because the aim of this Chapter is to provide context for Chapter 6 and the observed financiers' expectations of stranded, which corresponds to step 3 on Figure 4.1. The evolution of the fleet is covered in Chapter 7, which covers the steps 4, 5 and 6 on Figure 4.1. The objective of Chapter 7 is however somewhat different to this Chapter and to Bullock et al. (2020)'s, which aims at assessing the scale of stranded asset risk. Chapter 7 aims at assessing the impact of financiers' expectations and behaviours onto the materialisation of stranded assets, and answer RQ4. It does not intend to provide an assessment of the absolute amount stranded assets across a wide range of scenarios involving other relevant factors, e.g. the behaviours of the shipowners.

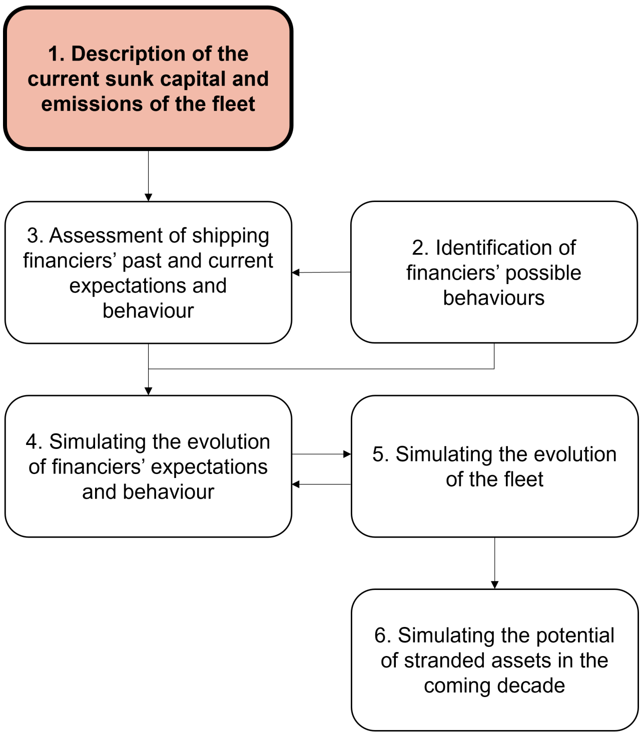


Figure 4.1: Sign-posting chapter 4: Description of the current sunk capital and emissions of the fleet

4.1 Research methods

To answer the research question, an estimate of the financial value of the existing stock of capital is first provided. As discussed in the introduction and according to Daumas (2023), stranded capital can be monetised as book loss and foregone earnings streams. To calculate those, Section 4.1.1 explains the methods for estimating the value of the current fleet, and of the future activity of the fleet. Of the resulting fleet value and expected profits, Section 4.1.2 then explains the method to assess supply side risk, and Section 4.1.3 the method to assess demand side risk.

4.1.1 Valuing capital and expected profits

Before proceeding to examine the risk of assets stranded, it is necessary to understand the value, expected future activity, and expected future profits of the current fleet.

4.1.1.1 Fleet valuation

The[1] fleet valuation method first involves estimating the newbuild value of each ship, based on the parameters obtained with a regression analysis of newbuild prices of the ships; and second to depreciate it to its second-hand value.

The newbuild price of a ship can be influenced by several variables. Larger ships can be expected to be more expensive, but the intensity of this effect is likely correlated to the shipping segment: building an additional deadweight on the liquefied gas tanker is likely to be more expensive than an additional deadweight on an oil tanker. An interaction term between deadweight and a series of dummies on the shipping segment (IMO shipping segment) is included, which represents the ship hull and non-propulsion equipment. A large component of the ship price is directly related to the machinery, which is likely to depend on the size of the machinery and the type of engine. The cost of the machinery is represented by the interaction term between the Maximum Continuous Rating (MCR) of the main engine and a series of dummies of the fuel type (conventional HFO/MDO, noted Heavy Fuel Oil (HFO),

[1] This section is based on the Section ”Fleet valuation” of the study ”Fossil fuel carriers and the risk of stranded assets”. I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

LNG and methanol). Finally, unobserved market conditions could affect the price of the ship, such as the share of the shipyard capacity used or the strength of the demand for new ships. These market conditions might be more specifically related to each market segment, especially since the demand for one segment of ship could be very high if the shipping activity is strong, while very sluggish for another. They are controlled by interaction variables between shipping segments and a series of variables in the year the ship was built.

The results of the regression analysis are detailed in Appendix B.2. Ignoring the short-term market conditions, the estimated parameters of model (3) are used to interpolate the newbuild value of each ship, using the below equation:

$$P^{new}_{mcr,dwt,f,s,t} = \sum_{s \in shiptypes} a^1_s \times dwt \times \mathbb{1}_s + \sum_{f \in fuels} a^2_f \times mcr \times \mathbb{1}_f + \sum_{s \in shiptypes} a^3_s \quad (4.1)$$

With a_1, a_2, a_3 three vectors of coefficients, $\mathbb{1}_s$ a vector of dummy variables to control for the shipping segment, $\mathbb{1}_f$ a vector of dummy variables to control for the fuel type, *dwt* the deadweight of the ship and *mcr* its MCR .

To calculate the second-hand value, for each ship in the fleet at each time step, the newbuild value is linearly depreciated to its scrappage value based on the expected lifetime of the ship. The expected lifetime is proxied for each shipping segment and size bin by the average scrapping age (see Table B.1 in Appendix B.1).

The resulting second-hand value is computed as follows:

$$V_{second-hand} = V_{scrap} + (V_{new} - V_{scrap})(ScrapAge - age)/ScrapAge \quad (4.2)$$

With *ScrapAge* the expected scrapping age, V_{scrap} the scrapping value, and *age* the age of the ship. The scrappage value is estimated as a linear relation to the ship's deadweight:

$$V_{scrap} = c \times dwt \tag{4.3}$$

The parameter c the average demolition price in \$ / dwt from WFR demolition prices.

This approach to calculate second-hand prices suffers from several limitations. First, it ignores short-term market drivers, which have been found to play a major role in the formation of second-hand prices, such as earnings or London Inter-Bank Offered Rate Adland et al. (2018), Hong et al. (2022), Jia (2004), and Merika et al. (2019). The underlying assumption is that the intrinsic second-hand value of a ship is equal to its linear depreciation and that its second-hand market value will tend to it in the long term. Second, it might be that ships do not depreciate linearly but along a convex curve. If this is the case, i.e., if they depreciate faster in the earlier years of their lifetime, then the current method overestimates the intrinsic second-hand value of ships, and therefore the total amount of stranded assets. The literature shows opposing views: MSI (2019) assumes a convex depreciation, whose slope depends on the second-hand market. In contrast, Hong et al. (2022) implicitly assumes a linear depreciation by using an ordinary least squares regression to estimate the second-hand value of ships based on their age (among other variables), an assumption that is also supported by Adland et al. (2023) and Jia (2004). Merika et al. (2019) find a broadly linear decreasing curve between age and the log of second-hand value using a non-parametric regression, which, when converted into absolute value, suggests that depreciation is linear[2]. Third, it might be that the ships depreciate to an earlier date than their scrapping age. Those validity of those assumptions are sense checked against the depreciation curves induced by second-hand ships prices reported in Clarksons Research (2023). The results, discussed in Appendix B.5, broadly support the validity of those two assumptions.

The estimated value of the fleet validates well with the estimates from Clark-

[2]The coefficients of marginal effects of age onto log of value read on Figure 1, second graph were converted into absolute marginal effect, assuming a $100m initial price. The resulting curve is close to linear.

sons SIN (see Appendix B.3). This gives confidence that although individual ship second-hand market prices might differ to their estimated value, given the limitations mentioned above, the method is adequate to estimate the total fleet value.

4.1.1.2 Valuing expected profits

Let[3] us now turn to the estimation of expected earnings over a ship's lifetime and at the time of investment. The results provide an estimate of the committed supply of this fleet, i.e., the supply of transportation service (in tonnes miles) each ship is expected to provide over its remaining lifetime, that is, the supply it would provide if it were to operate in the conditions expected at the time of investment; and finally of the earnings attached to this committed supply.

Consider a ship i at time t_0. This ship provides a certain amount of transportation service each year $t > t_0$ which is computed using equation 4.4:

$$CS_{i,t} = dwt_i \times d_{s,z} \times u_s \tag{4.4}$$

with CS_s the committed supply expressed in tonnes-miles at time t; d is the average distance covered per year and is input for each segment s and each size bin z. u is the share of deadweight used for cargo and is calculated for each segment s. It is assumed that each ship is built in year *built* and with a life expectancy of *ScrapAge* years and will continue to operate under the same conditions of distance and utilisation in the coming $t_0 + ScrapAge_{s,z} - Built_i$ years (*ScrapAge* is again available for each ship segment and size bin). When aggregating for all ships, the expected profits for each segment are calculated as follows:

$$CS_s = \sum_{i \in F_{s,z}} \sum_{t \in [t_0, t_0 + ScrapAge_{s,z} - Built_i]} CS_{i,t} \tag{4.5}$$

with $F_{s,z}$ the fleet that contains all ships in the shipping segment s and of size bin z.

[3] This section is based on the Section "Valuing expected earnings" of the study "Fossil fuel carriers and the risk of stranded assets". I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

The owner of the ship has invested in that ship because she expects future revenue and future earnings from it. During the remaining lifespan of each ship, it is assumed that she expects to collect future earnings as follows:

$$\tilde{\Pi}_i = \sum_{t \in [t_0, t_0 + ScrapAge_{s,z} - Built_i]} CS_{i,t} \times P_s \times EarningsRatio \tag{4.6}$$

with P_s the price of shipping, expressed in $\$/tonne - mile$ and $EarningsRatio$ the average earnings as a share of revenue. It is assumed that she expects the revenue and earning ratio to remain constant and equal to its long-term trend. The author acknowledges that there will be large variations in the price of shipping and the operating costs to shipowners in the short term. However, given the long lifespan of the ships, this assumption might hold broadly true in the long term. Furthermore, it is meant to represent investors' expectations of earnings, not the actual earnings. By aggregating for all ships, the expected earnings for each segment are calculated as follows:

$$\tilde{\Pi}_s = CS_s \times P_s \times EarningsRatio_s \tag{4.7}$$

4.1.2 Method for calculating supply-side risk

Having[4] discussed how to estimate the committed supply, expected profits, and sunk capital of the fleet, this section explains the way the scale of the supply-side risk is estimated.

The methodology used to estimate supply-side risks is an extension for the shipping industry of the methodology used in the studies reviewed in the Introduction. In particular, this Chapter extends the analysis conducted by Bullock et al. (2020) to international shipping rather than only to European shipping. Committed emissions are the GHG emissions that the current fleet, existing and ordered, is expected to emit throughout its remaining lifetime if they continue operating as ex-

[4]This section is based on the Section "Methods for calculating demand-side risk" of the study "Fossil fuel carriers and the risk of stranded assets". I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

pected by their owners. Here again, "expected" is considered to correspond to past operational data. Committed emissions are therefore calculated at the ship level and then aggregated to the whole fleet with the following equation:

$$CE = \sum_{i \in F_B} \sum_{t \in [t_0, t_0 + ScrapAge_{s,z} - Built_i]} ae_{s,z} \tag{4.8}$$

With CE being the committed emissions of the whole conventional fleet F_B and ae the annual emissions of the ship i. Because data on annual operational emissions are not available at the ship level, the annual emissions of the ships are proxied by the average annual emissions per ship within each peer group. Again, the remaining lifetime of the ship $t_0 + ScrapAge_{s,z} - Built_i$ is calculated on the basis of the average scrap age within each peer group.

This approach assumes that future ships will keep an emission intensity similar in the future. In practice, ships might emit smaller emissions if their behaviour is optimised for energy efficiency, if the ships are retrofitted with energy-efficient technologies, and/or change their fuel over its lifetime. However, those will come at a cost for the shipowner which can be considered as stranded assets if the value of the ship is reduced as a result, and if the cost was not expected by the shipowner at the time of initial investment. The proposed approach hence does not provide any insight on whether stranded ships will be scrapped or whether they will continue to operate but will simply lose part of their value. The resulting amount of stranded assets should be considered as the maximum value at risk in a worst case scenario.

Those committed emissions are compared to the emissions that shipping can emit while limiting global warming to 1.5° C above preindustrial time, that is, the shipping carbon budget (CB). Committed emissions above carbon budgets should not be emitted to remain within the carbon budget (unburnable emissions). Those non-burnable emissions are equal to $CB - CE$. There is more than one possibility of how to allocate the emissions to specific ships and at a specific time. For example, stranded assets might not occur for the first few years, and then all ships can be stranded. Ships could be stranded starting from 2021, based on their operating cost, to optimise for cost; or, based on their value, to minimise the stranded loss. Of course, in reality, several factors will play a role in the decision whether to strand an asset, and it is beyond the scope of this chapter to provide a realistic allocation of stranded assets to the fleet. However, to illustrate what could be the scale of asset stranding, unburnable emissions are allocated to individual ships to minimise book loss on the one hand side; and foregone streams on the other. To do so, for each ship, the following two ratios are calculated:

$$PoverE_i = EP_i/CE_i \tag{4.9}$$

$$VoverE_i = V_i/CE_i \tag{4.10}$$

All conventional ships are then scrapped, starting from the ones with the lowest ratio, until the sum of their cumulative committed emissions reaches the amount of unburnable emissions. This approach provides two estimates of stranded assets, depending on whether foregone streams or book loss is minimised. The capital value and expected profits of each stranded ship are aggregated to the total book loss and foregone streams.

4.1.3 Method for calculating demand-side risk

Let us now turn to the estimation of demand-side risk. Demand for transportation fossil fuels is expected to fall if the land economies decarbonise. This means that part of the shipping activity that the shipowner described above expects from ship i (expected supply ES) may not materialise should the world economy decarbonise, nor the expected profits (EP) she expected at the time of investment. This oversupply of fossil-carrying capacity corresponds to the demand-side stranded assets. It is calculated by comparing the committed supply CS for each segment s with the shipping demand aligned with a 1.5 ° C carbon budget $D_{s,t}$. At any time t, shipping supply that exceeds shipping demand is considered at risk of being stranded on the demand side. The stranded supply $S^{Stranded,D}$ and the foregone streams $\Pi^{Stranded,D}$ are then summed throughout the period, as follows:

$$S_c^{Stranded,D} = \sum_{2024}^{2050} CS_{s,t} - D_{s,t} \tag{4.11}$$

$$\tag{4.12}$$

Calculating foregone earnings streams is fairly straightforward and consists in multiplying the supply stranded by its estimated value:

$$\Pi_c^{Stranded,D} = S_c^{Stranded,D} \times P_s \times EarningsRatio_s \tag{4.13}$$

Calculating book loss is less straightforward and requires an allocation of stranded supply to individual ships. This is done by minimising the amount of capital stranded for each segment. To do so, the ratio of ship value to committed supply V_i/CS_i is calculated and all ships starting from those with the lowest ratio are scrapped, until the sum of their cumulative committed supply reaches the amount of stranded supply $S_c^{Stranded,D}$.

4.1.4 Data collection

Individual[5] ship data was collected from Clarksons World Fleet Register Clarksons Research (2021), including :

- Demolition year and build year of scrapped ships; and build date which are used to estimate the average demolition price (62.1014 \$/ dwt), and the average scrapping age for each shipping segment and size. The ships were assigned to shipping segments and cargo according to the correspondence reported in the appendix A. Section B.1 in appendix shows the average scrap age calculated for each peer group (segment and size bin) using Clarksons WFR scrapping and built dates. Size bins z are based on the IMO 4$^{\text{th}}$ GHG study size categories Faber et al., 2020.

[5]This section is based on the Section "Data collection" of the study "Fossil fuel carriers and the risk of stranded assets". I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis. Furthermore, the data collection behind the calculation of the carbon budget is new material.

- Build date, shipping segment, deadweight and main engine MCR of existing ships and ships in orderbook, which are used to calculate the value and supply of each ship.
- Owner, operator and builders of each ship, which are used to identify the main actors of the fleet.

This Chapter further focuses on 5 segments, namely bulk carriers, oil, LNG and LPG tankers, and containers. Descriptive statistics on the fleet (existing and orderbook) are provided in Table 4.2.

Future shipping demand has been taken from the IMO 4th GHG study, which itself builds on the GDP and energy projections of the IPCC, collected in the Institute for Applied Systems Analysis (IIASA) database. This database compiles results from integrated assessment models (IAMs) to explore future scenarios of global socioeconomic and environmental changes. It includes data on greenhouse gas emissions, land use, energy systems, and socioeconomic variables like population and GDP. These scenarios help analyse the potential impacts of different climate policies and future socioeconomic trajectories, informing projections on climate change mitigation, adaptation, and impacts. Several input scenarios and methods were used in the IMO 4th GHG study to estimate the shipping demand:

- Shipping demand for non-energy commodities: In the IMO 4th GHG study, the demand for non-energy commodities is a function of GDP and population. GDP and population input are taken from the IIASA database for five Shared Socioeconomic Pathways (SSP), each of which describe potential future global developments in terms of socioeconomic factors, such as population growth, economic trends, and technological advancements (Riahi et al., 2017; see Table 4.1). In the IIASA database, several interpretations of each SSP exist across various modelling groups. To narrow the options, a selection of 'marker' scenarios—representative of each SSP—was made (Riahi et al., 2017; see Table 4.1 for a list of the markers). In the 4th GHG study, the link between GDP/population and transport work was estimated using two methods, leading to two estimates of transport work for each SSP: using a logistic model (e.g. SSP1_L) and a gravitational model (e.g. SSP1_G).

- Shipping demand for energy commodities (coal, gas and oil) : those were estimated for a range of representative concentration pathways (RCP), which corresponds to different targets for temperature increase (see Table 4.1). Although many scenarios are available in the IIASA database for each RCP, in practice, for demand aligned with 1.5°C, only one scenario from the IIASA database (IMAGE SSP1-19) was fully reported in the 4th GHG study. For each RCP, two mutually exclusive methods are used in the IMO 4th GHG study, one estimated using the logistic model (e.g. RCP19_L), and one where the change in energy demand projections was applied to the initial amount of transport work (marked with a star e.g. RCP19*).

To answer the research question, only the scenarios aligned with a 1.5°C target provided by the 4th GHG study were selected in this Chapter. For energy commodities (coal, oil and gas), the shipping demand corresponding to the RCP1.9 is used as the shipping demand aligned with a 1.5°C carbon budget. It is worth noting that multiple fossil fuel consumption pathways are possible to remain under 1.5°C increase in temperature, so this one IIASA input scenario is only one possibility for future fossil fuel consumption among others. For non-energy commodities (in practice only containers and non-coal bulk in this Chapter), each SSP compatible with RCP19 was used in this Chapter, namely, SSP1, SSP2 and SSP5. As a result, the following shipping demand scenarios were used in this Chapter:

- For oil and gas tankers, two scenarios were used, corresponding to two methods linking consumption and shipping demand: RCP19_L and RCP19*
- For containers, 6 scenarios were used, corresponding to three socioeconomic pathways and two methods linking consumption and shipping demand : SSP1_L, SSP1_G, SSP2_L, SSP2_G, SSP5_L, SSP5_G
- For bulk carriers, which covers both coal and non-coal bulk, 12 scenarios were used, corresponding to three socioeconomic pathways and three

methods linking consumption and shipping demand: SSP1_L_RCP19_L, SSP1_G_RCP19_L, SSP2_L_RCP19_L, SSP2_G_RCP19_L, SSP5_L_RCP19_L, SSP5_G_RCP19_L, SSP1_L_RCP19*, SSP1_G_RCP19*, SSP2_L_RCP19*, SSP2_G_RCP19*, SSP5_L_RCP19*, SSP5_G_RCP19*

Table 4.1: Description of consumption scenarios modelled in the IMO 4th GHG study. Adapted from Faber et al. (2020)

Non-coal dry bulk, containers, other unitized cargo and chemicals	**Coal dry bulk, oil tankers and gas tankers**
Long-term socio-economic scenarios	**Long-term energy scenarios**
SSP1 - Sustainability – Taking the Green Road: assumes a sustainable world with green growth and reduced inequalities. Marker scenario: IMAGE SSP1-baseline	RCP1.9 (1.5° C) in combination with SSP, SSP2 and SSP5
SSP2 - Middle of the Road: middle-of-the-road scenario with moderate development. Marker scenario: MESSAGE-GLOBIOM SSP2-baseline	RCP2.6 (2°C, very low GHG emissions) in combination with SSP1, SSP2, SSP4 and SSP5
SSP3 - Regional Rivalry – A Rocky Road: fragmented world with regional rivalry and slow progress. Marker scenario: AIM/CGE SSP3-baseline	RCP3.4 (2.4°C, extensive carbon removal) in combination with SSP1, SSP2, SSP4 and SSP5
SSP4 - Inequality – A Road Divided: growing inequality between global elites and marginalized groups. Marker scenario: GCAM4 SSP4-baseline	RCP4.5 (2.4°C, medium-low mitigation or very low baseline) in combination with SSP1, SSP2, SSP4 and SSP5
SSP5 - Fossil-fuelled Development – Taking the Highway: rapid economic growth driven by fossil fuel use and high technological advancements. Marker scenario: REMIND-MAGPIE SSP5-baseline	RCP6.0 (2.8°C medium baseline, high mitigation) in combination with SSP1, SSP2, SSP4 and SSP5

Stranded assets are estimated in all the above shipping demand scenarios and this Chapter reports ranges of results, rather than a single estimate. Using this range allows to control for 1/ the methodological uncertainty in deriving shipping demand from fossil fuel consumption, by controlling for two methods (logistics versus gravity/simple percent change), and 2/ for the effect of various socio-economic scenarios on non-energy shipping demand. Using this range of scenarios however does not cover however the uncertainty in the initial dataset. In particular, the uncertainty in the range of possible consumption of fossil fuel by the world economy under a 1.5°C scenario is not covered, as only one IIASA input scenario (IMAGE SSP1-RCP19) was fully reported in the 4th GHG study, while many more scenarios aligned with 1.5°C but using alternative SSP and alternative models were provided in the IIASA dataset. Furthermore, this range does not explore the uncertainty linked to changes in trading patterns, e.g. re-shoring or to which extend pipelines or ship transport would be used, as GDP and population are the only predictor of non-energy products. Finally, this range of scenarios does not cover the methodological uncertainty in projecting the evolution in fossil fuel, GDP and population, as all results in the IIASA database are derived from optimisation models (listed in Table 4.1), whose limitations have been discussed in Section 2.2. In particular they may oversimplify complex socioeconomic and environmental interactions and may not fully capture sudden technological and policy shifts, leading to uncertainties in projections.

Shipping demand is allocated to the shipping segments according to the mapping found in the appendix A. As the study does not differentiate between LNG and LPG trade, those two segments were grouped under "liquefied gas tankers".

Current fleet utilisation, which corresponds to the ratio of effective activity (tonne-cargo transported×miles) over the maximum potential activity (deadweight× miles) is computed for each segment as follows:

$$u_s = \frac{S_{s,2018}}{\sum_{z \in Z_s} dwt_{s,z} \times d_{s,z} \times N_{s,z}} \tag{4.14}$$

with Z_s containing all the size bins of the shipping segment s, $dwt_{s,z}$ the average deadweight in 2018 of the cohort, $d_{s,z}$ the average distance covered in 2018 of the cohort, and $N_{s,z}$ the number of ships in the cohort. The average annual emissions, average deadweight and distance in 2018 have been taken from the IMO 4th GHG study (Faber et al., 2020) by type and size of the ship. Past and current shipping demand $S_{s,2018}$ is taken from Clarksons SIN (Clarksons Research, 2023).

Future shipping demand was estimated in 2018 in the IMO 4$^{\text{th}}$ GHG study and is based on scenarios that assume a continuous and linear decarbonisation of the world economy starting from 2018. The main limitation of this assumption is that it does not match recent data of emission reduction. As Figure 4.2 shows, for liquefied gas and oil tankers, the modelled shipping demand aligned with a 1.5°C target is significantly lower than the demand observed until 2023. This reflects the findings of the 6th IPCC Report 2023 that the decarbonisation of world economies is not on track to meet the objective of the Paris Agreement (Rogelj et al., 2022). With the increased fossil use in the early 2020s, the transition has been delayed and meeting climate targets now requires a sharper decrease in fossil use. The use of the IMO 4th GHG study scenario might therefore overestimate the amount of stranded assets in the early years of the period of study (2018-2050), and underestimate them in the later years. The modelled and observed shipping demand validate well for bulk carriers.

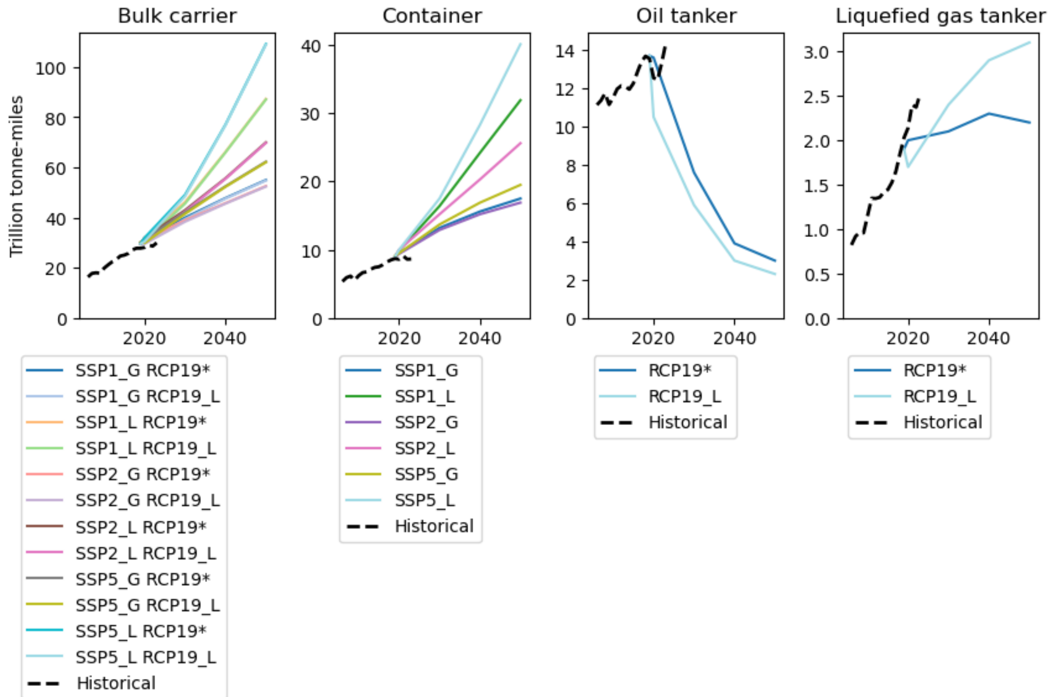


Figure 4.2: Validation of shipping demand against the shipping demand scenarios modelled in this Chapter

Allocating a carbon budget to international shipping is controversial, as there is no consensus on whether shipping should be allocated a larger or smaller share than its current emissions. This chapter follows the proposal of Traut et al. (2018), which has already been used in Bullock et al. (2020, 2021), that the share of the remaining budget should be the same as the current share of emissions in the sector. Therefore, the carbon budget for shipping is calculated as the product of the share of shipping in global GHG emissions and the carbon budget for the rest of the world at the start of 2021. The first is taken from the IMO 4th GHG study, which shows that international shipping represented 2.89% of total emissions in 2018 (Faber et al., 2020). The global carbon budget is taken from the 1.5 ° C report of the Intergovernmental Panel on Climate Change (IPCC), which estimates the remaining carbon budget from the start of 2018 consistent with a 50% chance of limiting the warming to 1.5 ° C to be 580 billion tonnes of CO2-e (Rogelj et al., 2018a). Of this estimate, 100 billion tons of CO2-e should be subtracted to account for permafrost thawing and the potential release of methane from wetlands in the future (Rogelj et al., 2018a), as well as shipping emissions from 2018 to 2023. These emissions are taken from Clarksons SIN (Clarksons Research, 2023) and equal 4.1 million tonnes of CO2-e. They are significantly lower in 2018 than the IMO 4th GHG study estimate, so the carbon budget might be overestimated and therefore supply-side risks are conservative estimates. Overall, the shipping carbon budget used in this Chapter is 9.7 billion tonnes of CO2-e from the beginning of 2023.

Data related to the price of shipping was collected from Clarksons SIN. Quarterly shipping spot rates were collected over the period 2009-2019 (later years were ignored to avoid the bias of the Covid pandemic) on 134 routes that cover bulk carriers, oil tankers, and liquefied gas tankers. The former are expressed in USD/tonne and were transformed into USD/tonne-mile by dividing with the route distance collected from sea-distances.org, or where available, route distance provided by Clarksons methodology note[6]. The results are reported in Table 4.3.

Not all this revenue would translate into earnings, as shipowners and/or operators would need to cover for operating costs. Most of those concern fuel costs (more than 50% of operating costs according to Rehmatulla (2015), Rehmatulla and Smith (2015b), and Zhen et al. (2020) and up to 45% of the revenue Stulgis et al. (2014)) and operating expenses such as crew costs, repair and maintenance, and insurance

[6]Where the port was not clear from the route name, the largest port in the region/country specified was taken.

(Rehmatulla and Smith, 2015b). To estimate the share of fuel cost in revenue, the average tonne of fuel burned per tonne-mile transported is first estimated for each fuel in HFO, Marine Diesel Oil (MDO) and LNG; and for each shipping segment. This is done using the total shipping work in 2018 from Clarksons SIN per shipping segment; and the total fuel consumption in 2018 from the IMO 4th GHG study. The average bunker price from Clarksons SIN of HFO and MDO from 2009 to 2019 is then used, and up from Q1 2020 to Q1 included 2021 for LNG (as the prices before 2020 were not available, and the prices after Q2 2021 were largely impacted by the Covid-19 pandemics) and the price of shipping reported in Table 5 to calculate the ratio of fuel cost to revenue. A ratio ranging from 0.36 for liquefied gas tankers to 0.48 for oil tankers is found (see Table 4.3). It was not possible to calculate this ratio for containers, so the average of the other segments (0.36) was used instead.

The ratio of non-fuel operating expenses is calculated using the estimated OPEX from Clarksons SIN from 2012 to 2019 (speed data are only available from 2012 onward), expressed in USD/day, and the spot rates previously described. The latter are expressed originally in USD/tonnes and were converted to $/day by estimating the voyage time using the sea distance previously described, and average speed from Clarksons SIN; and assuming that ships spend 4 days in port. Larger ships appear to have a lower non-fuel OPEX/revenue ratio than smaller ships. Only for bulk carriers is there sufficient data across various sizes to judge for this effect, and the difference in this segment is limited (capesize bulk carriers have a ratio of 0.21 while handymax carriers have a ratio of 0.26). For simplicity, the average for each shipping segment is used. Resulting non-fuel to revenue ratios range from 0.23 (bulk carriers) to 0.22 (oil and liquefied gas tankers) (see Table 4.3).

The ratio of earnings over revenue E/R is finally computed for each shipping segment as $1 - F/R - OPEX/R$, with F/R the ratio of fuel expenditure over revenue, and $OPEX/R$ the ratio of non-fuel expenditures to revenue.

Table 4.2: Descriptive analysis of the fleet

Ship type	Av. build year)	Av. scrapping age	Av. remaining lifespan	Total dwt	Av. build year
Bulk carrier	2010	29	17	1,074,498,071	2010
Oil tanker	2002	30	12	634,660,699	2002
Container	2011	25	13	409,282,965	2011
Chemical tanker	2008	26	12	150,039,808	2008
Liquefied gas tanker	2012	35	24	135,573,776	2012
General Cargo	1995	37	13	98,797,199	1995
Offshore	2003	32	15	85,348,816	2003
Service - other	1998	36	14	37,355,327	1998
Vehicle	2010	23	11	16,703,700	2010
Ro-Ro	2001	36	15	8,964,703	2001
Ferry-RoPax	1995	40	16	5,338,011	1995
Refrigerated bulk	1993	35	6	5,044,447	1993
Cruise	2005	36	21	3,072,255	2005
Service - tug	1999	47	25	2,646,255	1999
Miscellaneous - other	2002	33	15	1,404,275	2002
Other liquids tanker	1981	52	13	516,689	1981
Ferry-pax only	1995	39	15	412,227	1995
Yacht	1950	56	6	9,399	1950

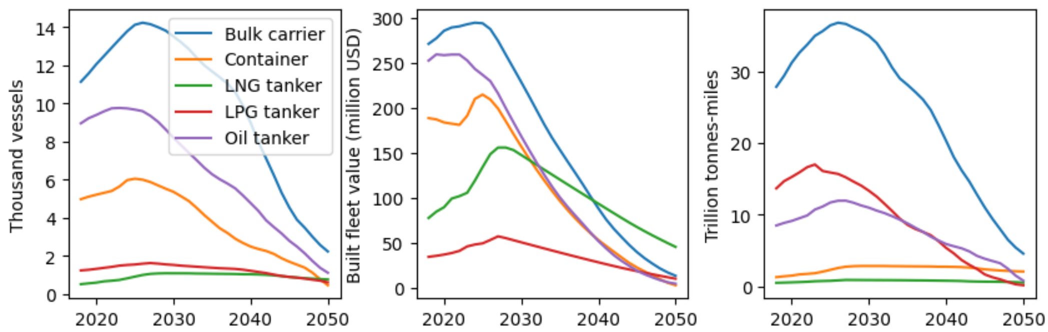


Figure 4.3: Natural fleet evolution

Table 4.3: Utilisation, price and cost of shipping, by shipping segment

	Utilisation	**Price of shipping ($/tonne-mile)**	**Fuel cost / revenue**	**Non-fuel OPEX / revenue**
Bulk carrier	0.4957	0.0026	0.42	0.23
Oil tanker	0.3656	0.0044	0.36	0.22
Liquefied gas tanker	0.2762	0.0119	0.48	0.22
Containers	0.3128	0.0184	0.42	0.22

4.2 Results

Let us now turn to the results of the analysis. The next section describes the main actors who are economically involved with the fleet, by focusing on the main segments. A summary of the main findings regarding supply and demand side risks is then in Sections 4.2.2 and 4.2.3, respectively, and then compared with each other in Section 4.2.4.

4.2.1 Identification of the main actors

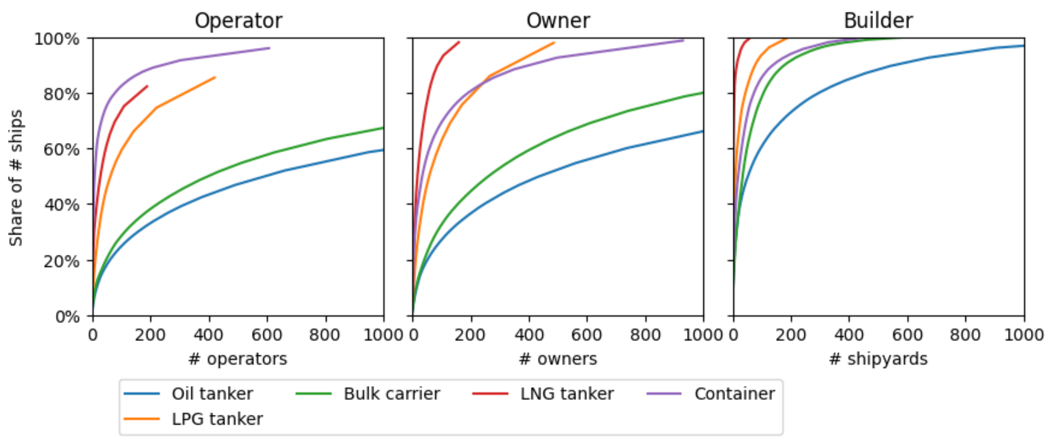


Figure 4.4: Concentration of ships by operators, owners and builders

(a) The plotted lines correspond to the cumulative number of ships owned/operated by/built by actors.

(b) The actors are ordered by their share of the fleet, with the largest actors plotted first. Read as such: the top 200 operators operate 30% of oil tankers.

(c) The share of operators does not reach 100% some ships are not registered under an operator in the Clarksons WFR.

Let [7] us first look at the actors who are economically involved with the fleet of fossil fuel carriers. Should the risk of stranded assets materialise, these would be at the forefront of the losses: owners would write down the loss in value while builders and operators would likely suffer foregone earnings streams.

The operation and ownership of the ships is largely fragmented, with oil tankers and bulk carriers spread across thousands of owners and operators, and

[7] This section is based on the Section "3.1. A myriad of actors concentrated in space" of the study "Fossil fuel carriers and the risk of stranded assets". I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis. In particular, the results have been extended to containers.

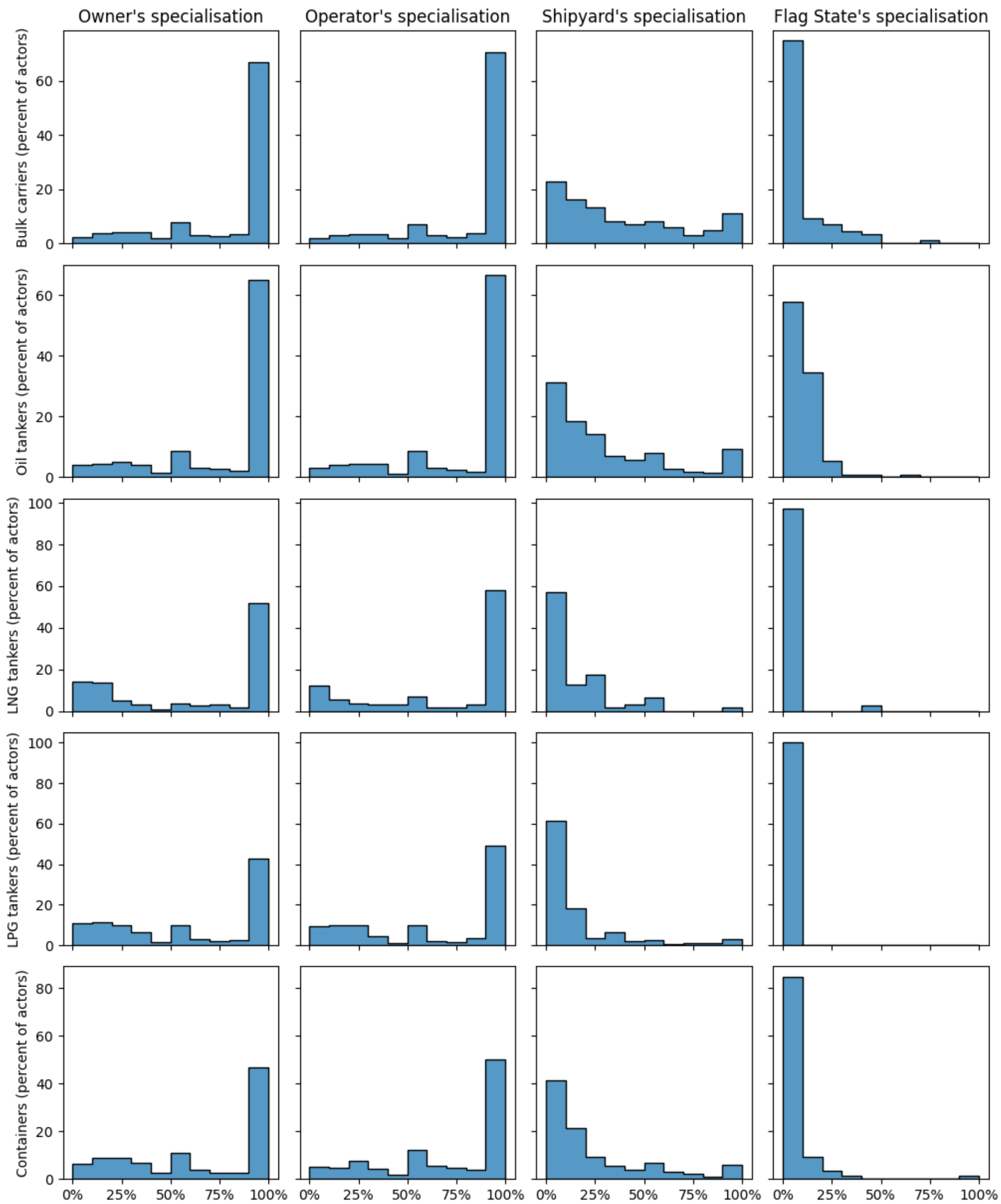
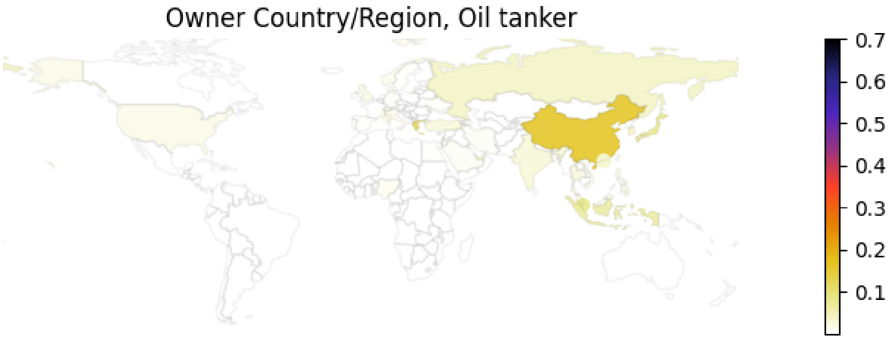


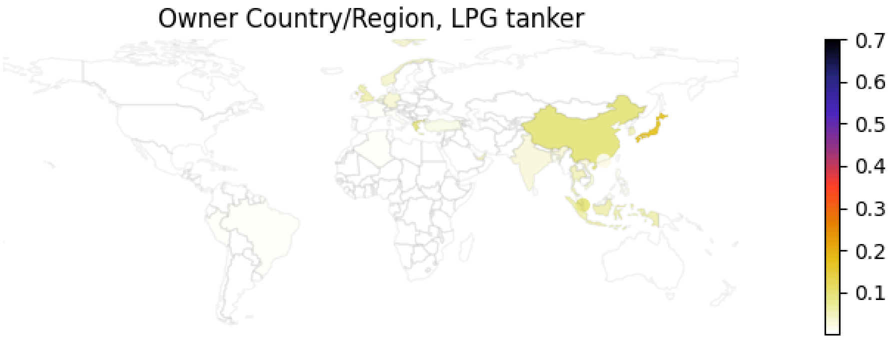
Figure 4.5: Concentration of ships by operators, owners and builders

(a) Only the actors who operate/own/have built at least one fossil fuel carrier are represented.

(b) All numbers plotted are expressed in number of ships.

(c) The x-axis represents the share of operated, owned and built ships which are fossil fuel carriers. Each column represents a decile of specialisation. The y-axis represents the share of operators/owners/shipyards which falls in this bandwidth. Read: for 64% of the owners of oil tankers, above 90% of their fleet (in number of ships) is an oil tanker.


Owner Country/Region, Oil tanker
0.7
0.6
0.5
0.4
0.3
0.2
0.1


Owner Country/Region, LPG tanker
0.7
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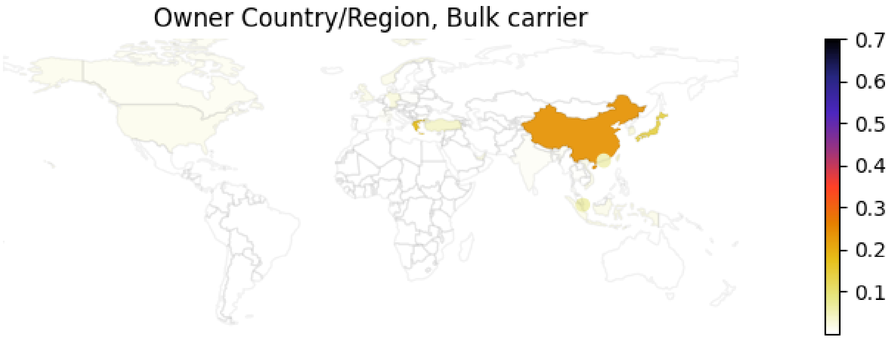
0.4
0.3
0.2
0.1


Owner Country/Region, Bulk carrier
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0.4
0.3
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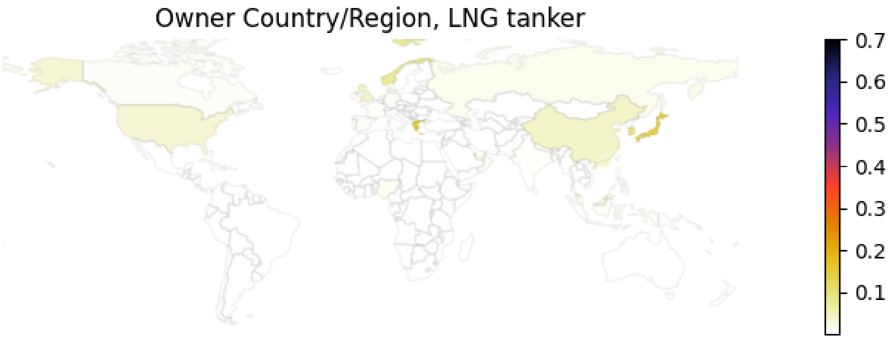
0.1


Owner Country/Region, LNG tanker
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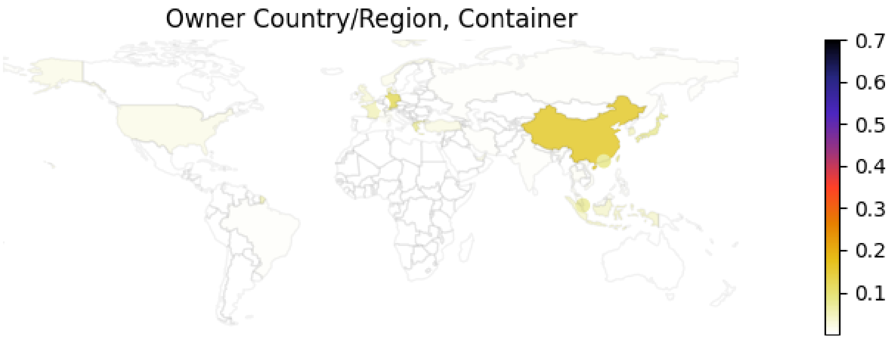
0.6
0.5
0.4
0.3
0.2
0.1


Owner Country/Region, Container
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0.5
0.4
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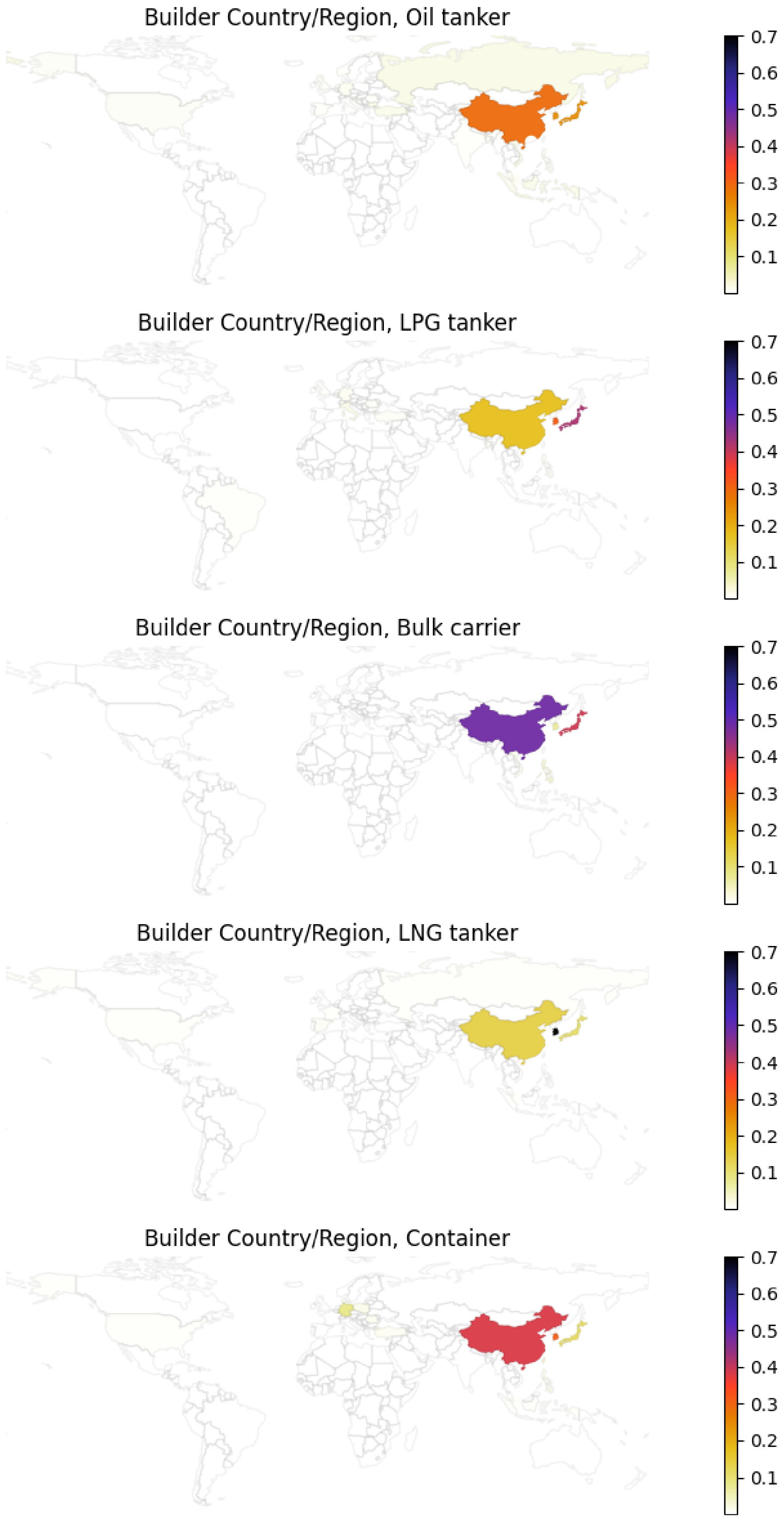

Figure 4.6: Share of the fleet of ships, by country of ownership and country of shipyard

(a) The country corresponds to the country of the ship owner of the shipyard, as reported by Clarksons WFR

Liquefied Petroleum Gas (LPG) and Liquefied Natural Gas (LNG) tankers spread across hundreds (see Figure 4.4c). Oil tankers and bulk carriers are particularly fragmented, while LNG tankers constitute the most concentrated segment (see Figure 4.4c). The distribution of operators shows a similar profile.

Furthermore, it appears that many of the operators and owners are highly specialised in fossil fuel carriers (see Figure 4.5), which makes them more susceptible to demand-side risks. More than 40% of the owners and operators of each segment cover a fleet which is at least 90% dedicated to this segment (see Figure 4.5). Bulk carriers and oil tankers are particularly specialised.

In contrast to the fragmentation across a large number of actors, the ownership is more concentrated geographically, with large shares of the fleets owned by firmed headquartered (as a proxy for ownership) in Greece, China, and Japan (both existing and ordered; see Figure 4.6a). In particular, Greek shipowners own 15 to 25% of the fleets of bulk carriers, oil tankers, and liquefied gas tankers (LNG and LPG tankers); Chinese shipowners own 18% and 13% of the bulk carrier and container fleets respectively and Japanese shipowners 15 and 14% of the bulk carrier and liquefied gas tanker fleets respectively. Norwegian shipowners also own a significant share of the liquefied gas tanker fleet.

The construction of ships is much more concentrated with fewer actors and geographies (see Figure 4.6a). Nearly all ships are built in China, Japan, and Korea, with China building nearly half of the bulk carriers and nearly 40% of containers, and Korea leading the building of oil and liquefied gas tankers (see further details in the supplementary material). However, shipyards are largely diversified in terms of shipping segments, and few are dedicated to building only fossil fuels carriers (see Figure4.5). This diversification would make shipbuilders less sensitive to the materialisation of demand-side risks, and to the materialisation of supply-side risks, but only if those should materialise first in one or few sectors.

4.2.2 Supply-side risks

Let us now move to the estimate of supply-side risk. Figure 4.7 shows the committed emissions of the existing fleet by ship type and year of construction. The large amount of committed emissions carried by bulk carriers, containers, oil tankers, and liquefied gas tankers is due to the fact that they are the four largest sectors in terms of activity (tonnes-miles). Containers and liquefied gas tankers are more energy intensive than oil tankers and bulk carriers, so the share of committed emissions is higher than their share of capacity. Most of the emissions committed are embedded in container ships, bulk carriers, oil tankers, and liquefied gas tankers, which together represent 71% of the fleet's committed emissions. Oil and liquefied gas tankers are affected by demand-side risk, but only represent around a third of the committed emissions. Younger ships tend to have higher committed emissions, as they have a longer lifetime. However, the large ordering of ships after 2010, in particular on the bulk carrier and container segments, means that there is a large amount of committed emissions by those generations. They also represent a large share of the capital sunk in those two segments (Figure 4.8). On the other hand, the large ordering in the container and even more in the liquefied gas tanker segment means that a large amount of emissions and capital is just built or in the orderbook (Figure 4.8).

Overall, the fleet's committed emissions are estimated to be 19.4 million tonnes of CO2-e at the beginning of 2021. 50% of these emissions exceed the shipping carbon budget (9.7 million tonnes CO2-e) and cannot be emitted if the shipping sector is to adhere to its allocated carbon budget. Let us look at what this means in terms of book loss and foregone streams by focusing on the four largest segments in terms of deadweight and emissions, namely bulk carriers, containers, oil tankers, and liquefied gas tankers. Together, they represent 73% of annual emissions and should therefore be allocated 73% of the carbon budget of shipping, that is, 7.1 million tonnes of CO2-e. Depending on whether book loss or profits are minimised, the unburnable committed emissions correspond to 422-570 trillion tonnes-miles of activity, or the emissions emissions of ships representing 574 to 1173 million deadweight. That is, if upholding the carbon budget was imposed exogenously on the fleet in 2021, ships representing 574 to 1173 million deadweight would have to retrofit to zero-emission ships (ships which can potentially have zero lifecycle

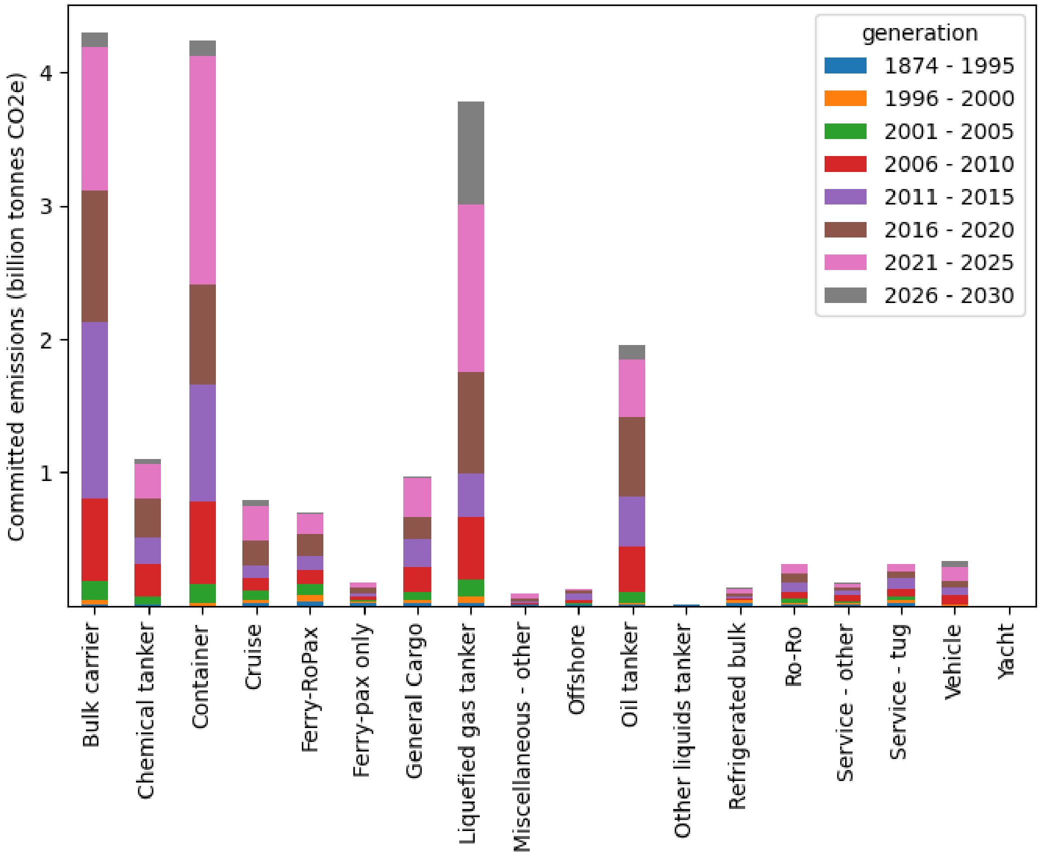

Figure 4.7: Committed emissions by ship type and year of built

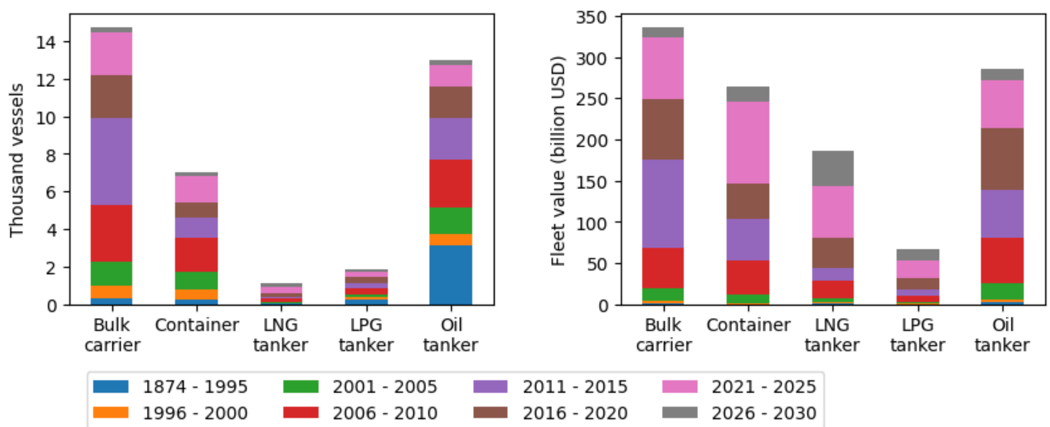

Figure 4.8: Sunk capital: fleet value by segment and build year in 2023

(a) The plotted numbers include both the existing fleet and the ordered fleet, at the time of data collection.

greenhouse gas emissions) or be scrapped (and replaced by zero-emission ships) now.

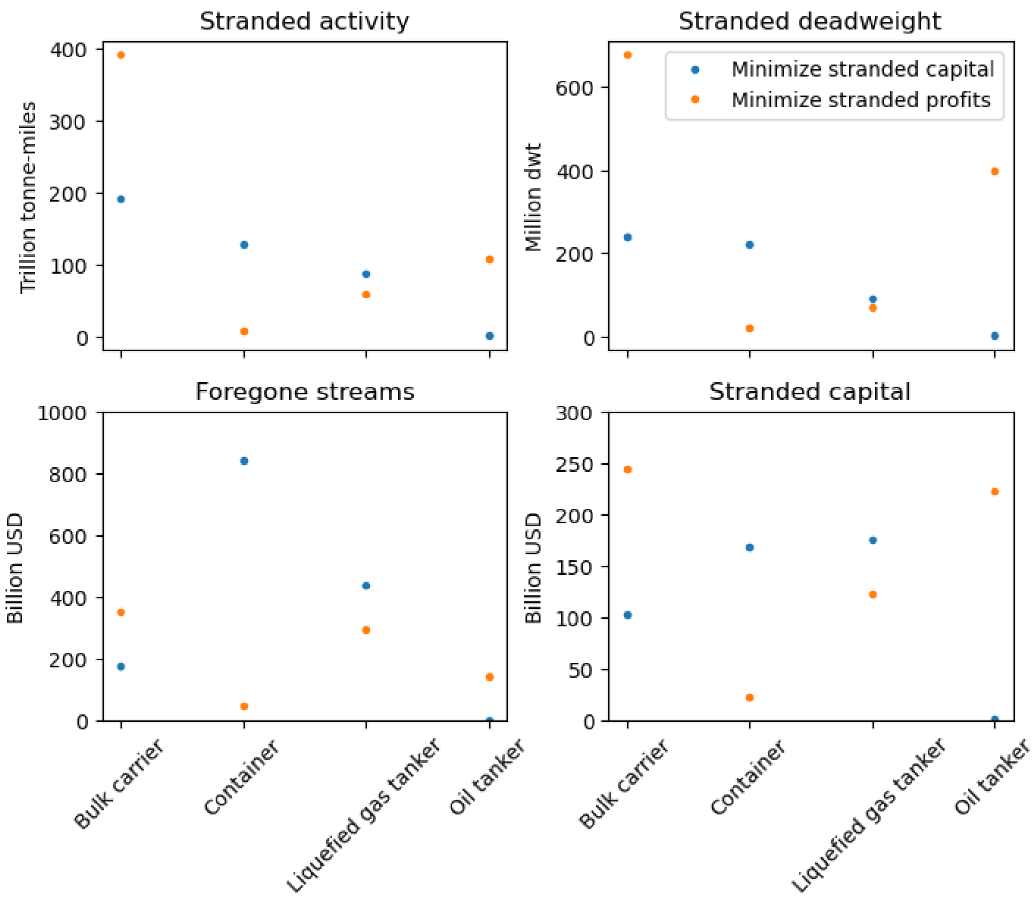

Figure 4.9: Supply-side risk allocation by shipping segment

This stranded activity corresponds to 863 to 1479 billion USD of foregone streams and 457 to 622 billion USD of book loss. There is a large uncertainty about the allocation of stranded assets that would occur, as the results broken down by ship type varies greatly depending on the adopted method (Figure 4.9): minimising book loss results in a large share of container profits being lost, while minimising foregone streams results in containers suffering a very low amount of stranded assets.

4.2.3 Demand-side risks

Let[8] us now look at the potential amount of stranded assets arising from demand-side risks.

Oil and liquefied gas (LNG and LPG) tankers seem to have a high risk of being stranded because they are by design dedicated to their cargo, and because the committed supply reaches well above the projected demand in a 1.5°C scenario up to 2050 (Figure 4.10b), and thus despite the fact that these scenarios aligned with 1.5°C all embed assumptions about the rapid and large scale roll out of negative emission technologies, and therefore might be optimistic about the level of fossil fuels consumption. The demand for transporting oil products decreases constantly after 2018 (the two demand scenarios were produced in 2018), while the committed supply increases up to 2023, and decreases afterwards due to the natural depreciation of the oil tanker fleet. As a result, the committed supply to transporting oil is above the projected demand until 2040. As the committed supply falls relatively fast during this period - many ships can be expected to retire naturally due to the old age of the fleet - the gap between supply and the rapidly declining demand in a 1.5 °C scenario is reduced. Both scenarios modelled (RCP19* and RCP19_L) give fairly similar results, although RCP19_L is leads to a slightly larger gap, suggesting that the choice of method to derive shipping demand from oil consumption only slightly impacts the results.

On the contrary, the large orderbook and long lifespans for liquefied gas tankers[9] result in their committed supply increasing dramatically until 2029, while the shipping demand for fossil gas stabilises or increases gradually. This suggests that the current and ordered fleet of liquefied gas tankers is at risk of oversupply until the mid-2040s and even beyond. The great variation between the demand scenarios considered (blue area) suggests that there is a large uncertainty about the

[8]This section is based on the Section ”A large portion of the fleet of fossil fuel carriers is at risk of being stranded” of the study ”Fossil fuel carriers and the risk of stranded assets”. I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis. Only the results of the ”No further ordering” scenario were included.

[9]The shipping demand for gas does not distinguish between LPG and LNG in the IMO 4th GHG study, so LNG and LPG shipping demand is grouped under “liquefied gas”.

future demand for transporting fossil gas, so the results are also subject to a large uncertainty. In particular, the scenario RCP19_L, which derives shipping demand for gas from gas consumption by using a logistic relationship, shows significantly lower oversupply as scenario RCP19*, which does so by applying a simple percentage change to initial transport work. However, the committed supply remains much larger than demand in both scenarios aligned with 1.5°C target.

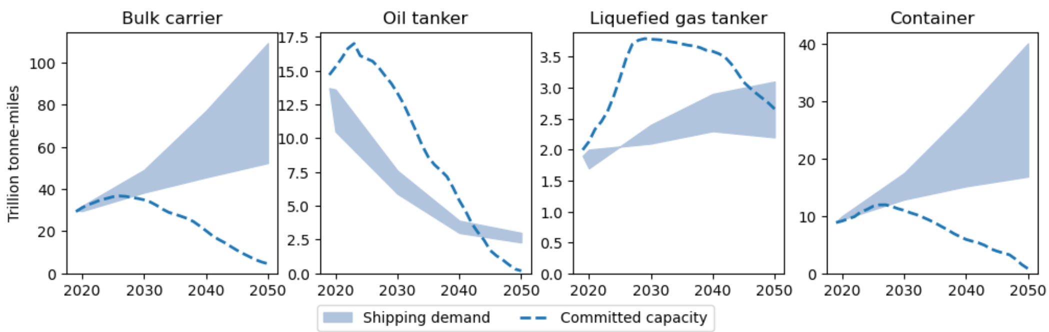

Figure 4.10: Projected shipping demand and committed supply

(a) The blue area represents the range of shipping demand estimates in various demand scenarios (see the evolution of shipping demand under each scenario in Figure 4.2).

(b) The larger the area, the larger the uncertainty of the future shipping demand. Only the uncertainty tackled in the IMO 4th GHG study are represented, i.e. the methodological uncertainty of deriving transport work from consumption, and the uncertain evolution of GDP and population for non-energy commodities. Types of uncertainty which are not covered include recent events (e.g. consequences of the conflicts in Ukraine and Gaza and the Covid pandemics on trade), the uncertainty in fossil fuel consumption given a set temperature target, and further potential long term trends such as changes in trading patterns (e.g. close-shoring or friend-shoring).

The results suggest that both oil tankers and liquefied gas tankers are at risk, as the shipping activity and the associated earnings that were expected at the point of their investment decision are unlikely to materialise with the transitions towards a low or zero-carbon economy.

At the peak, up to USD 10 billion of oil tankers' annual earnings and USD 8 billion of liquefied gas tankers' annual earnings fail to materialise (Figure 4.11b). The share of oil and fossil gas shipping demand which does not materialise is found to increase until 2030; by then, it represents 46 to 55% of the total expected supply, depending on the demand scenario, with RCP19_L leading to somewhat higher estimates (Figure 4.11b). Those annual foregone earning streams reduce fairly rapidly until 2040 for oil tankers, and slowly until 2050 for liquefied gas tankers.

The possible response to the oversupply of the tanker fleet is either that a large share of the ships would not be used or that all ships are used but at much reduced rate. In the first case, the value of unused ships would reach USD 26 to 43 billion or around 12 to 19% of the fleet value in 2026 for oil tankers depending on the demand scenario, with scenario RCP* leading to higher risk, and USD 59 to 66 billion or 27 to 31% of the fleet value for liquefied gas tankers in 2027/2028, with scenario RCP_L leading to higher risk. Those estimates might not translate directly into book loss, as part of the ships not used in 2030 would be used before and after, and therefore able to recover part of their capital invested. These estimates should therefore be considered an indication of the maximum value at risk, rather than an estimate of the capital effectively stranded.

For the bulk carrier segment, the results show that the move away from coal does not significantly threaten bulk carrier values and earnings, as the projected growth in the transportation of other dry cargo will more than compensate for the decrease in coal transportation (Figure 4.12b). As expected given that they do not transport fossil fuels, containers are not significantly affected either. As a consequence, bulk carriers and containers do not appear to face a risk of oversupply in the coming decades, and further investments will be needed to service the projected future demand, as the committed supply falls below the committed demand by the late 2020s (Figure 4.10b). Only in some of the demand scenarios does the bulk carrier and containers fleets become slightly underutilised, and the scale of this is limited (Figure 4.11b) as is the number of potentially unused ships (Figure 4.12b).

The cumulative value of stranded asset from demand-side risk in a 1.5°C scenario is particularly large for oil and liquefied gas tankers (Figure 4.13a). Foregone earnings streams are found to be much larger than the worst-case book loss in both segments. This suggests that many ships would be better off scrapping early, rather than continue operating at a loss. Oil and liquefied gas carriers undergo similar foregone earnings streams: combined, those reach USD 288 billion and for all tankers together, and this estimate is similar between both demand scenarios (RCP19* and RCP19_L). The latter represents 37% of their combined expected earnings. Some caution should be used when considering the resulting book loss, as this corresponds to the value of the maximum capacity unused at any point of the period, but in practice part of this capital would be utilised before and after this point, and therefore able to recover some of its initial investment. Taking this into consideration, worst-case book loss of the tanker segments together could amount to USD 92 to 100 billion in 2027 representing around 21 to 23% of the fleet value. The demand scenario RCP19_L, using the logistic curve, shows slightly higher risk than demand scenario RCP19*, but the range is fairly small, suggesting that the estimate is not too affected by the methodological uncertainty of deriving shipping demand from fossil fuel consumption when all tankers are combined.

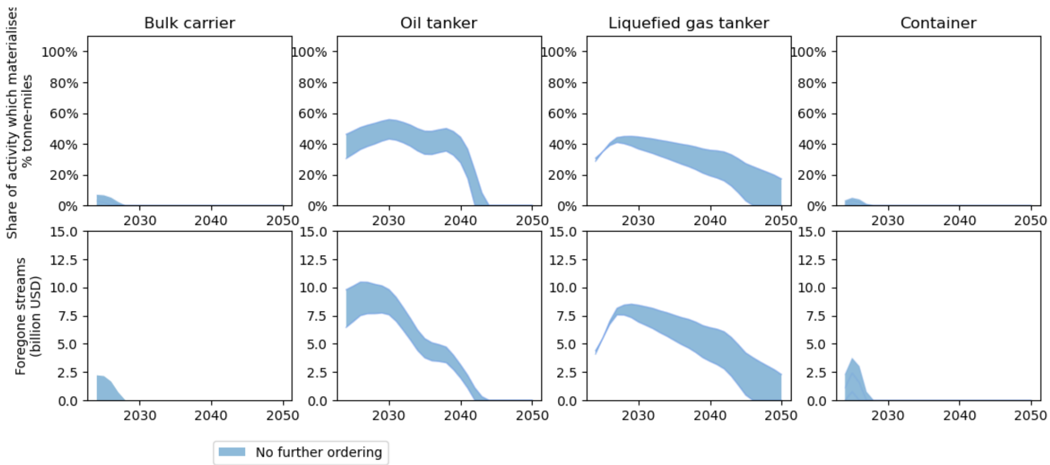

Figure 4.11: Demand-side risk and foregone streams

(a) The blue area represents the range of shipping demand estimates in various demand scenarios (see the evolution of shipping demand under each scenario in Figure 4.2).

(b) Results from 2018 onwards, as the demand was estimated in 2018 for the IMO 4th GHG study

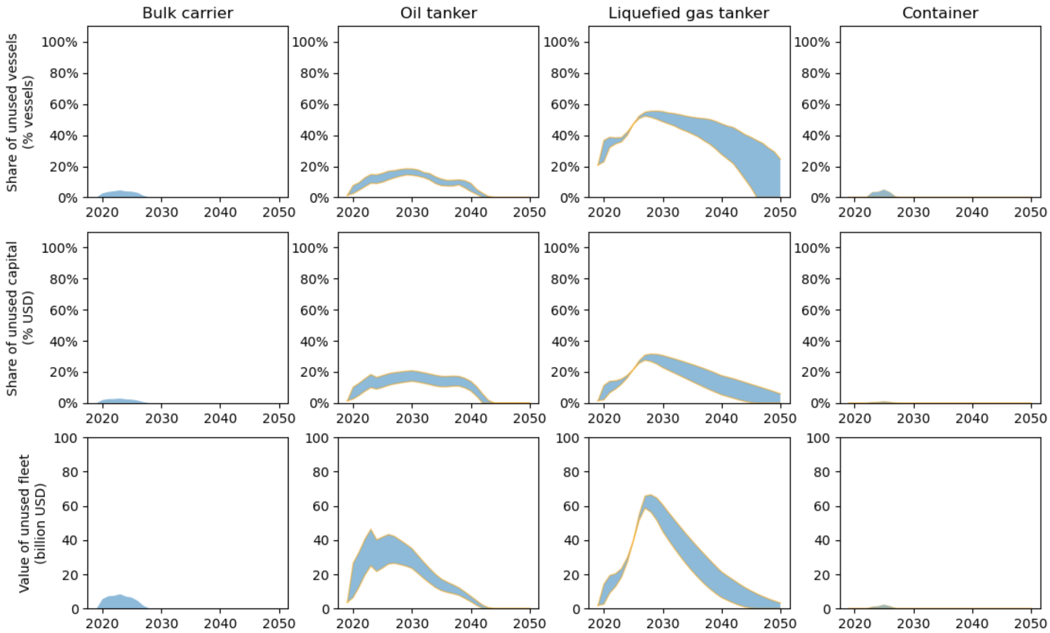

Figure 4.12: Demand-side risk and book loss

(a) The blue area represents the range of shipping demand estimates in various demand scenarios (see the evolution of shipping demand under each scenario in Figure 4.2).

(b) The value of the unused fleet can be considered a worst-case proxy for book loss. It is a cumulative value rather than an annual flow.

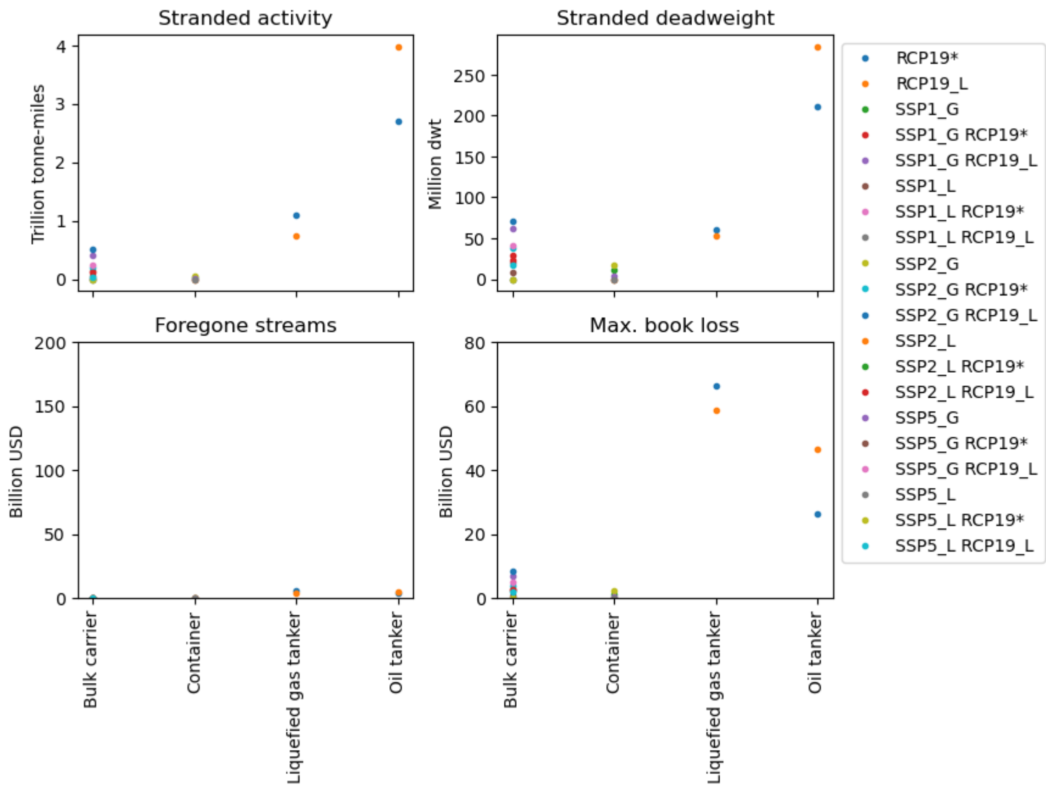

Figure 4.13: Cumulative demand-side risk over the whole period

(a) Book loss corresponds to the maximum value of the unused fleet due to the lack of demand at any point in time over the 2018-2050 period. This is likely to be an overestimate, as some of those ships would be used at other points in time.

4.2.4 Comparison of demand-side and supply-side risks

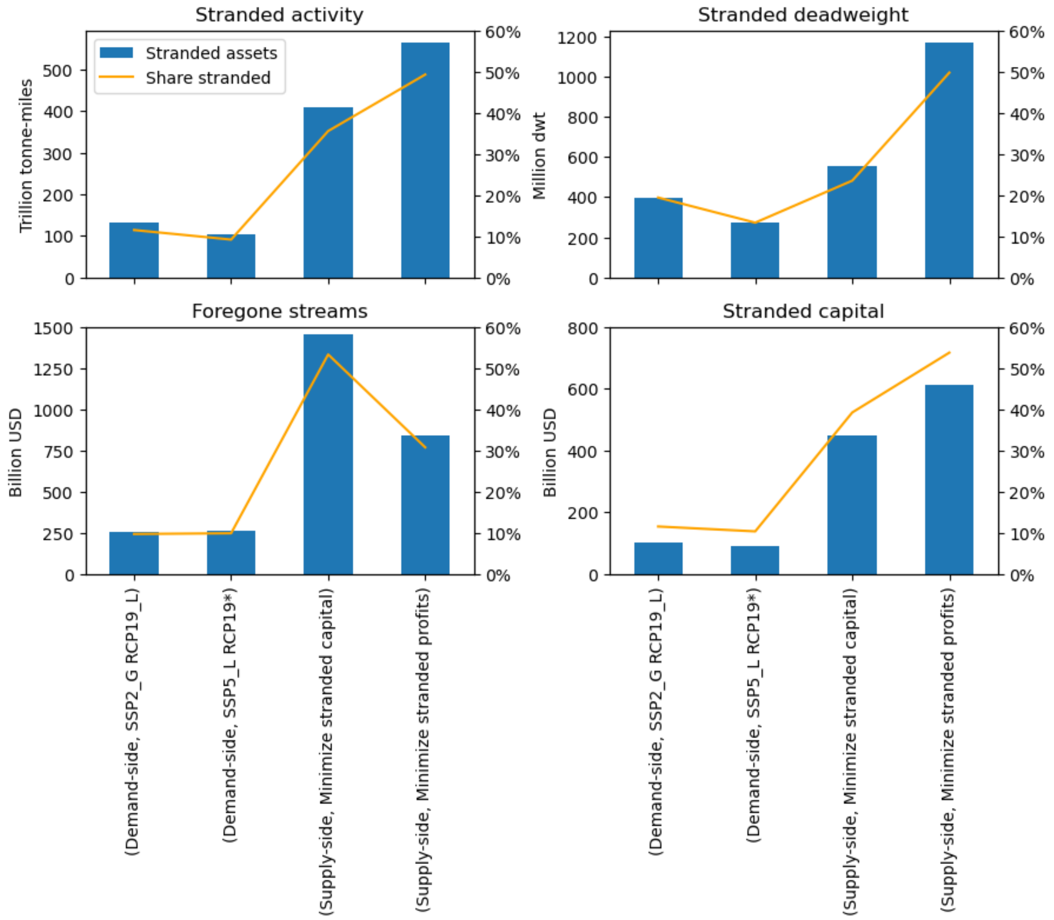

Figure 4.14: Demand- and supply-side risk of stranded assets for bulk carriers, oil tankers, containers and liquefied gas tankers

(a) Book loss due to demand-side risk corresponds to the maximum value of the fleet unused due to the lack of demand over the 2019-2050 period. This is likely to be an overestimate, as some of those ships would be used at the other points in times.

(b) The results correspond to those plotted on Figures 4.13a and 4.9 summed across all 4 shipping segments considered. RCP19* and RCP19_L scenarios were used for oil and gas tankers, and were added onto scenarios SSP2_G_RCP19_L and SSP5_L_RCP19* for bulk carriers and containers, as those were most extreme estimates.

(c) The bars corresponds to the absolute amount of stranded assets. The lines correspond to the share of activity/deadweight/profits/capital stranded.

Having examined the scale of the risk of asset stranding from demand-side and supply-side risks separately, let us now compare them for the sample of interest (bulk carriers, oil tankers, containers, and liquefied gas tankers). Figure 4.14c compares the amount of stranded activity, deadweight, profits and capital between demand-side and supply-side risks in various scenarios.

For all scenarios and all asset stranding measures, the supply-side risk appears to be a greater threat than the demand-side risk. Between 31% and 55% of the capital and expected profits of the sample of ships are found to be at risk due to supply-side risk, while this only reaches 10-11% for demand-side risks (Figure 4.14c). For demand-side risks in particular, this means that although there is a significant risk of oversupply for oil and gas tankers, this effect is more diluted when looking at the overall fleet - in this case and on Figure 4.14c, when including bulk carriers and containers. This suggests that this demand-side risk could be hedged against by a diversified portfolio of ships across various segments.

Furthermore, it is possible to anticipate in which segments demand-side risks are most concentrated, namely oil tankers and liquefied gas tankers, while there is large uncertainty regarding which ships are most at risk of supply-side risk, as the large discrepancy between the results using different methods for allocating unburnable emissions shows.

4.3 Discussion

Having analysed the results in the previous section, the next section moves on to summarise the main findings and discuss how they related to similar studies (Section 4.3.1), discuss their implications (Section 4.3.2) and limitations (Section 4.3.3)[10].

4.3.1 Discussion of the results

This chapter aimed to answer the first research question of this thesis: What share of the existing sunk capital in ships is incompatible with land and shipping carbon budgets? This Chapter (along with its published version) is one of the first to quantify in monetary terms the risk of stranded assets in the shipping industry and the only one to focus on demand-side risks. To do so, the invested capital and shipping activity, and the consequent upcoming earnings that can be expected from the fleet, have been quantified. These estimates were compared to the energy transi-

[10]This section is based on the Section ”Discussion” of the study ”Fossil fuel carriers and the risk of stranded assets”. I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis and paragraphs on the supply side risks have been added.

tion pathways that can limit climate change to a 1.5°C temperature increase, that is, the demand for transporting fossil fuels in line with such pathways and the carbon budget for shipping. The results indicate that the current invested capital is at odds with the 1.5°C carbon budget, which is consistent with the results obtained in other sectors (Löffler et al., 2019; Y. Lu et al., 2022; McGlade and Ekins, 2014, 2015; Pfeiffer et al., 2016; Welsby et al., 2021). This suggests that shipping is similar to other capital- and carbon-intensive industries with respect to the risk of stranded assets.

In particular, existing ships are expected to emit 50% more emissions than this carbon budget. This estimate is slightly higher than the one of Bullock et al. (2020), who found that 42% of the emissions committed by European ships exceed the carbon budget, despite the fact that the European fleet in Bullock et al. (2020) is on average younger than the one described in this Chapter, and so carries more committed emissions. This can be largely explained by the timing of the studies: Bullock et al. (2020)'s analysis was carried out on the 2019 fleet, but more ships have been ordered since then and more shipping emissions have been emitted. The scope of Bullock et al. (2020)'s work also differs from this chapter, as it focuses on European emissions rather than world ones, which might further explain the difference. However, the magnitude of the results is similar, which provides some assurance on the validity of the results. The large discrepancy between committed emissions and the shipping carbon budget means that if the shipping industry is to respect its fair share of the carbon budget and align with a 1.5°C trajectory, a large share of the existing and ordered fleet will have to retrofit to cleaner options or be scrapped and replaced by zero-/low-emission vessels. Any newly ordered conventional ship adds to the stock of sunk conventional capital at risk of being stranded and committed emissions. This puts a significant amount of investment at risk: around 40% of the value and deadweight of the fleet would be at risk if the constraint of the carbon budget was imposed suddenly and endogenously today. The results also show that it is not clear which ship and segment would suffer the bulk of the asset stranding.

However, the results indicate that demand-side risk is more limited than supply-side risk when looking at the entire fleet (around 8-9%), and it is clearer which segments would be affected. The results indicate that some segments would be strongly affected, particularly ships that are by design dedicated to fossil fuel transportation, such as oil and liquefied gas tankers; these would be in great oversupply in the late 2020s to 2040 even if no new ships are ordered after 2023, resulting in cumulative foregone earnings streams around USD 239 to 260 billion on both segments together. Coal carriers, were not found to be impacted because they can transport other commodities with similar characteristics in a large market of bulk shipping which is projected to grow further. Those results are in line with those of Walsh et al. (2019), who find that dry bulk shipping is less sensitive to the decarbonisation of the world economy. However, some ship size categories might be significantly impacted, as larger bulk carriers have been traditionally more focused on iron ore and coal and therefore more sensitive to a shift in bulk trade away from coal and towards grains and minor bulks (MSI, 2019).

Oil and liquefied gas tankers show a different risk profile: oil shipping demand is expected to fall steadily in all 1.5°C scenarios and retrofitting these carriers to move other types of cargo that would be needed in the transition may technically be limited or economically not be viable. The fall in oil demand might be replaced by an increase in the demand for transporting biofuels or synthetic liquid fuels, but the increase in biofuel trade is expected to be very small compared to the trade in crude oil and oil products today (Jones et al., 2022; MSI, 2019; Sharmina et al., 2017). With the expected rapid fleet depreciation due to the fleet‘s age structure, the committed supply is expected to fall naturally.

In contrast, the committed supply of liquefied gas tankers is not expected to decrease soon. The fleet is relatively new in particular due to the large recent ordering following the Ukraine war (OECD, 2023) and these ships have long lifespans. As liquefied gas tankers are more expensive, they rely on more earnings per tonne mile, which makes their earning streams more sensitive to the decrease in demand. From this point of view, they are at great risk of asset stranding. However, there are large uncertainties about the future demand for gas products, since the role of fossil gas as a bridge fuel in low-carbon transitions is largely debated (see, for example, the contradictory results of the scenarios of IEA (2021), IPCC (2022), Sharmina et al. (2017), and Walsh et al. (2019)), and many of those scenarios rely of high level of negative emission technologies, whose viability are uncertain (Deprez et al., 2024). Furthermore, some argue that there could be a long-term increase in demand for LNG transport due to the Ukraine war (OECD, 2023) . The United States' decision in January 2024 announcing a temporary pause on pending approvals on exports for LNG also illustrates the evolving understanding of the gas' climate and environmental impacts at production and during transport (The White House, 2024).

4.3.2 Implications

Let us now consider the implications of the findings described above. Regarding supply-side risk, a substantial portion of the current fleet must undergo significant emission reductions, achieved either through retrofitting with cleaner fuels or by enhancing energy efficiency, potentially involving operating at lower speeds. Failure to remain competitive with more carbon efficient ships poses risks such as reduced income due to lower productivity from decreased speeds compared to more efficient ships, lower activity or early retirement, leading to premature write-downs. This poses challenges for shipowners, ship financiers, and policymakers, as each option incurs substantial and unforeseen costs. Newer ships are particularly vulnerable as they will remain in operation longer, resulting in higher emissions. Ships with higher operating costs or carbon emissions, as well as those with designs that are not easily retrofittable, are also at risk. Orders for conventional ships placed from 2021 onwards contribute to committed emissions, escalating the threat.

Regarding demand-side risks, although the analysis showed that the risk was more limited than for supply-side risks, segments dedicated to fossil fuels could be strongly impacted. However, there could be an increase in the trade of other commodities as a result of the low-carbon transition of the world economy, such as hydrogen and hydrogen-derived commodities or CO2 (Egerer et al., 2023; Hampp et al., 2023; Schmidt et al., 2019; Sharmina et al., 2017), but it is not yet clear whether different liquefied gas carriers would be able to repurpose to them, and how much of the current demand for transport of fossil gas could be replaced by the future transport demand for these commodities (Jones et al., 2022; Schreiner et al., 2022; Sharmina et al., 2017). In particular, ammonia is usually shipped in LPG carriers. 36 of these carriers are on the orderbook (Clarksons Research, 2022a) at the time of writing, driven by the expected increase in demand for ammonia derived from clean hydrogen (Mandra, 2023), and two of these LPG tankers in the orderbook are also capable of transporting CO2 (Clarksons Research, 2022a). This Chapter estimates that LPG tankers only represent 21% of the committed supply of liquefied gas tankers (see Figure 4.3), while most of the committed supply is provided by LNG tankers, as they represent a larger share of the fleet deadweight and are on average younger. For those, it is not clear from the literature whether they would be able to retrofit to other energy cargoes (e.g., biofuels, hydrogen derivates) or CO2 neither how expensive such a retrofit would be.

Overall, these findings closely resemble those of other long-lived fossil gas assets (e.g., gas power plants, gas terminals) that are caught in uncertainties related to the future role of fossil gas in low-carbon transitions (Caldecott and McDaniels, 2014; Lockwood et al., 2020; Löffler et al., 2019) and the uncertainties related to these assets' potential conversion to low-carbon energy carriers such as ammonia or hydrogen (IEA, 2022; Schreiner et al., 2022).

Finally, the results show that ownership, construction and operations of ships are fragmented across a myriad of actors, which makes it difficult to anticipate the actors' exposure as well as the cascade effects of the demand-side and supply-side risks on their financiers, for example the banks which have underwritten their loans, or of their beneficial owners, that is the person or company who ultimately owns and control the registered owners. Owners and operators tend to be specialised in one segment, which makes them vulnerable to demand-side risks, and supply-side risks, should the latter materialise first in one specific segment, whereas shipyards were found to have a more diversified portfolio. This issue echoes the difficulty but also the importance in other sectors to quantify and anticipate the transmission of stranded capital to further financial actors (Battiston et al., 2017; Daumas, 2023), what Daumas (2023) referred to as "stranded paper".

Furthermore, retrofitting ships to alternative cargoes might provide a way to save some of the value at risk. However, even when retrofitting is a less expensive alternative to scrapping it still leads to fleet devaluation due to retrofitting costs as well as to competition with the existing fleet and newbuilds in these segments. If retrofitting is not feasible due to technical limitations or lack of financing solutions, the entire value of the ship is at risk. Shipowners and financiers can mitigate these risks by investing in ships designed for potential retrofits and planning for future retrofitting costs when valuing ships today. While there is now work on the topic for retrofitting fuel and propulsion systems to manage climate risk, there is less work on retrofitting for a different cargo (Lagemann et al., 2022, 2023), there is therefore a lack of evidence of the cost and asset stranding on the cargo side, and further research is needed on the topic.

Although the decrease in shipping demand for fossil fuels constitutes a risk for investors, it also contributes to the decarbonisation of the sector and therefore contributes to limiting supply-side risk in other segments, as the stranded demand estimated in this article represents between 1.8 and 2 billion tonnes of CO2-eq emissions until 2050[11]. To put this into perspective, this represents around 1.7 to 2.4 times the 2018 annual emissions from shipping (Faber et al., 2020) and 15 to 22% of the estimated remaining shipping carbon budget aligned with 1.5°C trajectory left. This suggests that although the decrease in shipping demand for fossil fuels is not sufficient to align shipping emissions with a 1.5°C trajectory, the impact of this demand lever is significant.

4.3.3 Limitations and future work

This chapter was limited in several ways, which offer opportunities for further research. First, the trade scenarios are based on the 2018 estimates in the 4th GHG study, which are now outdated as the consumption (Rogelj et al., 2018b) and conse-

[11] Using the carbon intensity, Energy Efficiency Operating Indicator, from the IMO 4th GHG study, and assuming a ratio well-to-wake to take-to-wake of 1.21 (Comer and Carvalho, 2023)

quent transportation of fossil fuels has not aligned with a 1.5°C trajectory. The results therefore likely overestimate the amount of demand-side stranded assets in the early years of the study period (the study period runs from 2018 to 2050), and underestimate them in the later years. Furthermore, there are necessary limitations of any quantitative assessment of future fossil fuel consumption and associated trade. In particular, the input data to future demand, which are taken from the IMO 4th GHG study, are themselves limited, as they only cover one scenario aligned with 1.5°C temperature increase among a large number of possibilities. Even in a given consumption scenario, it is uncertain which fossil fuel resource would be used last, which would have an impact on the traded quantities and the modal share (pipeline versus shipping). The results would therefore benefit from further sensitivity analysis, when more shipping demand scenarios become available.

In this initial estimate of stranded assets, the evaluation of committed supply is based on peer group averages, making the findings a preliminary and rudimentary estimate. To improve precision, it might be beneficial to refine this estimate by incorporating more detailed data at the individual ship level; to distinguish in particular between the different types of liquefied gas tankers, as LNG tankers and LPG tankers likely have different cost structure and, as previously discussed, drivers of asset stranding; or to focus on a case study, as has already been done for ship propulsion (Jeong et al., 2023). Similarly, further insight into shipowner expectations about operational characteristics throughout a ship's lifetime—specifically, scrap age, distance travelled, and utilisation—and on the risk of upcoming low-carbon transitions, would contribute to a more comprehensive analysis.

Furthermore, the possibility of ships to retrofit to cleaner propulsion technologies, or to alternative cargoes, was only qualitatively discussed, but the quantitative estimates ignore them and should therefore be considered as the maximum value at risk rather than a realistic estimate of asset stranded. Daumas (2023) shows that this limitation is shared by various other studies , with exceptions including Bullock et al. (2020) and Y. Lu et al. (2022), which, however, do not monetise stranded assets or retrofitting cost; and Saygin et al. (2019) in the building sector only. This point is addressed for supply-side risks in Chapter 7.

Moreover, the analysis has looked at only one factor of demand-side risk and in practice only three segments concerned (bulk carriers, liquefied gas tankers, and oil tankers), but other drivers linked to low-carbon transitions could put further pressure on the future demand for transportation: for example, a move of the world economy away from fossil fuels would likely reduce offshore activity linked to fossil extraction: similarly, increased regionalisation of trade, and demand for local products would reduce the shipping distance and therefore activity (Walsh and Mander, 2017; Walsh et al., 2019). On the contrary, the estimates of shipping demand in the IMO 4th GHG study and therefore the demand used in this Chapter largely ignore the potential uptake of new commodities such as biofuels, CO2, hydrogen-derived fuels that may compensate for the decline in fossil fuel transport to some extent. New opportunities are also expected to arise in the offshore wind industry. More research is needed to investigate the future trade of those and whether current ships are economically retrofittable to serve these purposes.

This Chapter, like others (for example, Bullock et al. (2020), Löffler et al. (2019), Y. Lu et al. (2022), McGlade and Ekins (2014, 2015), Pfeiffer et al. (2016), and Welsby et al. (2021); see a more detailed list in Section 2.3.3), provides a normative and static assessment of potential stranded assets under the condition that shipping demand and emissions align with 1.5 ° C carbon budgets and overlooks the ships to be commissioned in the coming years. However, these could further contribute to the stock of committed emissions and supply incompatible with shipping and land carbon budgets. The underlying assumption is that of an orderly transition from 2018 (demand side) and 2023 (supply side) onwards. However, in recent years, this assumption has been challenged by various authors who have argued that transitions might take place in a delayed and disorderly manner (Batten et al., 2017; Monasterolo, 2020). This argument is supported on the one hand by the observed demand from 2018 to 2023, with the demand for the transport of oil and liquefied gas being higher than the trajectories of the IMO 4th GHG study aligned with a 1.5°C transition; and on the other hand, by the observed shipping emissions since 2018, which have not been significantly reduced (Clarksons Research, 2023). If a delayed transition occurs and shipowners continue to invest in new ships while disregarding stranded asset risks, a scenario may unfold in which an ”inevitable policy response” (PRI, 2021) is implemented only after some time, with the aim of averting the catastrophic effects of climate change. The realisation of such a scenario means that this chapter might overestimate the risk of stranded assets in the short term and underestimate it in the long term, as a delayed transition would translate into a steeper reduction in emissions. A dynamic assessment of stranded assets, accounting for future newbuilds, is needed to account for these dynamics. This is the focus of the following chapters. In particular, Chapter 6 investigates the current behaviour and expectations of financiers for supply-side risks, and therefore investigates whether an orderly scenario is underway. Chapter 7 models the evolution of the fleet until 2030 and looks at the potential for asset stranding in the context of a delayed transition.

Lastly, the research has not looked at the roles of and impacts on other stakeholders of the fossil fuel shipping industry, such as the financiers, the beneficial owners who may be behind the registered owners, as well as the flag states of these ships, which are important stakeholders in the value chain as they may carry some of the stranded value risks. Some of those impacts are considered in Chapter 7 for supply-side risks only.

Chapter 5

Financiers during socio-technical transitions; theoretical framework

This section aims to answer the third research question: How could the expectations of financiers of upcoming low-carbon transitions in shipping evolve during shipping low-carbon transitions ? It provides a novel theoretical framework to understand the evolution of expectations and the behaviour of financiers as a socio-technical transition unfolds.

To do so, it builds on the literature review conducted in Section 2.1.3 : this section has reviewed the evidence of financiers' behaviour reported in the literature looking at socio-technical transitions which have already happened historically. For most of this literature, the financiers' behaviour are not the focus of the analysis, but a part of a broader analysis of the case study. The literature is synthesised by grouping the evidence found under similar behaviours (this grouping is already done is the way section Section 2.1.3 is written, with one group corresponding to one paragraph). The content and justification of the behaviours are then linked to the concepts of the MLP and AMH literature (e.g. evolving heuristics, agency, niche innovation, regime incumbents, new entrants). The result of this analysis is a set of 5 archetypal behaviours, which constitute an original theoretical contribution.

The remaining of the Chapter is organised as follows: the section section describes how both finance and shipping would be understood within the MLP framework. The following section describes the theoretical framework of financiers' behaviours. Finally, the last section discusses the implications and limitations.

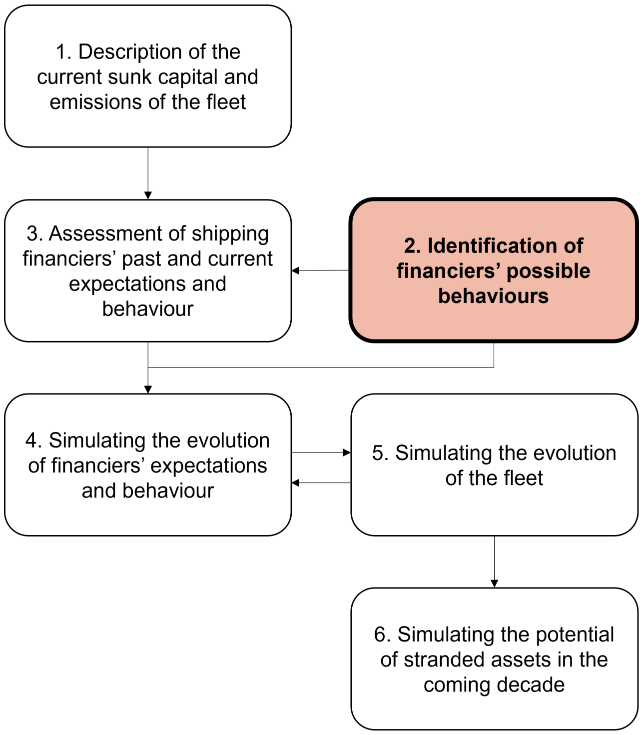

Figure 5.1: Sign-posting chapter 5: Identification of financiers' possible behaviours

5.1 Characterising the shipping and financial MLPs

As discussed in Section 2.1.2, the shipping regime as comprised of a large range of industry incumbents including shipowners, charterers and customers, ports and fuel providers and regulators (see Figure 5.2) (Pettit et al., 2018; Stalmokaite and Yliskylä-Peuralahti, 2019).

Let us now characterise what constitutes the shipping financial MLP. Previous[1] research has explored the idea that finance can be conceptualised within the MLP framework. Geddes and Schmidt (2020) and Geels and Gregory (2023) proposed that finance is situated at the level of the regime, alongside others such as the technology regime or the energy regime, while Cairns et al., 2023 assumes that it is located between the landscape and the regime levels. Urban and Wójcik (2019) suggested that finance is made up of three levels: the financial landscape, the fi-

[1]This paragraph is directly taken from the article ”Exploring financiers' beliefs and behaviours at the outset of low-carbon transitions: a case study on shipping”, section 2.4, whom I am the main author of. I have written the first draft of this section and it has been reviewed by the co-authors.

nancial regime, and the financial niche, where financial innovations emerge. They also argued that the financial regime can experience a transition. This chapter builds on the conceptualisation of finance as made of three levels proposed by Urban and Wójcik (2019), so that the financial regime can undergo a transition (see Figure 5.3a).

As in Urban and Wójcik (2019), a financial regime is a understood as a network of incumbent financial actors who share culture, beliefs, financial tools and instruments, and are subject to financial policy and regulations. In the case of shipping, the financial regime includes for example major shipping banks, who provide fairly standardised loans to finance ships, increasingly export credit agencies who are providing guarantees, often to transactions provided by shipping banks and leasing agencies (see Section 2.1.1). Within the same country, they share similar regulations, although those might vary from country to country (e.g. Basel regulation), and might share beliefs and science (e.g. option options, NPV approach, view of climate risks) - which are investigated in the next chapter. It is worth noting that financial regime actors are likely linked to industry regime actors, at least through past and current activities - e.g. shipping banks hold loans of shipowners.

A financial niche is understood as a protected financial space, where a financial innovation can emerge and develop. Such financial innovation has not been documented in shipping within an MLP framework, but some were documented in other sectors (e.g. paytech or green bonds; see Section 2.1.3). Those financial innovation might be carried by new entrants, or by financial incumbents.

The financial landscape is understood as broader exogenous environment that influences and constrains the dynamics within the financial regime and niches. Part of this landscape is common between the financial and industry MLP (e.g. climate change, capitalism) but others are more specific to the financial MLP (financial crisis, Basel regulation, Central Banks' policy).

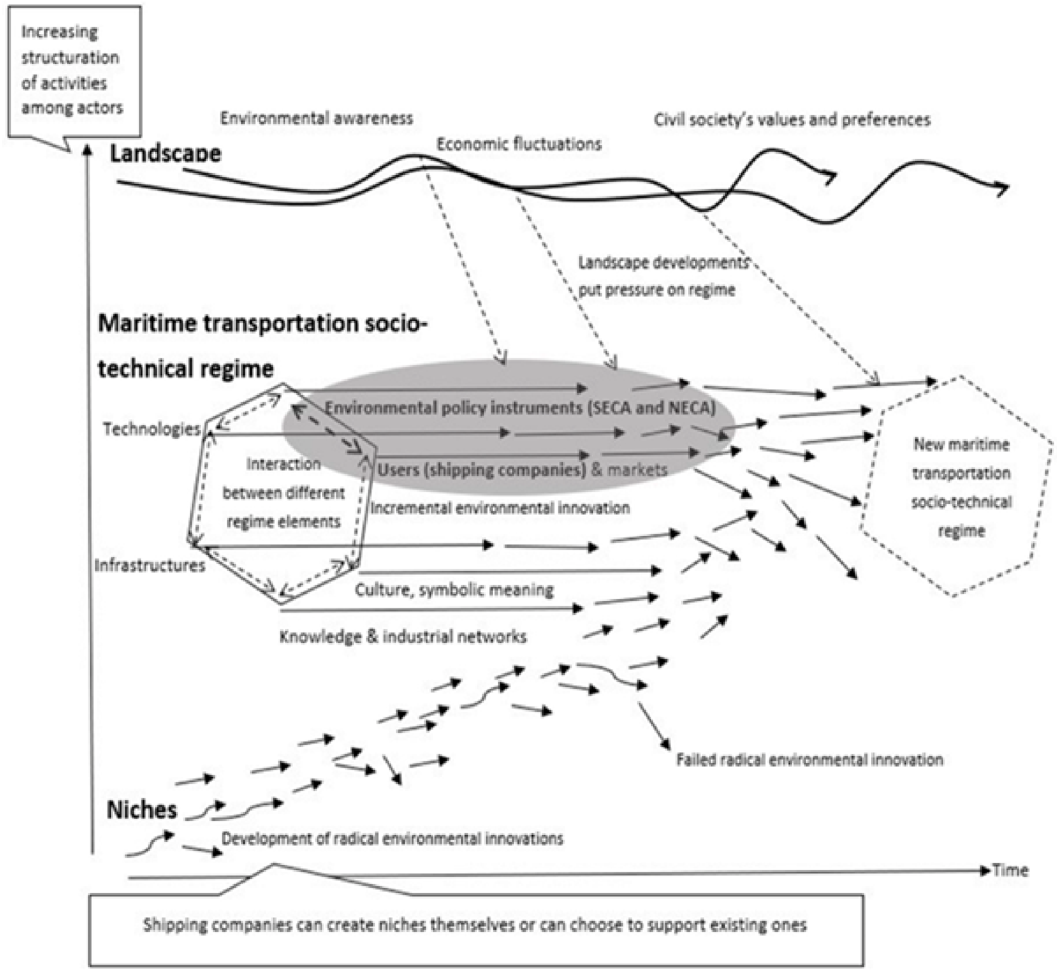

Figure 5.2: MLP of shipping low/zero-carbon transitions (recall, from 2.1.2). Taken from Stalmokaite and Yliskylä-Peuralahti (2019)

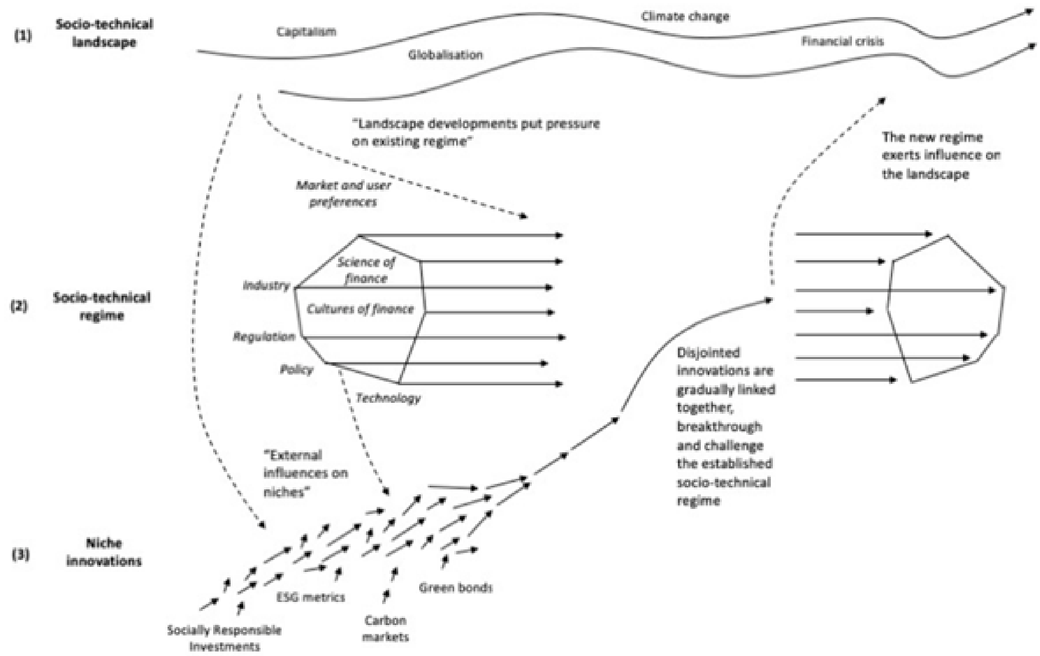

Figure 5.3: Finance in the MLP framework. Taken from Urban and Wójcik (2019)

(a) This diagram suggests a financial transition where new entrants carrying competitive niche financial innovations (level (3)) replace incumbent financiers (level (2)). In this proposed framework, as for industry transition, transitions might also unfold by the incumbent financiers (level (2)) adopting symbiotic financial niche innovations and therefore surviving into the new regime.

5.2 Proposal of theoretical framework

An[2] extended theoretical framework is proposed here to explain the various roles financiers can take during a transition and the relationships between the industry and the financial MLP. To do so, it builds on the theoretical insights from the Adaptive Market Hypothesis (AMH) proposed by S. Hall et al. (2017) and Lo (2004) and described in more details in Section 2.2 of the literature review.

5 types of archetypal behaviours are proposed (represented schematically in Figure 5.4a), depending on whether financiers are expectations of the risks and opportunities of the transition to materialise, and on whether they can adapt to the new technology:

- **Inert**: financiers anticipate stability of the existing industry socio-technical regime. The financiers would therefore continue interacting with the actors of the industry regime level. For example, German banks and institutional investors were originally wary of financing renewables before the KfW pro-actively gave positive signals towards those technologies (Geddes et al., 2018).
- **Creative self-destruction**: financiers anticipate growth opportunities in the industry regime and steer industry incumbents to increase investments in the incumbent technology. This echoes the notion of Creative Self-Destruction proposed by Wright and Nyberg (2015) that the response to a problem arising from the continuous expansion of the industry incumbents is to further extend their reach. For example, E.ON and to a lesser extend RWE invested in the late 2000s' into fossil fuel electricity generation under the pressure of their shareholders (Ferguson-Cradler, 2022; Kungl, 2018; Kungl and Geels, 2018).
- **Loyal enabler**: financiers anticipate the upcoming socio-technical transition and support the industry incumbents to invest in technology innovations (e.g. large support from the UK banks to the incumbent UK electricity utilities

[2]This section is directly taken from the article "Exploring financiers' beliefs and behaviours at the outset of low-carbon transitions: a case study on shipping", section 2.4, whom I am the main author of. I have written the first draft of this section and it has been reviewed by the co-authors.

during the ”dash for gas” to build gas-power plants or to large-scale renewable electricity generation in the UK, R. Bolton and Foxon (2015), Geels and Ayoub (2023), and Kern (2012)). This suggests that the financiers anticipate that the transition will be led by the regime incumbent adopting a symbiotic niche innovation, i.e. would happen as a transformation or reorganisation. The term Loyal Enabler is chosen because they support the transition by investing in the new technology but remain loyal to their existing customers. Several conditions are necessary for them to be able to do so:

  – Either industry incumbents are already first movers, or financiers have the power to steer them in this direction; and

  – They are able to finance the new technological innovation by adapting their heuristics.

- **Redirecting enabler**: financiers anticipate the upcoming socio-technical transition and redirect their investments from industry incumbents towards industry niche new entrants (e.g. support from some banks, such as the German Savings and Cooperative Banks or the KfW, to small-scale solar and wind in Germany Geddes et al. (2018) and F. Zhang (2020)). This type of financier also supports the transition by investing in the new technology but contrary to Loyal Enablers, they redirect their capital from one industry player (regime) to another (niche) in its ideal-typical form. This behaviour suggests that financiers anticipate a transition where regime incumbents are not able to adopt the competitive niche innovation and are therefore replaced by niche new entrants carrying this innovation (substitution or de-alignment and re-alignment). Financiers are able to do so because they can adapt their heuristics to those new entrants and/or the new entrants able to fit into their requirements, for example by aggregating small-scale projects to fit into the transaction size desired by the financiers (those processes are described in Geddes and Schmidt (2020)).

- **Winding down**: financiers anticipate the upcoming socio-technical transition, but they are incapable of financing the new technology, so they reduce exposure altogether from the sector. That leaves the door open for other types of financiers to fill in the space, or potentially means that no new investment altogether take place. An example of the former is the case of the UK transition to low-carbon steel (as discussed Geels and Gregory (2023), although non-climate related factors dominate the reason for Winding Down). An example of the latter is the partial replacement of utilities' balance sheet and debts as the main sources of finance to a coalition of project developers, utilities, institutional investors, banks and corporation (Geels and Ayoub, 2023; S. Hall et al., 2017).

This typology of behaviours can apply to both the regime and the niche levels of the MLP framework, i.e. to both incumbent financiers and financier new entrants, when they face financial and industry landscape pressure. One could assume that new entrant financiers would be more willing to finance industry niche new entrants, i.e. play a Redirecting Enabler role in the typology (bottom right behaviour in Figure 5.4a). Similarly, one could assume that an incumbent financier would be more loyal to industry incumbents (e.g. existing shipowners), i.e. play an Inert, Creative Self-Destruction, or Loyal Enabler role (two most left behaviours and top right on Figure 5.4a). However, there are examples in the literature of financiers supporting industry new entrants, as discussed in the previous section, and there is no a priori reason why new entrant financiers would not also be resistant to changing their behaviour in an upcoming transition (Inert), so it is assumed here that both levels of the MLP can adopt all types of behaviour.

Furthermore, it is worth noting that the gradual change in heuristics (orange left arrow in Figure 5.4a) does not happen by itself but is constructed by the interaction with peers and other actors such as policy makers, wider public, users and technology providers, a process which is described for firms in general in Geels and Gregory, 2023 (in the case of finance at least, one should probably add the shareholders). Often, the intervention of policy makers is necessary to create those expectations: for example, Geels and Ayoub (2023) and Polzin et al. (2019) show that policy announcements and mandates have been critical in creating positive views on renewables, Geddes and Schmidt (2020) shows that the intervention of State investment banks were instrumental in creating trust into those technologies and Braunholtz-Speight et al. (2020) and Cairns et al. (2023) show that the emissions of grants in the early stages of the projects, even when small, and the guarantees of future tariff by the implication of Feed-in-Tariffs, play a large role in de-risking investments in community cooperatives renewables in the UK.

Finally, it is worth noting that in many cases, the emergence of a financial innovation was needed for financiers to be able to play a Loyal Enabler or Redirecting Enabler role (blue arrows ”adaptation of heuristics” on the right). Examples of symbiotic financial innovations include the creation and uptake of green bonds since 2006 and of Environmental, Social and Governance (ESG) metrics in the last few decades to evaluate firms (Monk and Perkins, 2020; Seyfang and Gilbert-Squires, 2019; Urban and Wójcik, 2019), or the adoption of project finance to enable alternative financiers such as institutional investors to participate into the financing of offshore wind (Geels and Ayoub, 2023; S. Hall et al., 2017).

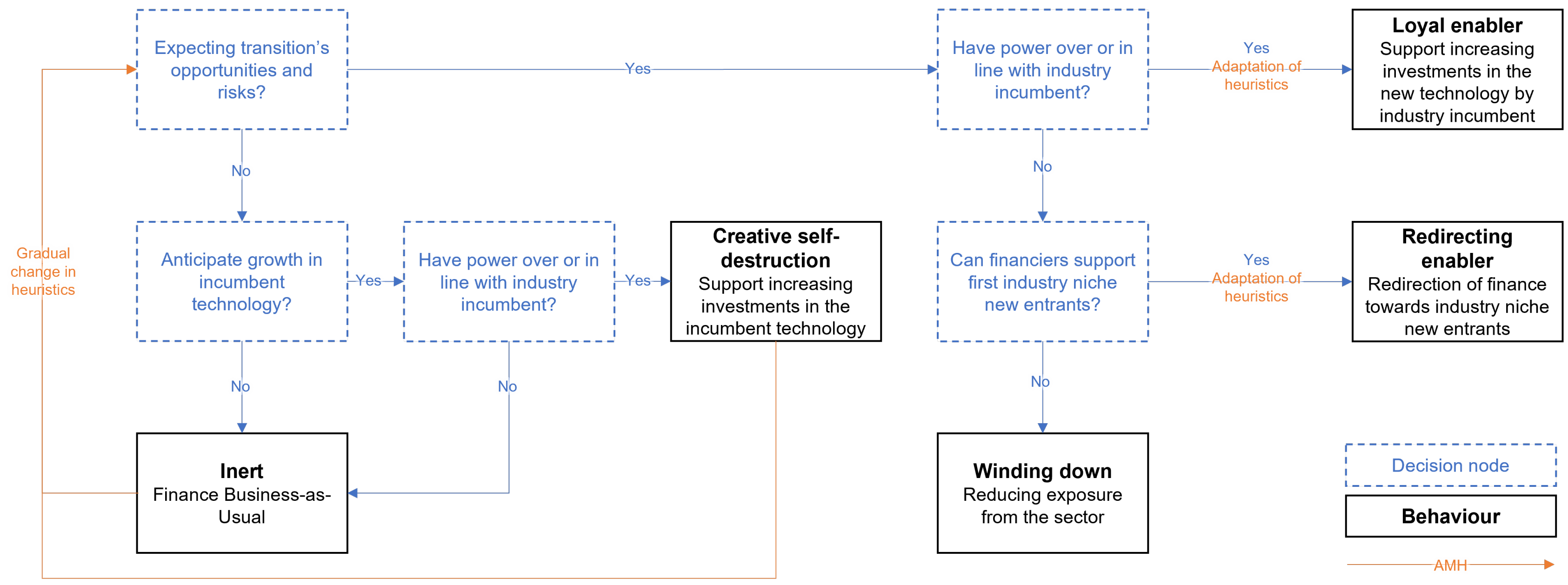

Figure 5.4: Schematic representation of the extended MLP framework.

(a) The above figure should be read from top left to bottom right. The black boxes represent the possible behaviours that financiers (either niche or regime) can adopt while an industry transition unfolds.

5.3 Discussion

This chapter presents a novel and extended theoretical framework to comprehend the role that financiers play in sustainability transitions. This framework is based on the Multi-level Perspective to explain an energy transition and the Adaptive Market Hypothesis to explain how financiers adjust their expectations after a breakdown in heuristics. It directly builds on the existing literature in two ways: first, it builds on the work of Urban and Wójcik (2019), which considers finance as being made of the three levels - landscape, regime, and niche - itself; second, its construction made sure the empirically observed behaviour of financiers in other industries fit into those categories (for example the work of R. Bolton and Foxon (2015), Falcone et al. (2018), Ferguson-Cradler (2022), Geddes and Schmidt (2020), Geddes et al. (2018), Geels et al. (2016), S. Hall et al. (2016), Hughes and Downie (2021), Kern (2012), Kungl and Geels (2018), Monk and Perkins (2020), Seyfang and Gilbert-Squires (2019), Stenzel and Frenzel (2008), Urban and Wójcik (2019), Yip and Bocken (2018), and F. Zhang (2020) described in Section 2.1.3 of the literature review). The framework's theoretical contribution to the literature is the classification of financiers into five archetypes to consider the diverse range of financing behaviours observed in the empirical literature of other industries and their adaptive nature, which is not taken into account in extended MLP frameworks. By doing so, it fills a theoretical gap in the literature and in particular of the MLP, which depicts finance as a passive and neutral resource without agency, and lacks an explanation for the diverse range of behaviour observed in the literature, for example, within the framework of Geddes and Schmidt (2020) and Urban and Wójcik (2019). However, Naidoo (2019, 2020) demonstrated that finance is not neutral, but should be analysed through a behavioural lens.

This chapter was limited in several ways. First, since this chapter is purely theoretical and based on a literature review, further research is needed to examine the validity and usefulness of this theoretical framework to study the behaviour and expectations of financiers during socio-technical transitions. This is the objective of the next chapter. Furthermore, the theoretical framework does not provide information on the evolution of the behaviours in time and in particular on the timing of their evolution. For example, let us consider the hypothetical case of a transition by substitution, where niche new entrants gradually replace incumbent industry players who are themselves initially financed by a set of incumbent financiers. In this hypothetical transition, let us assume that, after some time being Inert, the financiers are able to support the niche new entrants, and therefore play a ”Redirecting Enabler” role. When would incumbent financiers realise that a transition is underway (box ”expecting transition’s opportunities and risks?” in Figure 5.4a)? When would they start redirecting their investments towards the niche new entrants? The answers to those questions are likely critical in determining the amount of stranded assets or at least in determining the amount which is passed onto the financiers (stranded paper). This study provides the basis for further empirical work needed to understand these issues.

Regarding research question 3, ”How could the expectations of financiers of upcoming low-carbon transitions in shipping evolve during shipping low-carbon transitions ?”, this chapter provides a range of possible behaviours that shipping financiers might adopt as the transition unfolds. For example, they might choose to continue financing conventional-fuelled ships (Inert) or even push their clients for increased investments in fossil-fuelled ships doomed to be stranded (Creative Self-Destruction). On the contrary, they might choose to support their existing clients to be first movers in the transition (Loyal Enabler), or rethink their business relationships by redirecting their support from incumbent clients to new ones (Redirecting Enablers). Finally, they might chose to reduce their involvement in the sector, for example if they saw that the financing instruments they provide are not well adapted to the upcoming shipping clean technologies (winding down), possibly to be replaced by new financier players.

The next chapter explores which of the behaviours is currently adopted by shipping financiers. The behaviour to be dominant in the coming decade is not known, but its impact on how the transition to low-carbon shipping will materialise can be tested in a scenario analysis. This is the subject of Chapter 7.

Chapter 6

Exploring shipping financiers' expectations and behaviours at the outset of the low-carbon transition

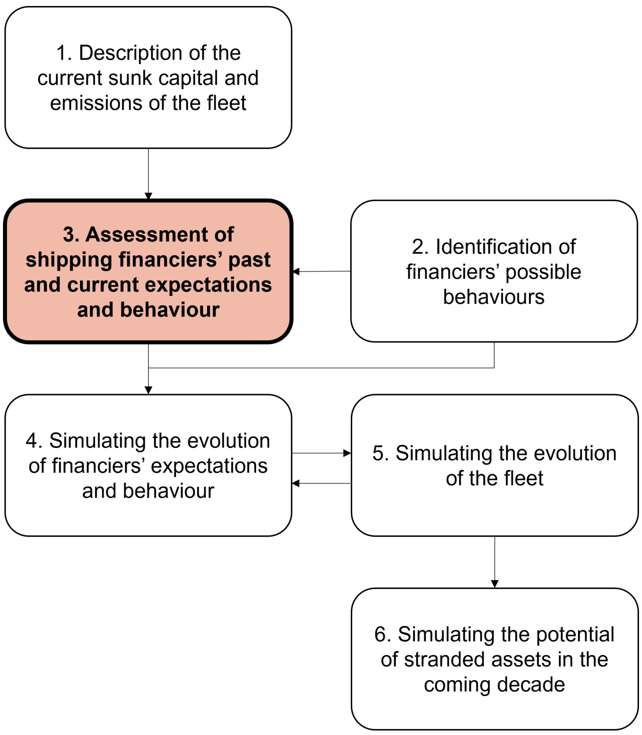

Figure 6.1: Sign-posting chapter 6: Assessment of shipping financiers past and current expectations and behaviour

This chapter aims to answer the second research question, namely: what are the current expectations of financiers regarding the upcoming shipping low-carbon transition? The purpose is to learn about the current beliefs and behaviour of external shipping financiers, as well as their evolutions over the past decade (Figure 6.1 shows where this fits into the thesis structure). A sequential mixed methods design is used (Creswell, W. John & Creswell, 2018), and it involves collecting quantitative data first and then explaining the quantitative results with in-depth qualitative data.

In the first quantitative phase of the study, a regression analysis is performed on a dataset of syndicated shipping loans to test whether the perception of climate performance affects loan margins. The quality of the existing instruments available to financiers to measure climate performance at the corporate (e.g. ESG metrics) and at the asset level (e.g. carbon intensity) is not investigated, nor their relative quality towards one another; but whether they have an influence on the pricing of shipping loans. More specifically, the regression tests whether climate performance measured at the asset level and the corporate level are reflected in the lending activity of lenders. The underlying assumption is that if lenders were assessing the climate performance of the assets for the companies they finance as a factor influencing financial resilience, they would incorporate such factors into a lower cost of debt. The regression tests whether this positive pricing of climate performance has increased since the Paris Agreement and with sectoral disclosure initiatives, namely the Poseidon Principles.

The second qualitative phase is conducted as a follow-up to the quantitative results to help explain the quantitative results. This exploratory follow-up intends to elicit financiers' transition-related beliefs to understand their role in sustainability transitions, by building a case study of shipping financiers. It is not within the scope of this chapter to predict how the transition to low-carbon shipping will unfold, but rather to look at the heuristics and intentions of financiers at the beginning of this transition. The case study therefore focuses on whether they anticipate opportunities or specific risks to their portfolios from the demand-side and supply-side transition to low/zero-carbon shipping.

Methods for quantitative and qualitative research are outlined in the next section successively. Section 6.2 will then go on to analyse the results, which are finally discussed in light of the literature in the last section. In particular, this last section discusses how the qualitative findings are helpful in explaining the quantitative ones.

6.1 Research methods

6.1.1 Quantitative approach

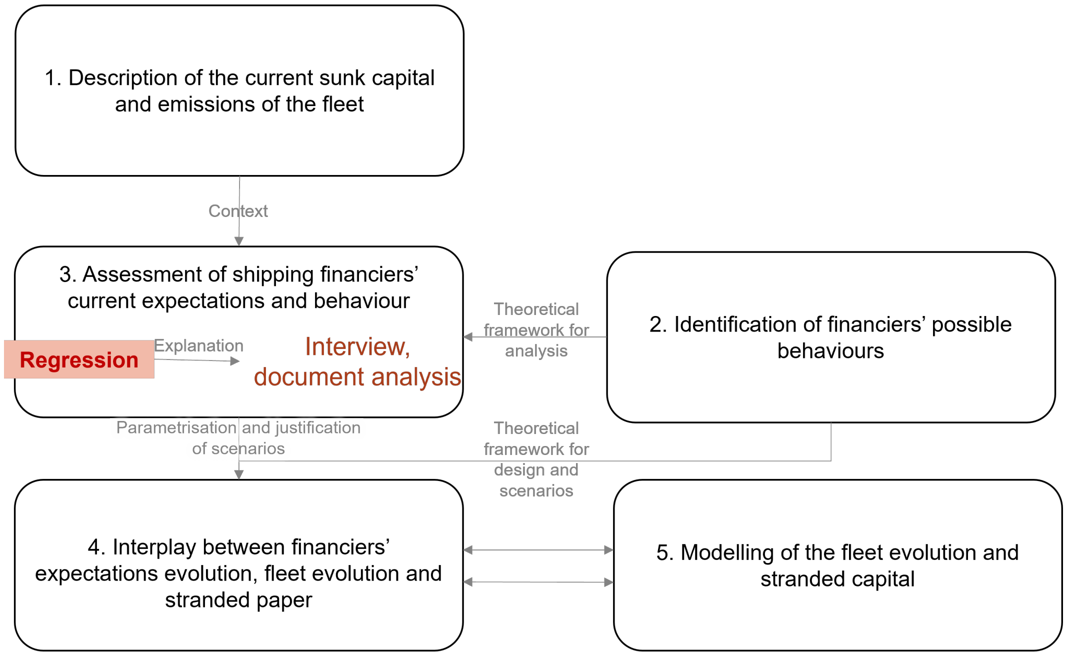

Figure 6.2: Sign-posting: Assessment of shipping financiers' current expectations and behaviour. Regression analysis.

Regarding the first quantitative phase (see Figure 6.2), in order to examine the potential influence of transition risks and climate performance on loan margins, an econometric analysis is conducted using a new dataset. This dataset is created by combining information from syndicated loans between 2010 and 2021, as provided by the Dealscan dataset, with data on associated shipowners and ships from Clarksons's WFR. The Dealscan database offers financial details on underwritten loans, including loan margins expressed as basis points above the London Interbank Offered Rate (LIBOR), as well as various loan attributes. The objective is to test for the following hypotheses:

H1: Borrowers with a higher climate performance receive better (lower) loans margins.

H2: Ships with higher climate performance attract better (lower) loans margins.

H3: The pricing of borrowers' climate performance increases after the Paris Agreement.

H4: The pricing of ships' climate performance increases after the Paris Agreement.

H5: The pricing of borrowers' climate performance increases when lenders have signed the Poseidon Principles.

H6: The pricing of ships' climate performance when lenders have signed the Poseidon Principles.

Next section describes the dependent variables used to represent the environmental performance, and justifies their choice. Section 6.1.1.2 outlines how the dataset of loans/ships financed was constructed. Finally, section 6.1.1.3 presents the regression model.

6.1.1.1 Choice of variables to represent climate performance

A[1] large range of tools and metrics are available to capture climate performance at company (e.g. climate performance of a borrower) (F. Berg et al., 2022) and asset level (e.g. the carbon intensity of a ship) (Parker et al., 2015).

Let us first look more closely at the variables used to proxy the corporate climate performance. The perceived climate performance of the company is proxied by the Carbon Disclosure Project (CDP) climate score. This choice is not intended to suggest that the CDP score, nor any climate performance metrics, is a good representation of the climate risks associated with a company. Indeed, the ability of current scores to represent the actual climate risks attached to a firm is largely debated. First, they fail to accurately predict future environmental performance and emissions (Levine and Toffel, 2009). Levine and Toffel (2009) shows that although

[1] This section is based on the Section "Experimental Procedures" and "Development of shipowners' financing costs" of the study "Lower margins are tied to companies environmental performance rather than to low-carbon assets". I am the main author of the paper and have drafted the first version of those sections, which have been reviewed by the other co-authors. The version used is not public and it addresses the comments received by the reviewers, hence the divergence with the online preprint version. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

the KLD (now MSCI) net environmental score does predict future pollution levels and regulatory penalties, its explanatory power is lower than those of lagged emissions, which suggests that it is not optimally aggregating historical dat. Furthermore, the environmental scores diverge between the rating agencies, mainly due to the divergence in measurement, which casts doubt on the reliability of the results (F. Berg et al., 2022). However, the objective of this Chapter is to study the impact of the perception of risk on the pricing of loans rather than the actual climate risks, so the choice of proxy for the perceived climate risk at the company level was driven by its use and perceived quality by financiers, rather than by its actual precision. The latter driver is ignored in the analysis.

Given these considerations, the CDP is chosen as a proxy for perceived climate risk at the company level for several reasons. First, the CDP offers one of the most comprehensive public databases of companies' climate performance, which contains scores for more than 13,000 companies based on their self-reported carbon emissions data and other factors such as governance and participation. Second, it is widely and freely available to lenders and is one of the oldest to be published, while other metrics are costly. Third, in 2022, surveyed investors ranked the CDP as the most useful (second most useful in 2018) and second most reliable rating (same in 2018) in a sample of 13 leading ratings, among which Sustainalytics, S&P and Bloomberg ratings, for example (SustainAbility, 2023). CDP scores are initially expressed from A (highest score), A, B, B- to E (lowest); they were coded from 0 (lowest) to 8 (highest) for the purpose of the regression. The robustness of the approach is tested by using an alternative proxy for perceived climate performance, i.e., a combined indicator equal to the Refinitiv environmental score – Refinitiv environmental controversies score. It is worth noting that this rating was ranked much lower by investors in terms of both usefulness and quality, so results should be taken with caution (SustainAbility, 2023).

The climate performance of each ship is proxied by its carbon intensity. Specifically, the Estimated Index Value (EIV) is used as the standard measure of the ship's carbon intensity. As of 2013, new ship designs are mandated that exceed a reference level corresponding to their ship type, known as the Energy Efficiency Design Index (EEDI). This benchmark is set to be progressively strengthened every five years. The objective of this regulation is to stimulate innovation and technical improvements in ship fuel efficiency. This study uses the Estimated Index Value (EIV), which is an approximation of the EEDI and measures an existing ship's design carbon intensity as if it operated at design speed, in calm water, and fully loaded. It therefore ignores the operation of the ship[2]. However, the real operating conditions of a newbuild ship would not be known to lenders, and hence they would need to rely on the design efficiency. Fleet efficiency has increased over time as a result of high fuel prices rather than regulation (Faber et al., 2016), so that younger ships are on average more energy efficient than older ones (Ross and Schinas, 2019). In addition, larger ships have on average a lower carbon intensity than smaller ships; the ship type has a large impact on the carbon intensity (Ross and Schinas, 2019). As a result, the carbon emissions of the ship per deadweight are highly dependent on the type of the ship, i.e. whether it transports passengers or commodities, and in the latter case which cargo is transported, and on the size of the ship, so using it directly might bias the results. To control for these variations, the difference in the carbon intensity for each ship relative to its cohort was used as a proxy of the ship's transition risk, rather than its absolute carbon intensity, as follows:

$$CI_i = (EIV_i - EIV_{szt})/EIV_{szt} \tag{6.1}$$

with EIV_i the carbon intensity of the ship which is part of the peer group defined by ship type s, size bin z and built in year t. Finally, since more than one ship could be associated with a loan, the transition risk of a loan is computed as the average carbon intensity of its associated ships.

The robustness of the results to the choice of metrics are controlled by running

[2]While there is publicly accessible data that provides an estimate of a ship's technical efficiency at the time of construction, the efficiency of a ship in its designed condition at age 0 may not precisely align with its operational efficiency. This discrepancy arises because the formula (EEDI) involves certain assumptions about parameters. The EEDI is gauged based on the design speed and specific fuel consumption, both of which play a crucial role in determining efficiency (Parker et al., 2015).

the model using two alternative metrics. First, shipowners have to measure the Annual Efficiency Ratio (AER) of the ship above 5,000 gross tonnage to comply with the DCS introduced by the IMO. This indicator measures the CO2 emissions of a ship divided by the product of its capacity and the distance sailed per year, thus capturing transition risks at asset (ship) level. Since the introduction of the Poseidon Principles, the AERs of the ships are widely collected and scrutinised by shipping lenders, as acknowledged by the interviewees. As DCS data is confidential to the shipowner and requires the consent of the shipowner to be shared, estimated data for EIV/AER was taken from the UMAS Fuel Use and Emissions (FUSE) model, which uses satellite and terrestrial AIS data to calculate speed, fuel consumption and CO2 emissions (UMAS, n.d.). Second, the effect of having energy-saving technologies installed onboard ships on the margins is looked at. A variable that corresponds to the share of ships financed by the loan that are equipped with one energy-saving technology on the ship is included, as indicated in the Clarksons WFR. In the sample, those include propeller ducts, rudder bulbs, propeller boss cap fins, and wake equalising duct. The results of this sensitivity analysis are presented in the appendix D.1.

Our empirical analysis focusses on syndicated loans that have been provided between 2010 and 2021 to companies that own at least one ship. The transaction data for the loans are sourced from Dealscan, which collects information on underwritten loans. This database provides various information on the loans, including all-in-spread-drawn, the lenders, tranche amount, loan conditions (repayment type, tenor etc) and the borrower. The subset of this database where the borrower owns at least one ship is selected by matching the borrowers to the shipowners of the Clarksons WFR database, which provides information on the ships owned and the shipowners.This overall dataset of loans awarded to shipowners over the period includes 18,747 observations corresponding to 808 combinations (unique borrower, deal amount, date of deal), called “deals” in the rest of the chapter. There are more observations than deals in the dataset because one deal is often divided into tranches with differing loan conditions and each tranche is financed by several lenders. One lender × tranche combination constitutes one observation.

Shipowners can borrow money through corporate finance to finance various purposes (e.g. general purpose, takeover, restructuring), not only to finance ships. The climate performance of the borrower might have an influence on the pricing of any of those types of loans; however the impact of the climate performance of the ship can only be measured when the link between the loan and the asset is clear, i.e. in the case of ship finance. Two overlapping samples are built:

- A ship finance sample (Sample 1) that only includes loans whose purpose is specified as "ship finance", and where the ship(s) financed could be identified (see next section for how they were identified) using a non-recourse structure, typically a Special Purpose Vehicle (SPV); or via traditional recourse loans. SPVs are included in the sample and identified as they were marked as "Special-purpose co", "Project, Special-purpose co" or "Infrastructure SPV" in the Dealscan borrower type.

- A corporate finance sample (Sample 2) which includes any loans given to shipowners, no matter their specified purpose, and where the borrower had a CDP score. However, project finance loans and loans raised through a SPV are excluded from this sample.

Those samples are used to test the pricing by lenders of the perceived climate performance of the company (Sample 2) and of the perceived climate performance of the asset, i.e. the ship (Sample 1). The sizes and the overlap of the samples are showed on Figure 6.3.

A summary of the composition of the two samples can be found in Table 6.1 (second-hand ships, secured, project finance and short maturity) and in Appendix D.3 (deal purpose, repayment type, shipping segment, shipowner size). Most of the loans in Sample 1, and all the loans in Sample 2 by construction, concern recourse loans without the use of an SPV. Most of the loans in Sample 1 are secured by a collateral, which is in line with Stopford (2009) which argues that ship finance loans typically are. On the other hand, the minority of the loans in Sample 2 is, which

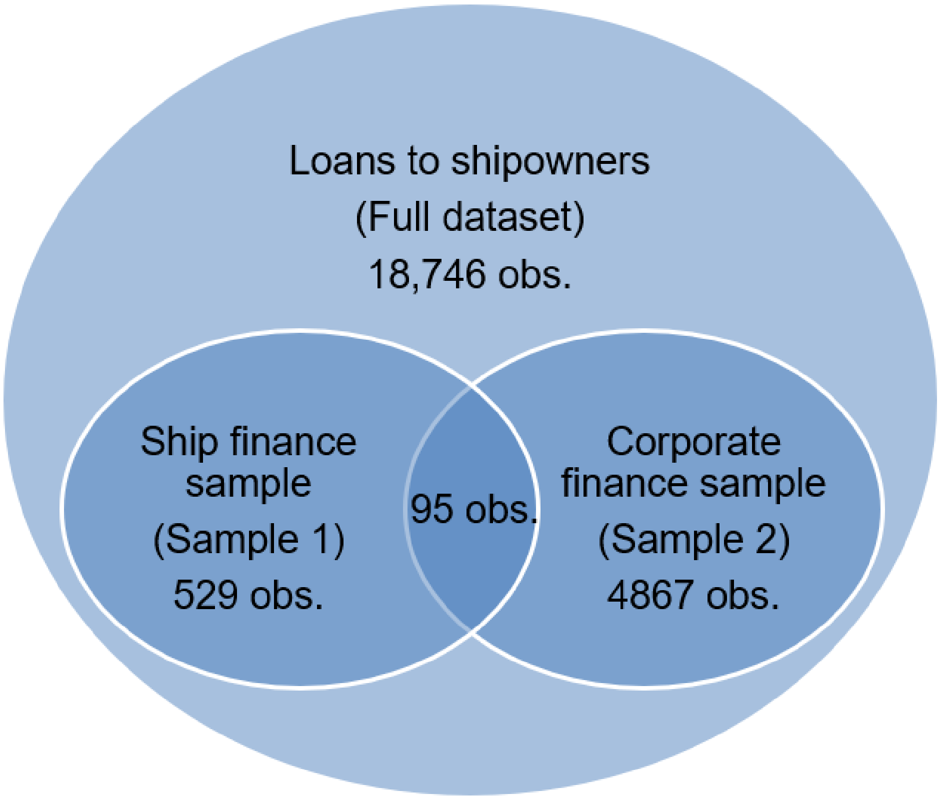

Figure 6.3: Observations per sample

(a) Counts are showed after removing the observations where borrower-related financial information (e.g. leverage, profitability) are missing, as they would be excluded from the regression in Stata.

Table 6.1: Summary statistics of the dummy variables

Variable	Level	Sample 1	Sample 2	Full dataset
Short maturity	0	498	1633	7847
	1	31	3234	10899
Project finance	0	468	0	18461
	1	61	4867	285
Collateral	0	48	4340	14544
	1	481	527	4202
Second-hand	0	402		
	1	127		
SPV	0	483	4867	18471
	1	46	0	275
Poseidon Principles	0	512	4769	18389
	1	17	98	357

(a) Counts are showed after removing the observations where borrower-related financial information (e.g. leverage, profitability) are missing, as they would be excluded from the regression in Stata.

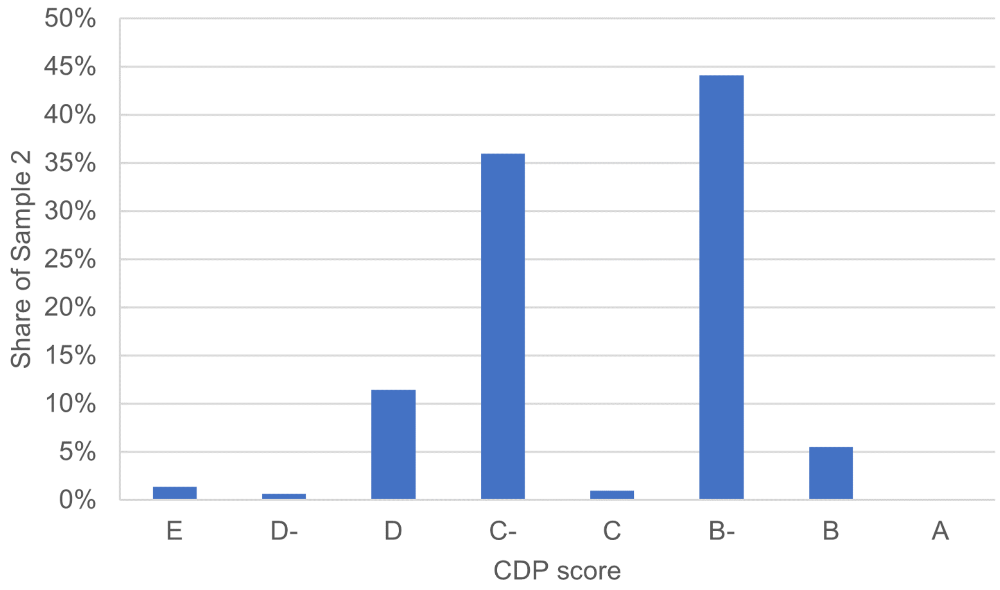

Figure 6.4: Distribution of loans by CDP score in Sample 2

(a) Counts are showed after removing the observations where borrower-related financial information (e.g. leverage, profitability) are missing, as they would be excluded from the regression in Stata.

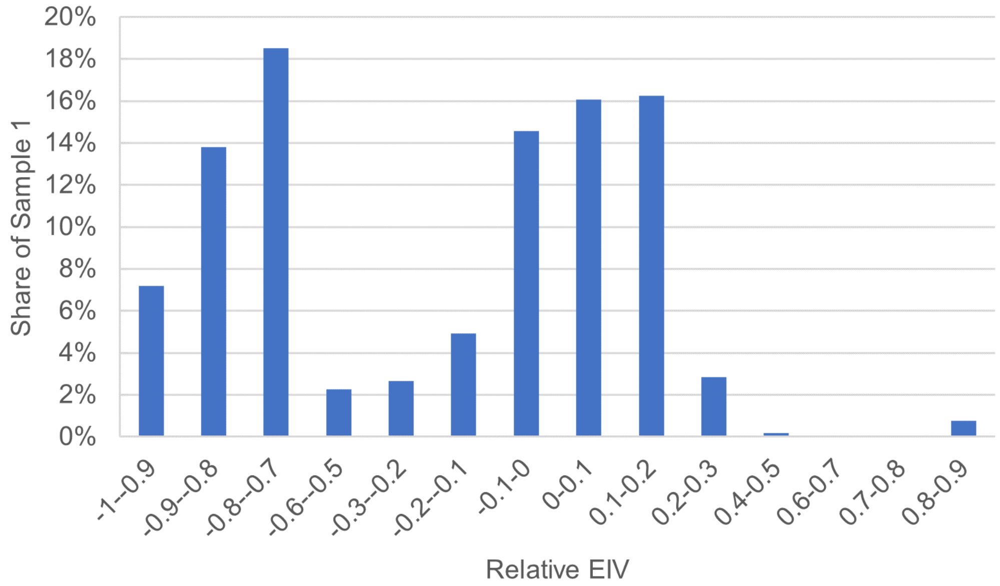

Figure 6.5: Distribution of relative EIV in Sample 1

(a) Counts are showed after removing the observations where borrower-related financial information (e.g. leverage, profitability) are missing, as they would be excluded from the regression in Stata.

suggests that most of this sample is not dedicated to ship finance. The majority of Sample 1 concerns newbuilds. This bias might be explained by two reasons. First, they are more easily identified when matching ships to loans (see details on the process in the next section). Second, the dataset might be biased towards newbuilds, as it only includes syndicated loans, which are usually used to finance larger transactions. Finally, only a minority of the loans have been provided by Poseidon Signatories. This is because the Poseidon Principles were introduced quite late in the period of the sample (2019), and that there are more data points before 2015 than after 2015 (see Appendix D.3). Figure 6.4 shows that most of the borrowers in Sample 2 have scores ranging from B to D, with few having really poor scores (E) and none reaching the top score (A). Figure 6.5 shows that Sample 1 includes a large range of carbon intensity, with some loans financing ships nearly twice as carbon intensive as their cohort's average (relative EIV > 0.8), and many ships having a very low carbon intensity, with EIV 70 to 90% lower than their cohort's average. A slight majority of ships have a carbon intensity close to average (up to 20% more/less carbon intensive than the average), but given the large amount of very efficient ships in the sample, it is somewhat biased towards more efficient ships, with EIV being on average 30% lower than the ships' cohorts'.

6.1.1.2 Loans-ships matching algorithm

Turning now to the construction of the dataset, due[3] to confidentiality issues, the Dealscan dataset does not identify the ship(s) which were financed by each loan, as lenders are sometimes unwilling to publicly disclose which ships they have financed and related financial terms. Because it is not publicly known which ships are financed by each loan, the construction of the dependent variables representing the transition risk requires the development of an algorithm to match individual ships to the loans. This algorithm is given more detail in this section.

Data on existing and ordered ships was collected on Clarksons WFR, and data

[3]This section is based on the Section "Experimental Procedures" and "Development of shipowners' financing costs" of the study "Lower margins are tied to companies environmental performance rather than to low-carbon assets". I am the main author of the paper and have drafted the first version of those sections, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

on loans were taken from Dealscan dataset. There is no direct correspondence however between ships listed in Clarksons WFR and the loans listed in Dealscan. An algorithm is developed to provide a "best guess" of which ships were financed by specific loans. This algorithm can be broken down in three steps:

- First, the correspondence between the list of borrower companies from Dealscan, and shipowners from Clarksons WFR, was built.

- In parallel, for many loans, the exact ships financed could be identified based on qualitative data given in Dealscan. Using this subset, the average time lag between 1/ the active date of the loan and 2/ the ship build date of the ship, was calculated.

- Finally, the ships were attached to single loans by matching shipowners/borrowers and build dates/loan active dates.

Figure 6.6 shows how Steps 2 and 3 were carried out. The following paragraphs describe in more detail the three steps.

Matching borrowers to shipowners In the first step, the algorithm identified the correspondence between:

- Borrowers in Dealscan, identified by the website provided (when available), the stock exchange name (when listed and provided) or their name; and

- Shipowners and shipowner groups in Clarksons WFR, identified by the website provided (when available), the stock exchange ticker (when listed and provided) or their name.

When an exact correspondence was found between either website, stock exchange name or names (in this specific order), those were automatically matched. For the others, an algorithm was run on the list of names to find the closest possible names, and the results were manually checked to find the correspondences between borrowers/shipowners or borrowers/shipowner groups. Note that this step probably missed some correspondences, when the company had changed names for example, but there is confidence that the correspondences found were properly matched. The step was very time-consuming and a total of 338 borrowers/shipowners correspondences (with ships, owners, owner groups or former owner) were identified. Those borrowers were identified as "shipowners", and the loans which they were awarded constitute the sample of corporate loans. Those shipowners have obtained 808 loans from 2010 to 2021 in the sample corresponding to $1,053bn.

Manual sample construction and statistics on the loans-to-built lag Once a ship has been contracted at a shipyard (contract date in the following), shipowners typically need to make pre-delivery payments to the shipyard, which may be covered by a pre-delivery credit if it has been arranged, or by the shipowner's own funds (Stopford, 2009) and a post-delivery payment, which is often the largest payments and is made on delivery of the vessel (build date in the following). The latter is typically obtained from commercial banks loans, leasing or shipyard credit scheme (Stopford, 2009). If pre- and post-delivery payments are covered by banks loans, it would have been agreed beforehand in a loan agreement.

To explore the timing between the contract date, loan active date and the build date, the ships which have been financed are first manually identified for a sample of loans. For some loans, a special vehicle was created to act as a borrower for one specific ship. Those loans have been identified because the name of the borrower is the same as the name of the ship or the hull, and the loan purpose is "ship finance". Furthermore, most of the loans categorised as "ship finance" contain qualitative information in the columns "Deal Remark", "Tranche Remark" and "Purpose Remark". This information often directly mentions the ships financed, either by their names, or by giving characteristics such as builder, ship type, size, build date and number of ships financed. When this information was sufficient to uniquely identify the ships described, it was matched. The combination of those two methods allowed a manual matching of loans to ships to be built, which is called "list of loans-ships 1" in Figure 6.6.

Furthermore, this sample was used to identify some characteristics related to the lag between the date at which the loan was active and the date at which the ship was built, which were used in step 3. The average and standard deviation of this lag lag_{mean} and lag_{std} could be computed. One could also use the lag between the ship contract date, and the loan active date. However, it appeared that the loan deal date was closer to the build date than the contract date; and that the dispersion of loan-to-deal lag was larger than the contract-to-deal lag. Based on this, it was considered that the lag between loan date and build date was a more robust indicator.

Matching ships to loans Apart from the loans clearly identified, it was not possible to find a direct correspondence between the ships and a loan. For those deals, ships were matched to each of the loans where the ship build date was found to be close enough to the expected build date from the loan data. The date was considered "close enough" when they met one of the following two criteria:

- Criterion 1: select all ships of the shipowner where the below two conditions were met: $date_{built} \in [date_{deal} + lag_{mean} - lag_{std}, date_{deal} - lag_{mean} - lag_{std}]$ With lag_{std} the standard deviation of the lags of the identified loans.

- Criterion 2: select all ships of the shipowner where the debt deal is reached between the date at which the ship is contracted to the shipyard, and the date the ship is built: $date_{contract} > date_{loan} > date_{built}$ With $date_{contract}$ the date at which the ship is contracted to the shipyard, from Clarksons WFR.

Before being added to the list of loans-ships 2 (see Figure 6.6), the results were manually checked against the qualitative data included in the deal remark, tranche remark and purpose remark. When the ships identified did not correspond to the remarks, when the remarks did not give any information on the ships, or when the loan covered not only ships but other transactions, the loan was not included. For example, they might be of the wrong segment, or built by another shipyard than mentioned. When the ships identified corresponded to the qualitative information contained in the loan's remarks, but more ships were identified than expected based on those remarks, they were added onto the list of loans-ships 2 only when their characteristics to be included in the regression (size quintile, age, segment) were identical.

Resulting dataset As a robustness check, a key lender validated the data matching process on a sample of transactions representing $7.5bn or 2% of the total underwritten shipping loans (calculated based on the portfolio of the top 62 shipping banks in 2021 from Petropoulos (2021)). This lender confirmed that the algorithm uniquely matched almost all transactions with the respective ships (90%), showing the validity of the approach. However, the sample of loans reported in Dealscan covers only a small part of the total loan activity (roughly 10% according to the person validating the sample), and is especially scarce after 2019.

The total amount provided to finance ships reported in the full dataset is $69bn, which is roughly 15% of the total shipping debt over the period (total $440bn calculated from Petropoulos (2021)). For 104 of the 224 ship finance deals, no ship could be matched, or the loan was not only used for ship finance. For a further 30 deals, EIV data was not available because there is no past observation yet. The remaining sample of observations used for the regression covers $30bn of debt provided.

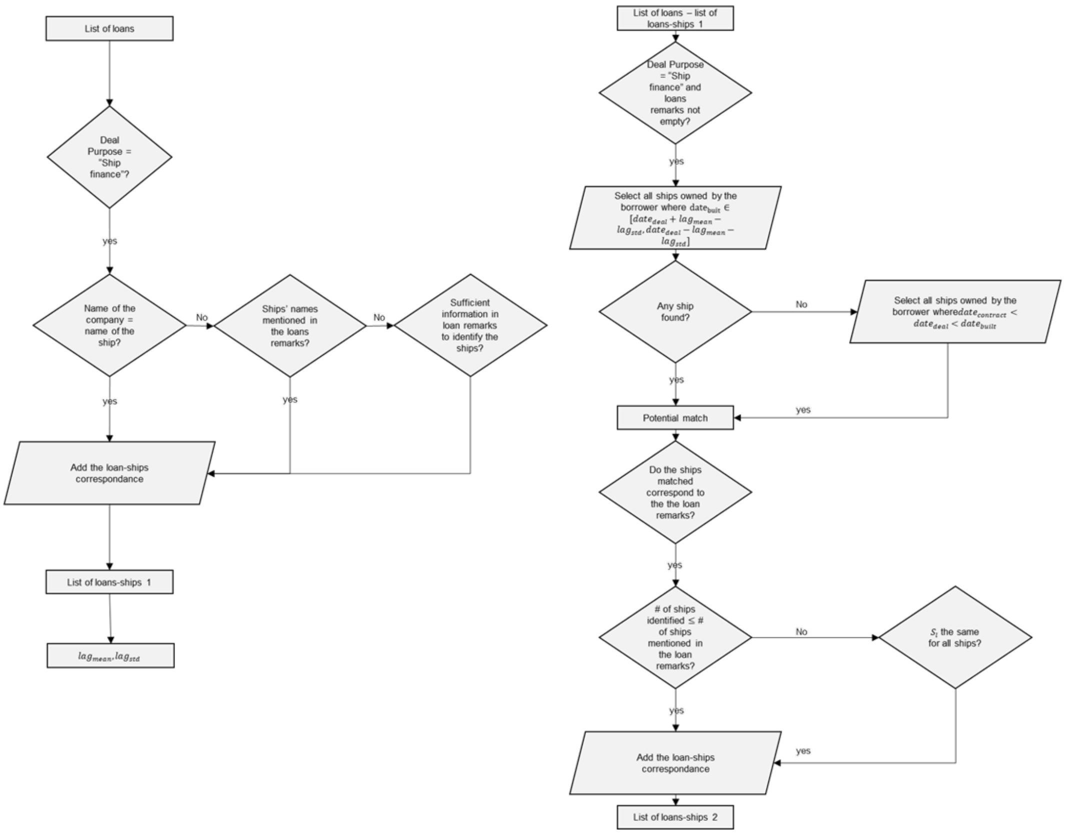

Figure 6.6: Graphic representation of the loans-ships matching algorithm

6.1.1.3 Regression model

Let[4] us now turn to the choice of regression. The dependent variable regressed is the all-in-spread drawn (AISD) of the loan, i.e. the basis points (bps) over the LIBOR. Note that one unique loan transaction (defined by a unique date-borrower combination) can correspond to several data points if more than one lender is lending and/or various loans characteristics (L_l) are applied. Typically, a loan can be made in two tranches with two different margins (called "all-in-spread-drawn", AISD in Dealscan) and tenors; each tranche is usually financed by more than one lender. The various data points corresponding to a single loan then have the same borrower- and ship-related information.

The empirical model used is described by the equation below:

$$AISD_{lbft} = \alpha_0 + \alpha_1 EV_l + \alpha_2 EV_l \times Post2015 + \alpha_4 L_{bft} + \alpha_5 F_{ft} + \alpha_6 M_t + \alpha_7 S_l + \varepsilon_{lbft} \tag{6.2}$$

with l subscripts indicating a unique loan deal, b the lender, f the borrowing company and t the time. EV_l stands for the climate performance, and corresponds to the carbon intensity attached to the loan, which is a function of the carbon intensities of the ships financed (EIV) or of the environmental rating of the borrower (CDP score). $Post2015$ is a dummy variable that takes the value 1 after 2015 (date of the Paris Agreement), 0 otherwise. L_{bft}, F_f and S_l are vectors of loan, borrower and ship characteristics that might affect the margin. M_t is a variable capturing the state of the newbuilding market. α_0 is a vector of fixed effects (year, borrower country and constant). ε_{lbft} is the remaining variation.

There is already an extensive literature on the drivers of loan margins for corporate loans, so that the control variables included in the model used on the corporate finance sample (Sample 2) were directly informed from those chapters (Delis et al., 2019; Kempa et al., 2021). The loan margin mainly depends on loan-, lender-,

[4] This section is based on the Section "Experimental Procedures" and "Development of shipowners' financing costs" of the study "Lower margins are tied to companies environmental performance rather than to low-carbon assets". I am the main author of the paper and have drafted the first version of those sections, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

borrower-, time-, and country- specific variables. The conditions of the loan and the financial characteristics of the borrower impact the price of the loan, as they are generally considered proxies for the potential risk that the borrower defaults (Chava, 2014; Delis et al., 2019; Huang et al., 2019; Kempa et al., 2021). Most shipping loans in the dataset are recourse loans, that is, if the loan defaults, shipping banks have the option to not only liquidate the financed vessels but can also use the borrower's other assets or income to recover the remaining amount. As a consequence, lenders place great importance on the financial strength not only on the collateral, but also of the borrower (K. R. Lee and Pak, 2018). Therefore, financial information on the borrower from Refinitiv-Eikon (profitability, size and leverage) are also included in the analysis. Time and country dummy variables further control for unobserved variables, e.g., the health of the market, which might also affect the riskiness of the loan. Finally, new buildings exhibit a distinct risk profile compared to second-hand assets and also receive a higher priority ranking in the credit system, so a control for the financed ships' age is included.

Regarding loan characteristics, the loan amount, tranche amount, number of lenders, collateral, repayment type (e.g. revolving loans, term loans), maturity, and a series of dummy variables representing loan purpose (e.g. general purpose, refinance, ship finance) are controlled for. Regarding borrowers' characteristics, company size (total assets), leverage (ratio of debt over assets) and profitability (ratio of return after tax on total assets) are included. Loan characteristics were taken from Dealscan directly; companies-related data are taken from Refinitiv-Eikon. The state of the ship price market by including 5 year old Clarkprice index is further controlled for. This indicator is provided by Clarksons SIN. It is calculated as a weighted average of five-year-old second-hand prices for the largest vessel types (oil tankers, bulk carriers, container and gas tankers) by the number of vessels in each fleet sector.

There is no econometric literature to my knowledge on the drivers of loan margins in ship finance. The Weighted-Average Least Square (WALS) procedure (de Luca and Magnus, 2011) is used on an original large list of variables to select a subset of controls. The initial list was compiled by including traditional margin drivers identified in the literature (those used in the regression model used on the corporate finance sample and tranche amount, a dummy for short maturity, a dummy for project finance and whether the borrower is an SPV and borrower's capitalisation) and additional variables that were suggested by the interviewed financiers (a ships' second-hand price index to represent market dynamics). The characteristics related to the ships are further included: the average age of the financed ships, the shipping segment of the ships financed; and the size quintile of the financed ships (the quintiles are calculated for each segment). After using the WALS procedure on the full list of variables, all those whose t ratio is lower than 1 in absolute value are removed from the list of original variables , as suggested by de Luca and Magnus (2011). The results of the WALS procedure can be found in the AppendixD.2. A series of dummy variables on the repayment types further added to the model, and tested for their joint significance by using a Wald test. The Wald test rejects the null hypothesis that the coefficients of those dummy variables are jointly equal to zero, so they are included in the final model. As capitalisation and company size are highly correlated, as shown in the correlation matrix in Appendix D.4, capitalisation is further removed, which barely affects the R-square of the model.

There might be further unobserved heterogeneity in the samples that might alter the results (omitted variables issues). To control for this, fixed effects for years and borrower countries are further included in both corporate and ship model specifications. Their joint significance are tested for through a Wald test on borrower country and time dummies. The Wald tests reject the null hypothesis at the 1% level for both corporate and ship model specifications that the coefficients of those dummy variables are jointly equal to zero. Therefore, those dummy variables are kept in the final model specification. Furthermore, the errors are likely to be clustered at the company (borrower) level, as argued in Kempa et al. (2021). The coefficients of the model are computed using an OLS regression with robust standard errors clustered at the company level, including time and borrower country dummies.

The logarithm of some control variables is used to improve the readability of the results (see details Table 6.2). The results of those should therefore be interpreted as follows: an increase in the independent variable by 1% increases the loan margins by $\alpha/100$ bps. Furthermore, a summary of the regression variables included in the model is provided in Table 6.2 and the summary statistics of the independent variables before the logarithm transformation in Table 6.3.

Table 6.2: Description of the regression variables

Name in Equation 6.2	Variable	Unit	Description	Source
	All in spread drawn (AISD)	Bps	Margin over LIBOR	Dealscan
Environmental performance (EV)	Carbon Disclosure Programme (CDP) score		The CDP scores were coded from 0 to 8 with 0 being the lowest (E) and 8 the highest (A).	Carbon Disclosure Project
	Refinitiv		Refinitiv environmental score (0 to 100)	Eikon-Refinitiv
	Relative Annual Efficiency Ratio (AER)		Ship Annual Efficiency Ratio relative to its cohort average AER.	Fuel Use and Emissions (FUSE)
	Relative Estimated Index Value (EIV)		Ship EIV relative to its cohort average EIV.	Fuel Use and Emissions (FUSE)
	Energy saving technology	Share of number of ships	Share of the ships financed which are equipped with at least one energy saving technology, as registered in Clarksons	Clarksons WFR
Loan characteristics (L_{bft})	Loan amount	Logarithm of loan amount, in million USD		Dealscan
	Tranche amount	Logarithm of tranche amount, in million USD		Dealscan
	Number of lenders	Logarithm of number		Dealscan
	Collateral	Dummy	Dummy equal to 1 if the loan is secured by a collateral.	Dealscan
	Repayment type	Dummy	Series of dummy variables corresponding to the type of repayment (e.g., revolving loans, term loans).	Dealscan

Name in Equation 6.2	Variable	Unit	Description	Source
	Loan purpose	Dummy	Series of dummy variables corresponding to the purpose of the loan (e.g., general purpose, refinance, ship finance)	Dealscan
	Performance	Dummy	Dummy equal to 1 if the loan includes performance pricing	Dealscan
	Poseidon Principles	Dummy	Dummy equal to 1 if the lender has signed the Poseidon Principles at the time of the loan	Poseidon Principles website
	Maturity	Logarithm of the tenor in months	Loan tenor	Dealscan
	Project finance	Dummy	Dummy equal to 1 if the loan is used in project finance	Dealscan
	Short maturity	Dummy	Dummy equal to 1 if the tenor of the loan <5 years	Dealscan
Borrower characteristics (F_{ft})	Company size	Logarithm of loan amount, in USD	Logarithm of the borrower's total assets	Eikon
	Leverage	Logarithm of ratio	Borrowers' total debt/total assets	Eikon
	SPV	Dummy	Dummy equal to 1 if the borrower is a special vehicle	Dealscan
	Profitability		Borrower net income (after tax profit)/total assets	Eikon
Assets characteristics (S_t)	Ships' size		Average quintile of ship size compared to ship segments	Clarksons WFR
	Age	Years	Average age of the ships financed at the time of the loan (0 for newbuilds)	Clarksons WFR
	Shipping segment	Dummy	Series of dummies corresponding to the shipping segment (chemical tankers, containers etc.) of the ships financed	Clarksons WFR
Market (M_t)	Second-hand price index	Logarithm of index	5-year old Clarkprice index	Clarksons SIN

Table 6.3: Statistics of the regression variables

	Obs.	Mean	Std. dev.	Min	Max
All in spread drawn (bps)	18,463	165	110	1	1,250
Carbon Disclosure Programme (CDP) score (E=0, A=8)	5,276	5	2	0	7
Refinitiv combined score	10,201	129	31	21	193
Relative Annual Efficiency Ratio (AER)	779	- 0.3	0.5	- 1.0	2.9
Relative Estimated Index Value (EIV)	779	- 0.2	0.4	- 1.0	0.9
Energy saving technology	846	0.3	0.4	-	1.0
Loan Amount (million USD)	18,744	3,260	4,670	9,98	45,000
Tranche Amount (million USD)	18,745	1,510	2,140	2	25,000
Number of lenders	18,705	26	22	1	94
Maturity (months)	18,685	45	32	-	722
Firm Size (million USD)	15,400	48,100	54,100	2,809,517	510,000
Leverage	14,774	0.4	0.2	0	1.7
Profitability	15,325	0.0	0.1	- 1.1	0.7
Newbuilding price	18,746	134	7	121	162
Age	940	1.0	3.5	0	40.0
Size quintile	830	4.3	0.8	1.0	5.0

(a) Variables are summarised before logarithm transformation.

6.1.2 Qualitative approach

Having discussed how to conduct the first quantitative phase of the explanatory research design, this section will now move on to discuss the second qualitative phase. Given that the research design is explanatory, the objective of this second phase is to explain the quantitative results: it focuses on the "why" – motivations and beliefs, values that drive people's actions, but also instruments and habits, not just the "what"what happened, although some qualitative results concern what has happened, from the point of view of the stakeholders, and can be used for triangulation.

The[5] second qualitative phase of this Chapter's mixed method approach (see Figure 6.7) follows a qualitative research design, using the thematic analysis method proposed by Braun and Clarke (2006) and Clarke and Braun (2013). Since the research questions concern financiers' beliefs and perceptions of their environment, the principal source of data for this work are interviews. The understanding of heuristics and intentions draws on data from 12 in-depth interviews with financiers, covering together around a quarter of the shipping debt, conducted between May and November 2022 (see Table 6.4). Eight interviews have been conducted with commercial banks active in shipping – including one State-backed bank with a mandate from the State – and 4 with asset managers, two of which are alternative lenders dedicated to the decarbonization of the shipping industry. It is worth noting that financiers 8 and 10 are effectively shipowners or ship managers who get some of their capital from asset managers. They provide a perspective on how asset managers and institutional investors view climate risks and make decisions, but their insights are not directly comparable to the findings from the quantitative phase, as they are not covered by the dataset of syndicated loans used in this phase. All interviewees but those two were mostly providing shipping debt to the industry, although some would also provide a range of products in addition to debt.

All commercial banks interviewed are represented in the quantitative dataset described in Section 6.1.1 used for the first quantitative Phase. Together, they represent 12% of the data points, and 16% of the loan amount. The qualitative data extracted from those interviews is therefore comparable with the quantitative data, and can be used to further explain the quantitative results of phase 1. However, one asset manager and the two alternative lenders are not represented in the quantitative dataset. This can be explained for financiers 8 and 10 by the fact that they do not provide shipping debt; and for interviewee AF1 by the fact that it started operating fairly recently, while the dataset covers fewer data points in the most recent year. There is no guarantee however that this financier would provide syndicated loans,

[5]This section is directly taken from the chapter "Exploring financiers' beliefs and behaviours at the outset of low-carbon transitions: a case study on shipping", section 3, whom I am the main author of. I have written the first draft of this section and it has been reviewed by the co-authors.

Table 6.4: List of interviews

Name	Type	Location	Poseidon Principles	Size	In quantitative sample?
CB1	Commercial bank	North America	Yes	\$5-10bn	Yes
CB2	Commercial bank	Western Europe	Yes	>\$10	Yes
AF1	Alternative financier	Western Europe	No	\$0-5bn	No
CB3	Commercial bank	Western Europe	Yes	>\$10	Yes
CB4	Commercial bank	Western Europe	No	>\$10	Yes
CB5	Commercial bank	Asia	Yes	>\$10	Yes
AM1	Asset manager	Western Europe	No	\$0-5bn	No
CB6	Commercial bank	Western Europe	Yes	\$5-10bn	Yes
AF2	Alternative financier	Western Europe	No	\$0-5bn	No
CB7	Commercial bank	Asian branch of a North American bank	Yes	\$5-10bn	Yes
CB8	Commercial bank	Western Europe	Yes	\$5-10bn	Yes

(a) The Poseidon Principles column represents the signature of the Poseidon Principles at the time of the interview.

(b) CB: Commercial Bank; AF: Alternative Financier; AM: Asset Manager

which constitute the quantitative dataset. Those financiers are not directly comparable to the quantitative data collected, and their views should be used not to explain the quantitative results, but rather to compare the beliefs and behaviours of the core actors (shipping lenders) with more niche and smaller actors.

Interviews were guided along a general interview guide (in appendix E.1) but were semi-structured to allow the interviewer to ask follow-up questions depending on the interviewee's responses. Data from a range of secondary sources were further collected to give some context to the case study and triangulate the interview findings, which provides some observations of past investment decisions of shipping financiers and explores the public communication of the financiers concerning their role in climate mitigation. Data for the top 20 shipping banks according to Petropoulos (2021) were collected and for all the financiers interviewed. News articles were collected by searching for the name of the bank and the keyword "shipping", "marine", "maritime" or "Poseidon Principles" for all articles published after 2007. Only articles which were related to shipping low-carbon transitions and to a specific financial deal, when mentioning the ship(s) or type of ship financed, were selected. In addition, ad hoc news articles were collected to confirm and expand the understanding of specific points mentioned by the interviewees during the interviews when the context was not clear. Public ESG/environmental/shipping reports and official communications related to shipping low-carbon transitions relating to those financiers, and the Poseidon Principles reports, using Google search, were collected. Finally, one financier agreed to provide non-public reports which they shared with their shareholders. 113 company reports and official communications, 235 newspaper chapters and 11 company reports shared with the companies' shareholders were collected and analysed. Finally, quantitative data on past shipping investments were collected to provide context to the narrative.

Our data analysis uses the thematic analysis method proposed by Braun and Clarke (2006) and Clarke and Braun (2013) and is conducted in two steps. First, high-level themes were built using the proposed theoretical framework proposed in Chapter 5. Second, interviews transcripts and collected secondary data were mapped to those high-level themes by "coding" them using NVivo software (top-down approach), but high-level themes were inductively adjusted to the internal logic of the data and detailed codes falling under each high-level theme were generated inductively (bottom-up approach). This second step is iterative, such the text is recoded as the detailed codes are iteratively developed. This method, also used in Kungl and Geels (2018), avoids artificial results which simply reproduce the theoretical categories. Both interview transcripts and secondary data were coded along the same high-level themes and detailed codes. The detailed description of each code is presented in Table E.1 in Appendix E.2. For example, the codes "Customer and charterer demand for low or zero-carbon shipping", "ESG as legitimacy demand from society to financiers", "Shareholder demand for ESG" are grouped under the sub-theme "Society & customer demand for climate mitigation". Relevant text parts were coded along each subcode.

The data coded was primarily interpreted qualitatively, by looking at the context in which an assertion was made, the past history of the company of the interviewee, how certain or nuanced the interviewee is when making this assertion – for example several interviewees would state that "I believe that X is unlikely to happen, but if it does happen, then I believe Y", or whether it was made spontaneously by the interviewee or to answer a follow-up question of the interviewer. When relevant, this was complemented by some quantitative analysis on the number of interviewees who mentioned a statement coded under a theme, and by the amount of times (words) an interviewee spent discussing this topic, which might reflect their interest or knowledge of the question. This quantitative approach is secondary to the purely qualitative approach.

The themes used to code the interview and the collected data are derived from the theoretical framework proposed in Chapter 5, as follows:

- A first set of themes cover the stickiness and evolution of the financiers' heuristics, in line with the AMH framework and with the framework proposed in Chapter 5. This Chapter distinguishes here between two types of heuristics, based on the coded data:
  - Beliefs: Those cover financiers' beliefs of the drivers of the transitions, such as the availability and risk of the incumbent and new technology and the strength of landscape pressures (policy, customer demand for example) behind the transition; and their beliefs on the role of incumbent shipowners (in green).
  - Financial tools and instruments : those include the tools and rules of thumbs used by financiers (e.g. the credit risk methodology adopted by each financier; the rule of thumb used to judge the quality of a transaction; and the financial instruments available to financiers).
- The roles of financiers in the transition to low/zero-carbon shipping are organised along the 5 ideal-typical behaviours proposed in Figure 5.4a.

The description of the themes and their underlying codes is detailed in Table E.1 in Appendix E.2. The following sections further explain the findings for both types of shipping transitions – demand-side and supply-side, and are organised along those three broad themes: beliefs on landscape pressures, financiers' behaviour in the transition and adaptation of the financial tools & instruments.

The numbering of themes is consistent with the one used in Table E.1 in Appendix E.2.

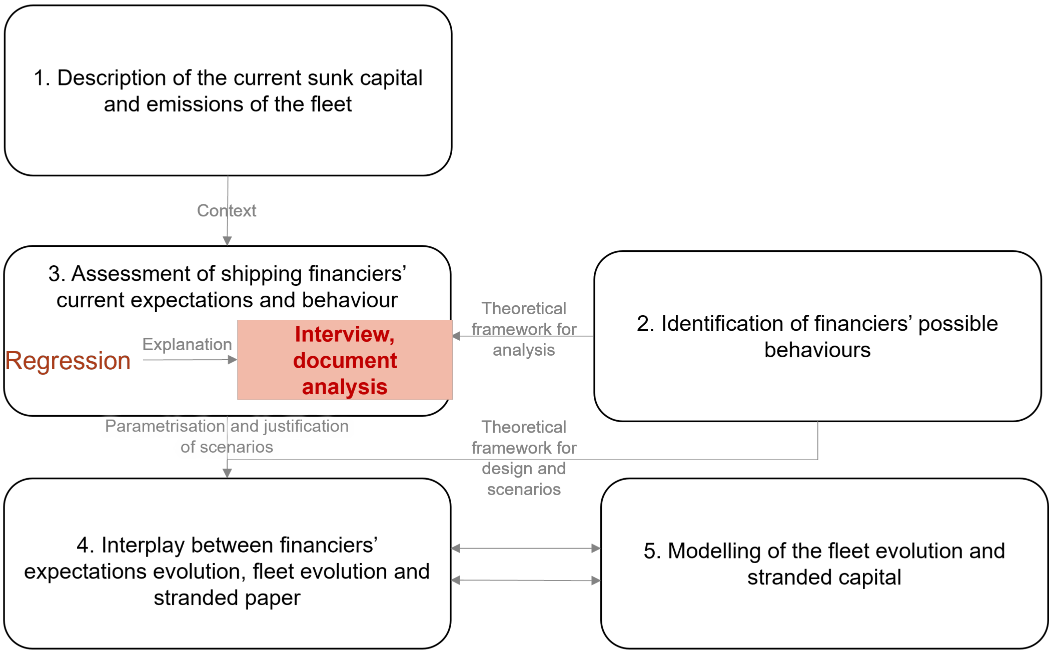

Figure 6.7: Sign-posting: Assessment of shipping financiers' current expectations and behaviour. Qualitative case study.

6.2 Results

Having described the methods used to answer the second research question, let us now turn to the results of the analysis. The next section describes the result of the first quantitative phase, and the following of the qualitative phase.

6.2.1 Quantitative findings

As a reminder, the hypotheses tested by the regression analysis are as follows: H1: Borrowers with a higher climate performance receive better (lower) loans margins.
H2: Ships with high climate performance attract better (lower) loans margins.
H3: The pricing of borrowers' climate performance increases[6] after the Paris Agreement.
H4: The pricing of ships' climate performance increases after the Paris Agreement.
H5: The pricing of borrowers' climate performance increases when lenders have signed the Poseidon Principles.
H6: The pricing of ships' climate performance increases when lenders have signed the Poseidon Principles.

The next section presents the results related to the pricing of climate performance and its evolution after the Paris Agreement (hypothesis H1 to H4). The following presents the results related to the influence of the Poseidon Principles on this pricing (H5-H6).[7]

6.2.1.1 Pricing of climate performance of the companies and ships assets

The Paris Agreement was a catalyst for increased ambition from the international finance community to align financial flows with climate priorities. This has led to increased pricing of climate performance on the cost of debt by lenders at the

[6] An increase in pricing of climate performance is equivalent to a decrease in the margin of a loan, where the climate performance is better

[7] This section is based on the Section "results" of the study "Lower margins are tied to companies environmental performance rather than to low-carbon assets". I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

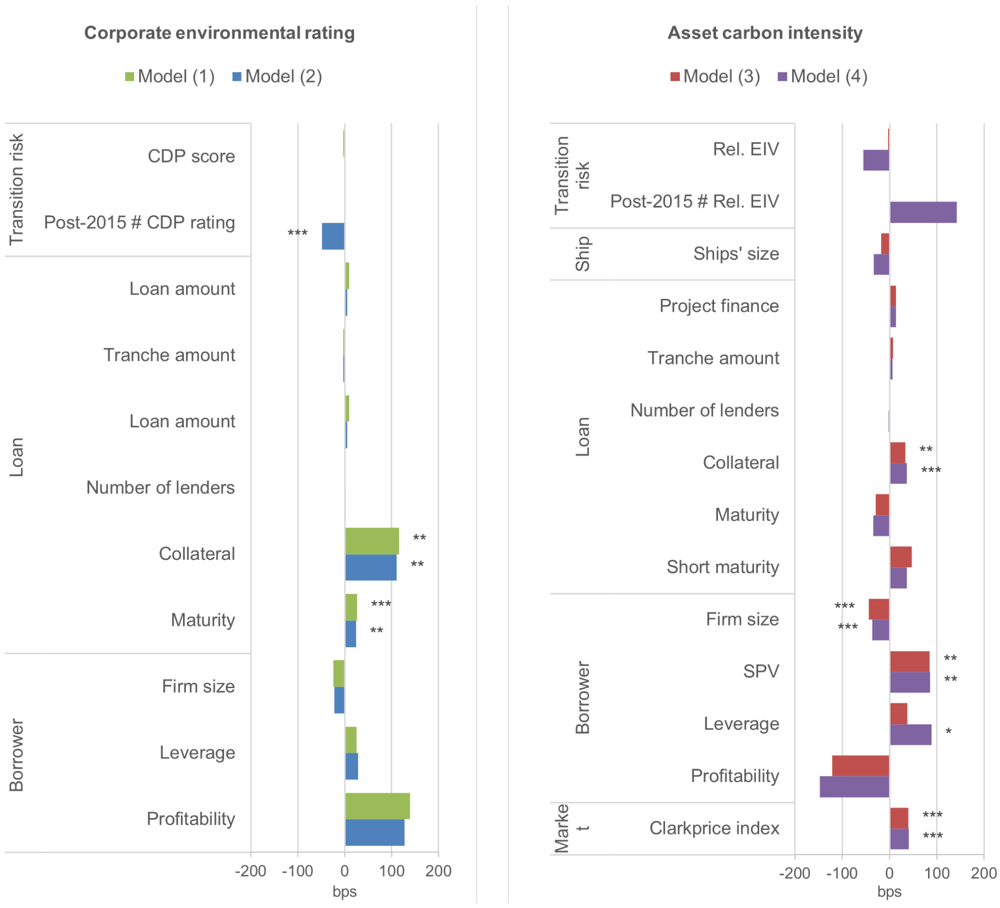

Figure 6.8: Corporate and asset climate performance, and cost of debt

(a) *P < 0.1, **P < 0.05, ***P < 0.01.

(b) The dependent variable is the loan margin.

(c) The regression coefficients plotted are estimated using the Ordinary Least Squares (OLS). The detailed results are in the appendix D.1, Table D.1

(d) The Carbon Disclosure Project climate change score is expressed as scores ranging from A (highest) to E (lowest) and was coded from 0 (lowest) to 8 (highest).

(e) The Estimated Index Value (EIV) is normalised by the average EIV of the cohort.

(f) Further controls of shipping segment (only in models (3) and (4)), loan purpose, repayment type, borrower country and year fixed effects are included in the models (see details results in Section 6.1.1.3). Estimates with robust standard errors clustered at the borrower company level.

corporate level (Figure 6.8).

Companies with a high climate performance attracted similar margins as companies with a low climate performance when using a sample covering all years in the time period (Figure 6.8 Model (1)). This suggest that hypothesis H1 is rejected. However, there is a clear increase in pricing after the Paris Agreement, which indicates that lenders have begun to price the climate performance of companies into the cost of debt (Figure 6.8 Model (2)). This shift is observed by including in Model (2) an interaction term between the companies' climate performance and a post 2015 dummy to capture the shift in pricing of corporate climate performance after the Paris Agreement, and by breaking the period between pre- and post- Paris Agreement (models (7) and (8)). This suggests that hypothesis H2 can be accepted. As a consequence, borrowers with higher climate performance started to attract lower margins only after the Paris Agreement (Figure 6.9).

However, carbon-intensive ships have attracted a similar cost of debt compared to their counterparts over the entire period (Figure 6.8 Model (3)), which suggests that hypothesis H3 should be rejected. From this, it appears that the carbon intensity of ships was ignored by lenders. There is no strong evidence of an evolution in pricing after the Paris Agreement, as the insignificant coefficient of the interaction term between the EIV and a post-2015 dummy in the Figure 6.8 Model (4)) suggests. As a consequence, hytpothesis H4 should also be rejected.

In addition, smaller borrower size is associated with higher margins, indicating increased risk on the loan. Furthermore, high risk transactions that need to be secured with a collateral have, on average, a cost of debt 0.3 to 1.1 percentage points higher (Figure 6.8 models (1), (2), (3) and (4)). For corporate financing, an increased maturity attracts higher margins (Figure 6.8 models (1) and (2)), but these do not appear to have a large impact on the cost of debt for ship finance only (Figure 6.8 models (3) and (4)). Surprisingly, a bullish second-hand ship market and higher profitability increase the loan margins (Figure 6.8 models (3) and (4)). This might be because, given the cyclical nature of the shipping industry, lenders expect grim future economic conditions when the market is high, and inversely. Another explanation would be that, during periods of high demand in the shipping market shipowners place orders for new ships, which increases the demand for loans. Consequently, as demand rises (with the supply remaining relatively constant in the short-term), banks are able to charge higher margins.

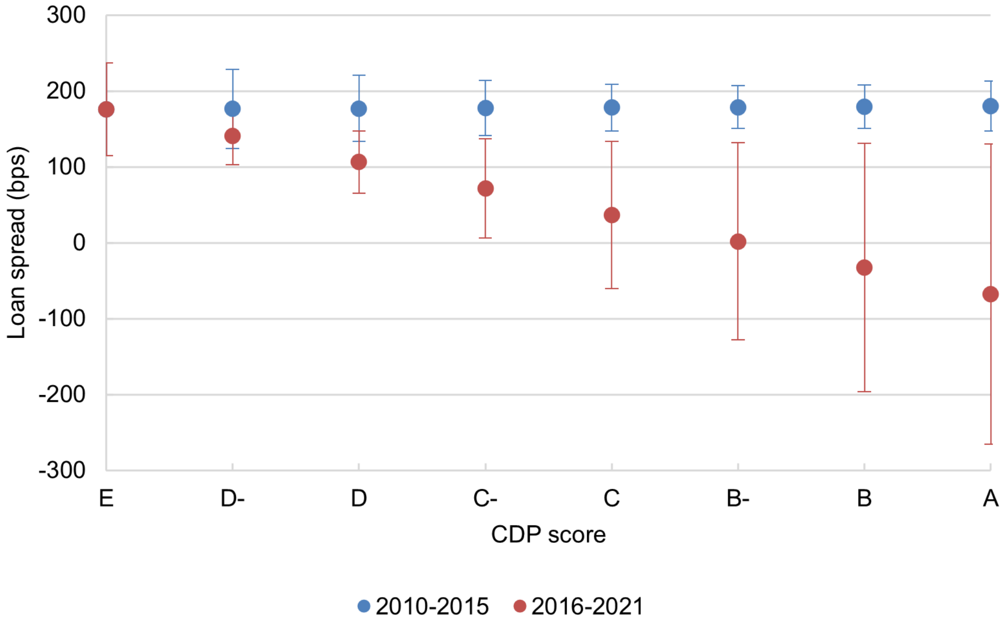

Figure 6.9: Company's climate performance, Paris Agreement and the cost of debt

(a) Effect of the dependent variable CDP score on the cost of debt before and after 2015, estimated using Model (2) in Figure 6.8 with 95% confidence intervals.

(b) The Carbon Disclosure Project (CDP) climate change scores were coded from 0 to 8 with 0 being the lowest possible climate performance and 8 the highest (A).

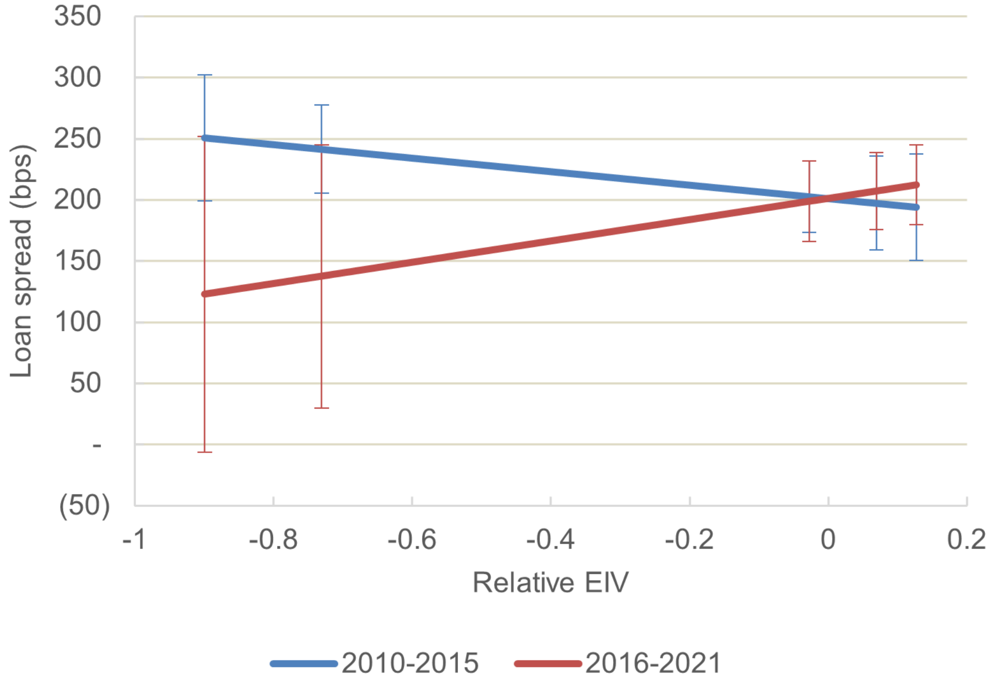

Figure 6.10: Carbon intensity of the financed ship assets, Paris Agreement and the cost of debt

(a) Effect of the dependent variable of the intensity of the carbon intensity of the ship on the cost of debt before and after 2015, estimated using Model (4) of Figure 6.8 with 95% confidence intervals.

(b) The relative carbon intensity is the Estimated Index Value (EIV) of financed ships compared to the average EIV of their year cohort.

(c) The predictions of the costs of debt were estimated for the 10, 25, 50, 75 and 90 percentiles of the relative EIV.

6.2.1.2 Effect of lenders' reporting commitments on margins

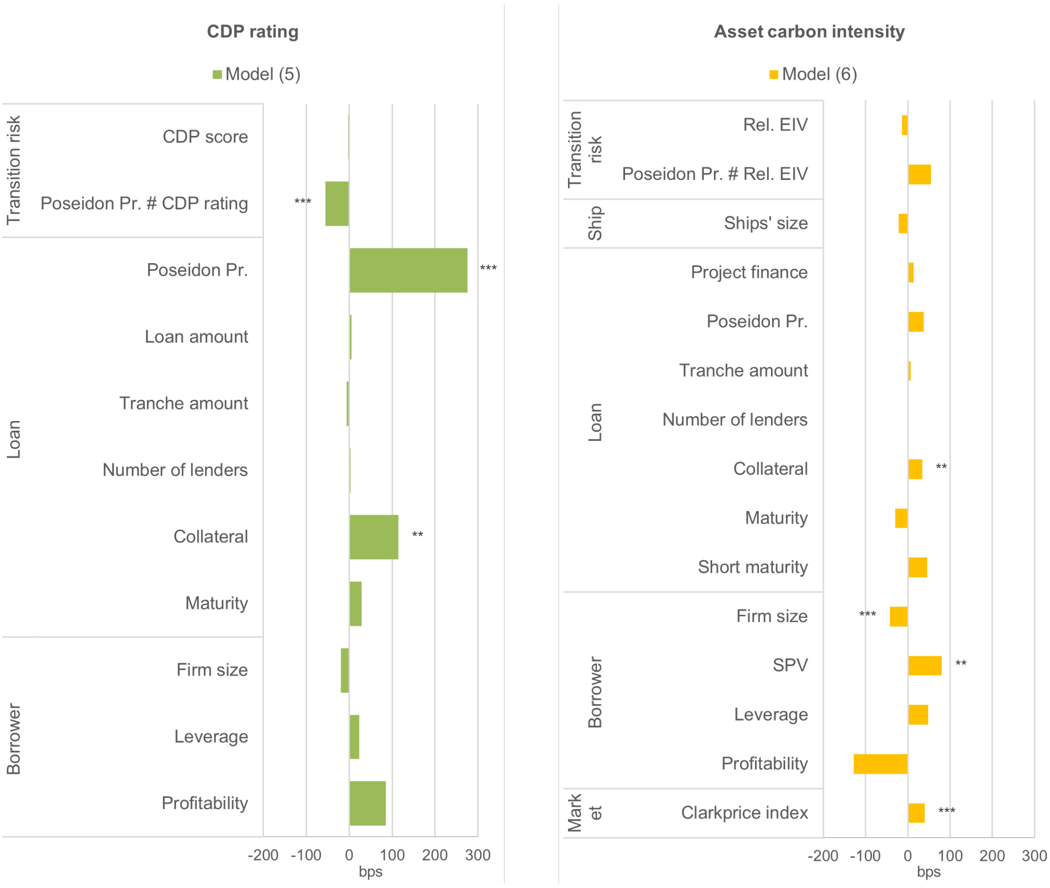

Figure 6.11: The role of lenders' commitments on the pricing of climate performance

(a) *P < 0.1, **P < 0.05, ***P < 0.01.

(b) The dependent variable is the loan margin. The regression coefficients plotted are estimated using the Ordinary Least Squares (OLS). The detailed results are in the appendix D.1, Table D.7

(c) Further controls of loan purpose, repayment type, shipping segments (only in Model (6)), borrower country and year fixed effects are included in the models (see detailed results in Appendix D.1).

(d) Estimates with robust standard errors clustered at the borrower company level.

(e) The Poseidon Pr. is a dummy variable which takes the value 1 when the lender has signed the Poseidon Principles, 0 otherwise. The relative EIV is the Annual Efficient Ratio compared to the years' cohort; the CDP is the Carbon Disclosure Project climate change score.

Whether lenders price the corporate and/or asset climate performance in loan margins might reflect emissions disclosure efforts. The Poseidon Principles allow us to investigate the impact of voluntary disclosure initiatives of lenders on the pricing of climate performance, since it is the first sector-wide alignment disclosure agreement with global coverage. This is done by including a dummy variable "Poseidon Principles" in the model which takes the value 1 if the lender has already signed up to the Poseidon Principles when the loan was issued.

The Poseidon Principles have a positive effect on the pricing of the company's climate performance (Figure 6.11). The scale of this effect is substantial: the lowest performing companies face a cost of debt 4 percentage points higher than the highest performing companies (Figure 6.12). Hypothesis 5 is therefore validated. However, the Poseidon Principles have a negligible effect on the pricing of the ship asset carbon intensity (Figure 6.12, Model (5); Figure 6.13). Hypothesis 6 should therefore be rejected. This suggests that the voluntary commitment to disclose its financed carbon emissions can have a concrete impact on investment decisions but is not ultimately reflected in the assets financed.

These results suggest that the climate commitments of lenders have translated into an increase in the price of the company's climate performance, but not of the transition risk of the asset. The expectation of the transition to low-carbon shipping had a concrete impact on lenders' behaviour, as they provided preferable conditions to shipowners with a higher climate performance. This is a clear incentive for borrowers to improve their climate performances and to be perceived as a more sustainable company. However, the results also suggest that even climate-proactive lenders are not expecting cascade effects of transition risks from the assets to their profitability, as they do not factor the transition risks of their assets into the pricing of the loans they provide.

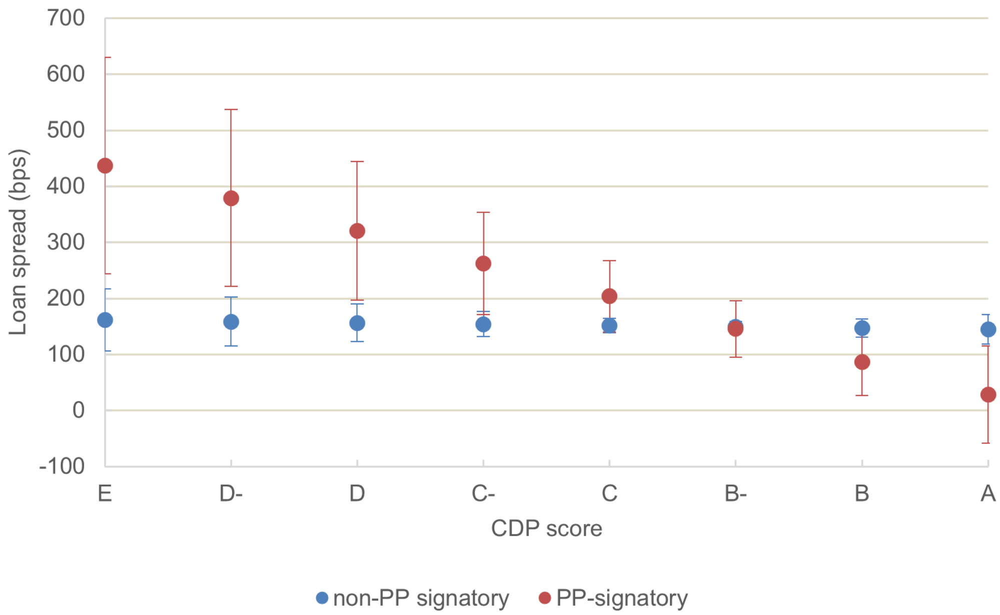

Figure 6.12: Lenders' carbon reporting commitment, company's climate performance, and cost of debt

(a) Effect of the dependent variable CDP score on the cost of debt estimated when lenders are Poseidon Principles (PP) signatories (red) and non-signatories (blue).

(b) The margins were estimated using Model (5) with 95% confidence intervals.

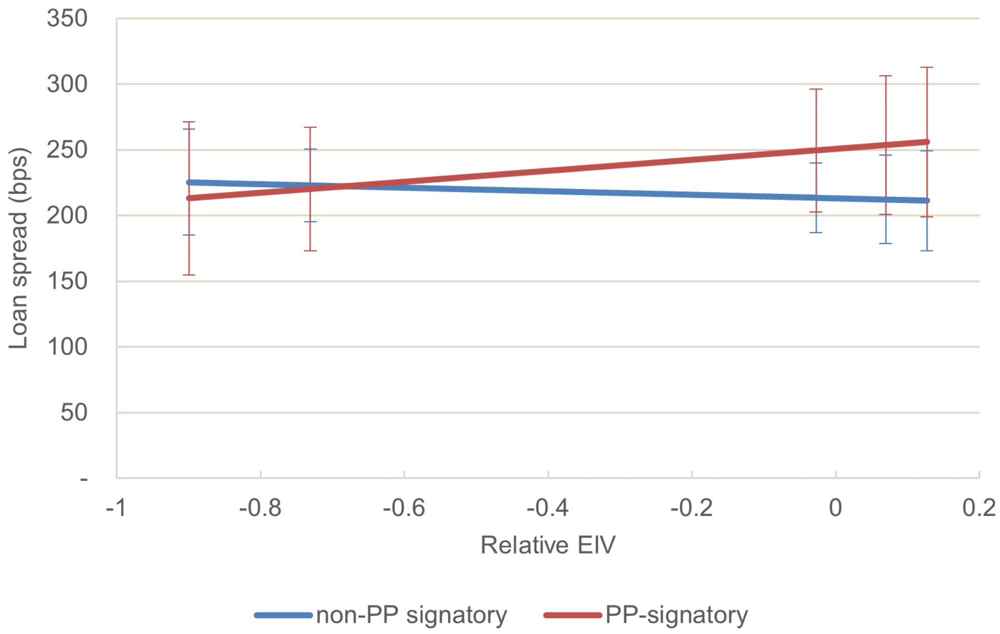

Figure 6.13: Lenders' carbon reporting commitment, financed ship assets' carbon intensity, and cost of debt

(a) Effect of the Estimated Index Value (EIV) on the cost of debt estimated when lenders are Poseidon Principles (PP) signatories (red) and non-signatories (blue).

(b) The margins were estimated using the Model (6) with 95% confidence intervals.

(c) The predictions of the costs of debt were estimated for the 10, 25, 50, 75 and 90 percentiles of the relative EIV.

6.2.2 Qualitative findings

So far this section has focused on the first quantitative phase of the explanatory research design. This section discusses the second phase qualitative results. It elicits what are shipping financiers' beliefs related to the upcoming transition to low-carbon shipping (Section 6.2.2), and how they impact their behaviour, i.e. the role they have played or intend to play, as defined by the theoretical framework presented in Chapter 5 (Section 6.2.2.2; and the financial instruments they use (Section 6.2.2.3).

6.2.2.1 Beliefs of the upcoming transition

All[8] financiers interviewed acknowledged the need to decarbonize the shipping industry, which has been driven by landscape pressures for all regime actors to invest in energy efficient ships and low/zero-carbon ready ships. All interviewees mentioned that landscape pressures have already started to materialise through various channels and that they expect that trend to increase in the coming decade.

Let us go through the different types of socio-technical landscape pressures which were mentioned by the interviewed financiers. The type of supply-side transition driver perceived to be critical varied from financier to financier (see Figure 6.14a). Most financiers were particularly sensitive to changes in customer demand and increasing demand from charterers for cleaner ships. The findings of Jameson et al. (2022) show that this belief is founded, as the authors show that most of the shipping customers surveyed are willing to pay a premium for low-carbon shipping, although the premium is still too small to compensate for the full cost of decarbonisation. This customer and charterer pressure is linked to the adoption of the Sea Cargo Charter initiative in 2020, which establishes a framework for assessing and disclosing the climate alignment of ship chartering activities Sea Cargo Charter (n.d.). This initiative seems to have shifted beliefs of banks in particular, but also some alternative lenders, so that they now view the possibility of a two-tier market in favour of low-emission ships as credible in the future. Most

[8]This section is directly taken from the chapter ”Exploring financiers' beliefs and behaviours at the outset of low-carbon transitions: a case study on shipping”, section 4.1, whom I am the main author of. I have written the first draft of this section and it has been reviewed by the co-authors.

financiers viewed regulation (at the regional level, in particular the EU, and in some cases IMO) concerning shipowners and financiers as an important driver. In particular, they anticipated further EU regulation on shipping emissions and increased capital requirements for financing carbon-intensive activities. Several anticipated increased IMO regulations in the long term, but many also mentioned that the institution was too slow or not ambitious enough. In particular, they anticipated further EU regulation on shipping emissions and increased capital requirements for financing carbon-intensive activities. Concrete policies mentioned by the interviewees include the EU Emission Trading System (a cap-and-trade program that aims to limit greenhouse gas emissions implemented in 2005), the EU taxonomy (a classification system designed to define environmentally sustainable economic activities implemented in 2020), the CII/EEXI regulations (Carbon Intensity Indicator and Energy Efficiency Existing Ship Index), which are performance standards international maritime regulations that entered into force in November 2022 and are designed to reduce greenhouse gas emissions from existing ships. This suggests that recent regulations and announcements have shifted some financiers' beliefs about increased regulatory pressure. These financiers were optimistic overall of these potential policy changes and highlighted that such regulations are needed for shipping markets and financial markets to properly price in the climate impacts of shipping.

Many also highlighted societal pressure due to increased concerns about climate change, particularly since the Global Financial Crisis. Several interviewees highlighted the consequential demand from financiers' shareholders to improve their ESG policies, a demand which is also highlighted in their public communication, so that appearing to be a leader in climate change was cited as a competitive advantage by some of the interviewed financiers.

This apparent strong confidence in the coming transition to low/zero-carbon shipping needs to be nuanced by the scepticism expressed by all but two interviewees about the speed of the transition (CB2 and CB5 did not express such statements) (see Figure 6.14a). Only one financier interviewed mentioned the decrease of shipping activity as a solution to reducing shipping emissions would potentially threaten the profitability of the shipping industry. Academic studies have shown that, if shipping activity is to continue growing as in the previous decade and shipping to remain in line with a 1.5° pathway, ships' carbon intensity needs to be reduced by at least 50 % by 2030 (Science Based Targets, 2022; Traut et al., 2018) and low/zero-carbon alternative fuels to be rapidly scaled up in the 2030s (Lloyd's Register and UMAS, 2019; Osterkamp et al., 2021). This ambition was deemed unrealistic by many financiers :

> *"There was a discussion in Poseidon [Principles] about this new potential new trajectory based on top-down (...) carbon budgeting, implying that (...) we need to take 50% of the reduction in the carbon intensity (...) before 2030. That's totally unrealistic." (Interviewee 9)*

When directly asked, many would acknowledge the existence of a technology risk but would often consider it as less important as it was felt that the technology for low/zero-carbon ships was uncertain and immature while it would take a long time to renew a whole fleet :

> *"It's in the pace of the creation of future fuels that may well determine whether a particular asset is viable forever till the end of its useful life or you know its life it's foreshortened and in the sense that it comes too expensive to retrofit and stuff. So these are fortunately not decisions that I will be making. (...) But I think the risk of stranded assets in shipping is quite low. 'cause I think if ships don't get finance they don't get built, so no one wants to order them. But of course they could get stranded if the pace of technological change turns out to be much faster" (interview CB1)*

Furthermore, several interviewees expressed technology lock-in for LNG, since LNG as a marine fuel has been shown to have limited GHG benefits, especially on a short-term time horizon (Balcombe et al., 2022; Laskar and Giang, 2023; Pavlenko et al., 2020) and its drop-in low/zero-carbon fuels such as bio-LNG and e-LNG are not expected to be available at scale nor cost-competitive compared to other low/zero-carbon fuels DNV GL (2020), IRENA (2019a, 2019b), Maersk Mc-Kinney Møller Center for Zero Carbon Shipping (2022b), and Smith et al. (2019a). Interviewed banks, all of which have already invested in LNG-fuelled ships (including LNG carriers) were however putting faith in drop-in fuels such as bio-methane or e-LNG. Arguments mentioned by interviewees for continuing to back this technology included the trust in the shipowners' judgement, belief in the availability of drop-in zero-emission fuels, lower SOx, NOx and CO2 emissions compared to Low-Sulfur Heavy Fuel Oil (LSHFO), and confidence that engine improvement will solve the issue of methane slip. This provides an example of the interactions between the industry regime (shipowners and their beliefs and past investments) and the financial regime (financiers, with their respective beliefs and investment decisions).

Only a few financiers on the other hand expressed concerns that the assets they finance – both conventional and low/zero-carbon – would face early obsolescence due to the uptake of new propulsion technologies:

> *"Today we're approached a lot of projects to finance (. . .) LNG-fuelled or methanol, that we didn't see before. Tomorrow we'll be approached on ships to finance with hydrogen or ammonia and that means that the current fleet will lose value faster than we could expect. And then these new ships, well, we don't really know what their value will be (. . .) in 10, 15, 20 years because they will probably be out of date too. So it's a real period of uncertainty" (interview CB5)*

Most of the financiers believed that the top-tier incumbent shipowners, which constitute the bulk of their clients, are anticipating the need to decarbonize and are first movers in the transitions (see Figure 6.15a), which is a condition for a "Loyal Enabler" behaviour to emerge. This finding is valid whether measured by count of words or by count of interviewed who expressed an opinion on the shipowners in line with one of the 5 types of behaviours proposed in the extended theoretical framework (see Figure 5.4a). The Poseidon Principles reports are full of such statements: "We thank our shipowner clients who have been very cooperative for this first "harvesting" data campaign concluded in a very tight schedule. This is the clear demonstration of their commitment to a greener shipping and their willingness to be actors of the energy transition for shipping" (CIC, Poseidon Principles (2020), p26). This view is largely supported by the interview data, although many interviewees would nuance this statement by stating that some shipowners are reducing their investments in any ship due to uncertainties about their future viability ("regime shipowners are Winding Down exposure" on Figure 6.15a) or that some shipowners are ready to move earlier than others ("Regime shipowners = Inert" in Figure 6.15a). In particular, it was felt that public shipowners and shipowners operating on shipping segments closer to customers (ferries, containers, offshore) were more advanced, a belief which is in line with the empirical findings of Mäkitie et al. (2022) and Stalmokaite and Yliskylä-Peuralahti (2019). With regards to the beliefs that their clients are first movers and that the decarbonization will be gradual, many financiers believe that in case of the materialisation of climate risks, their clients' ships will not be stranded because they are the most modern on the market and because the loan period is relatively short (around 7 years) so that they will have the time to adapt to the new regime, while other ships will be stranded first. It is therefore noteworthy that no incumbent financier considered that their clients were making value-destructive decisions ("regime shipowners = Creative Self-Destruction" on Figure 6.15a) or that new entrants would be better placed to take on the opportunities of the low-carbon transition ("Niche shipowners = first movers", on Figure 6.15a).

For most interviewees, investment in low/zero-carbon ships requires access to a varied and secure source of capital and the involvement of a large range of stakeholders to share the financial risk and additional costs – for example customers, charterers, fuel providers, public authorities and ports. Most banks interviewed believed that only large shipowners – which are also generally their target clients - will have the financial, relational and experience capabilities to do so. Some expected – and welcome – a consolidation of the market around the few top-tier regime shipowners they are financing. In particular, financiers – whether commercial banks

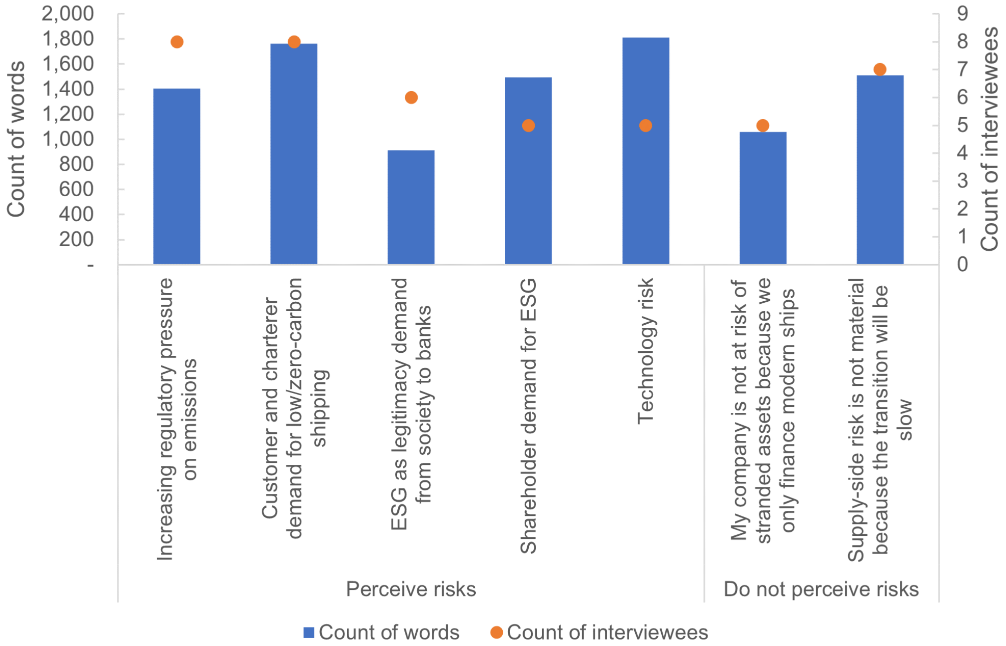

Figure 6.14: Coded words and coding presence in codes related to beliefs of supply-side landscape pressures.

(a) Interviewees are counted if the interviewee has expressed a statement in line with the code.

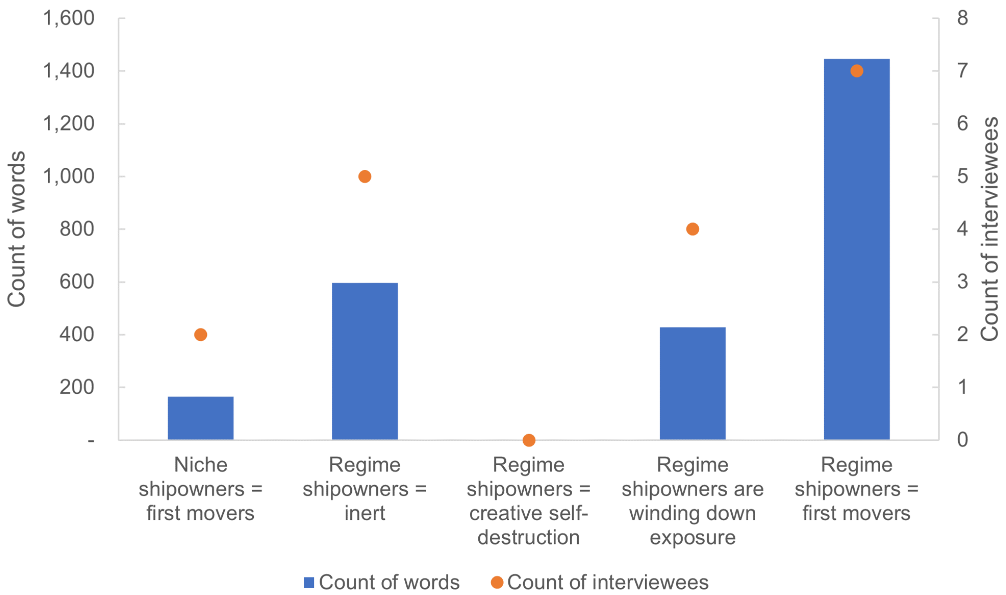

Figure 6.15: Words coded and coding presence in the codes related to beliefs on shipowners.

(a) The counts corresponding to “niche shipowners = first movers” come from interviewees 8 and 10 who referred to themselves when saying that niche shipowners were first movers.

or asset managers shipowners – were keen to pass some of the risks associated with new technologies to the charterers. This identified need has not translated so far into a financial innovation from banks, but two asset managers have highlighted that their business model was based on long time-charters and one of them is trying to add a clause in the contract which stipulates that the charterer would have to buy the ship back at the end of the charter period, which essentially displaces the residual risk from the shipowner/financier onto the charterer.

The question of low- and zero-carbon shipping technologies was not the focus of the interview guide, so the data provide fewer insights on the expectations, beliefs and preferences of financiers regarding their uptake. However, most of the interviewees spontaneously mentioned a range of alternative fuels, in particular methanol, ammonia, LNG (sometimes bio- or synthetic) being most often cited. This suggests that regime financiers have some awareness and knowledge on those industry innovations, and might be therefore more prone to facilitate a socio-technical transition towards them. On the other hand, only interview 10 mentioned energy efficiency - without citing specific technologies though - and CCS as options, which suggests that those technologies are not the main focus of them. Furthermore, there appeared to be various degree of knowledge within the sample: interviewees CB1, CB4 and CB7 remained fairly vague on the on the fuel technology, which might suggest a limited awareness - although, as this was not the focus of the interviews, they were not prompted to explain more - while others, such as interviewees CB6, AF2 and CB8 appeared knowledgeable about the various options and their technical requirements.

6.2.2.2 Role in the transition

Given the previously mentioned beliefs about supply-side risk, interviewees expressed an intention to play a Loyal Enabler role, i.e. supporting incumbent shipowners in the transition. Shipping financiers have publicly communicated this intention, in particular since 2019, in their annual reports and public communication but also through their involvement in various initiatives such as the Sustainable Shipping Initiative, Ship Recycling initiative, the Global Maritime Forum or the

Poseidon Principles.

The intention to play a Loyal Enabler behaviour seems to derive directly from the historical links between the financial socio-technical regime and the industry socio-technical regime through relationships with their clients which are often personal, in which they have invested in incumbent technologies, and common beliefs about the future availability of fuels. All banks interviewed considered ship finance as corporate finance rather than asset finance, i.e. finance to the shipowner as opposed to an individual ship asset. As a result, the importance of the ship as collateral often comes as a second or third priority. The focus on client was driven by credit worthiness of the borrower and in some cases to also ensure that the company fits into the financier's business strategy. A particularity of ship finance is that banks attach a large importance to the reputation, performance in past shipping cycles and the relationship with their clients, at least as much as to the current financial health of the shipowner company. This behaviour is corroborated by previous findings in the literature Gavalas and Syriopoulos (2015) and K. R. Lee and Pak (2018), and interviews support that this is still one of the main drivers of a financing decision. Several banks stated that those links would allow them to positively influence the evolution of the industry, through engaging with their clients and through making capital available for cleaner ships. On the other hand, many banks seemed cautious to support niche shipowners, but the interview with interviewee 10, a shipowner operator who has entered the ship-owning space a few years ago and who differs from other incumbent shipowners by their mandate to only invest in ships exceeding the climate ambitions of the Paris Agreement, contradicts this statement, as they have been able to access finance from regime traditional shipping banks. However, the interviewee highlighted that the fact that their company's management had decades of experience in the shipping industry and were personally known to the bank employees helped build the relationship.

The belief of incumbent regime shipowners as first movers, and the fact that all banks interviewed viewed their business as relationship-driven means that banks largely trusted their clients' judgement on the selection of ships in their fleet and their ability to transition to a low/zero carbon fleet. Although some have highlighted some reservations in the interviews, this trust remained strong:

> *So your question as to what we look at for new vessels [*in terms of carbon efficiency*], I would have said we listened to our client (...). But now we know that if we agree this science-based target, we can't make that assumption any longer. If it's an LNG-fuelled vessel, we know actually that it will make our results worse. That won't necessarily stop us financing them there because we're taking the decision to support our clients who are making the assumption that they will be able to run these LNG fuelled vessels on bio or synthetic LNG in years to come, which is a big... It's a mighty assumption, but it's one which a lot of these the sector is taking" (interviewee 2)*

This approach of shipping finance as relationship-driven corporate finance was largely shared by the banks, but not necessarily by the other types of financiers interviewed, due to the difference in business model. Institutional investors were found to attach a large importance to transparency, corporate financial and increasingly ESG metrics, but not to relationships. The financing behaviour of these interviewees can be characterised as a Redirecting Enabler, i.e. anticipating the upcoming socio-technical transition and redirecting their investments from industry incumbents towards industry niche new entrants. On the other hand, the alternative lender 3, which can be considered a niche financial actor, despite a much more ambitious climate agenda, had a business model similar to regime actors such as traditional banks based on secured debt lending and with a large attention to the reputation of the shipowner, although a major difference is that they put the ship characteristics, in particular climate-related ones, before the company.

For some financiers, their intention to play a Loyal Enabler role has started to translate into investment decisions in low carbon shipping assets. Two financiers reported having financed pilot projects of low/zero-carbon ships to improve their own knowledge of niche technologies and provide proof of concepts to the broader industry. It is worth noting that for both of those projects, the role of the State mandate and public finance was prominent. Several other banks mentioned they were wary of providing finance for unproven technology and would rather step in once the proof of concept has been established. The impact of this shift in investment decisions on the shipping portfolio is however marginal for all financiers interviewed but the two alternative financiers at the time of writing. Furthermore, many of the interviewees have provided finance to LNG-fuelled ships. The case of LNG-fuelled ships is insightful because it illustrates how financiers – in particular shipping banks – can play a Loyal Enabler role to support the uptake of this technology by their incumbent clients, who are part of the industry regime; but also good case demonstrating inertia and technology lock-in. Interviewed banks which have already invested in LNG-fuelled ships were reluctant to move away from those investments despite the risks (Balcombe et al., 2022; Pavlenko et al., 2020).

6.2.2.3 Adaptation of financial tools and instruments to supply-side climate risk

Traditionally, most of the commercial banks' and interview AF1's activity is debt secured by the ship asset with longer profile than tenor, i.e. the ship is depreciated along a longer period than the loan duration so that there is a balloon payment at the end of the loan period. Credit rating and investment decisions are mostly based on backward-looking financial (non-climate related) data such as profitability or leverage; where corporate metrics are prevalent while the asset characteristics remain secondary. Most financiers' risk management approach is to finance newbuildings over refinancings, or ships up to 10 years old. This way of working was found to persist in the interviews, but banks have started to collect data on the climate performance of their clients and on the assets financed over the last few years under the landscape pressure to decarbonise.

First, interviewees highlighted that while fuel efficiency was originally not taken into account in investment decisions by financiers – validated by previous literature which found that the most relevant metrics for fuel efficiency were not taken into account in 2016 (Mitchell and Rehmatulla, 2015), they have now started to collect data on the environmental characteristics of the ship assets they finance.

In particular, all interviewed signatories highlighted that the Poseidon Principles had induced a large change in the lenders' activities, so that data related to the carbon intensity of ships was collected and scrutinised systematically in the investment decision process. The main data collected is the Annual Efficiency Ratio (AER, a proxy of energy efficiency which assumes ships are fully laden on each voyage) of second-hand ships because it is the metric used in the Poseidon Principles, but some financiers mentioned looking at the design fuel efficiency, the fuel used, the age of the ship, the capacity to retrofit to alternative fuels and for a few the risk that a ship becomes stranded using qualitative assessment or basic desktop analysis. For example, one interviewee's approach was to have a distribution of ages, including older ships as these would leave the fleet in the short-term. They were wary of newer ships because technological and regulatory uncertainty might cause these ships to be outcompeted in the market with ships which will be more technologically advanced (e.g. in terms of fuel and machinery onboard) and compliant with regulations.

Second, the perceived socio-technical landscape pressure to decarbonise the shipping industry also translated into an increasing attention to the decarbonization strategy and ESG characteristics of the regime shipowners. As a result, banks have continuously been putting efforts over the last few years to develop tools to measure the ESG performance of the corporates. Those tools might incorporate, among other variables, the carbon intensity of the total fleet, with sometimes a consideration to the financed asset:

> *"It's not that we won't finance assets above the pathway, but we want to make sure that our owners have a strategy to decarbonize their fleet and particularly the ships that we're financing" (Interviewee 4)*

How[9] this newly collected data influences financier's actual behaviour and in-

[9] The next three paragraph not only use text from the chapter "Exploring financiers' beliefs and behaviours at the outset of low-carbon transitions: a case study on shipping" previously mentioned, but also some of the section "Development of shipowners' financing costs", of the chapter "Lower margins are tied to companies' environmental score rather than to low-carbon assets". I am the main author of both those chapters. I have written the first draft of these section and they have been reviewed by the co-authors.

vestment decisions is ambiguous and inconsistent across financiers. First, this data-driven approach is combined with the belief that the top regime owners (who they provide finance to) are most resilient to the energy transition and own the most fuel efficient ships. Second, for most interviewees (but not the two alternative financiers), those ship-level characteristics did not seem to be formally included in the financial assessments and credit rating used to inform the pricing and financing decisions. In particular, they did not incorporate carbon prices or future capital investments for low/zero-carbon fuel switching retrofits. This is also true of Poseidon Principles signatories :

> *"We use the Poseidon Principles to have a dialogue with their clients. So it's not that we won't finance a ship which is above the pathway, but we want to (. . .) understand from the owner what they [and] what their decarbonization strategy is" (interview CB3)*

As a result, it is not clear how the environmental data collected has translated into concrete decisions about loan pricing from the qualitative data collected, as answers from the interviewees were often vague in this respect. How these metrics impact the decision was not clear and appeared to be an addition to the loan assessment process, while having no effect on the calculated credit risk and therefore the pricing:

> *"I wouldn't say that banks are pricing ships lower if they've got a good AER, and worse it's got a bad AER. I don't think we've reached that basic situation yet" (interview CB2)*

The way the environmental performance of the ship assets and of the borrowers feeds into the credit rating and the pricing was not formally and explicitly defined, even when this environmental performance is measured and quantified in a scenario analysis. According to one interviewee:

> *"The full effect of ESG and climate is not yet included in that model [internal risk rating]. So that's the kind of additional assessment which we do on the outside. So we have in our credit proposal as separate.*

We have a full ESG scoring, a checklist of more than 70 questions. But we go through all aspects of ESG including Poseidon scores, including climate targets, including… it's a lot on climate and environment. But in addition to that on shipping we do a separate analysis in the credit paper on transition risk. Looking at the short-term regulatory risk and how they look to meet CII and EEXI scorings the Poseidon scores in relation to that and we also have done separate analysis then on CII. And also then discussing their longer term transition plan, fleet development plan etcetera. It's not yet in the quantitative terms included in the risk rating." (interview CB6)

"New build is really difficult when you don't have Poseidon Principles score or the relevant data for it. (…) Poseidon Principles performance depends a lot on the actual operation. It's not only the design of the vessel so even if we have second-hand vessels which have operated with the other client, we are aware that even just the ownership change might result in a change of Poseidon Principles score, maybe due to different trading patterns and so on. But we would try to get AER data, or if it's a new build or a second-hand vessel where 't's not available, we would try to go via the EEDI ". (interview CB8)

As a result, several interviewees mentioned that debt pricing did not reflect the climate risk of the ship, but rather the competition between banks to provide debt finance to the few regime top-tier shipowners they are after. In fact, they stated that the margin above LIBOR is set at a minimum above the lender's capital cost and the loan credit risk, whose calculation excludes any asset-related transition risks. This credit risk, which has not evolved significantly in the last decade, mostly uses backward-looking variables, such as the company's leverage and profitability, and expected earnings (which do not include carbon costs) based on the historical performance of the asset's shipping segment. The lenders interviewed confirmed that the use of this credit risk methodology is a barrier to pricing transition risks, reinforcing an inertia to change it:

> *"The capital requirements for our banks are based on our internal risk rating model. We are a so-called IRB Bank internal rating based model approved by the financial regulator (...). We cannot just change that model all the time. (...) But the full effect of ESG and climate is not yet included in that model" (interview CB6)*

Even when commercial banks mentioned using forward-looking scenarios, it was not specific to a shipping decarbonisation scenario. However, some shipping lenders include company environmental performance in the credit risk analysis:

> *"The pricing is still completely risk return driven. (...) What you see now if you have ESG, there are certain corporate facilities, but we see it more on the corporate facility basis. If you are, as a company, much more CO2-efficient then you can get slightly lower pricing. Or the other way around, you will be priced higher. (...) On the individual basis with ship finance in bilateral financings, which we do, there is no pricing differentiation yet. So it's more a selection, a method, you just don't do this asset anymore. " (interview CB4)*

This indicates that the environmental performance of a company influences pricing at the corporate level but not the asset level.

Although the ships' environmental performance did not influence the conventional financial instrument's pricing, many financiers highlighted that the perceived greenness of the ship would influence the engagement with the shipowner, and in some cases the decision to provide finance to a ship, in particular after signing the Poseidon Principles. For one bank and for the alternative financiers, climate risks were incorporated into guidelines on the carbon intensity of the ship above which they would not invest, but that position seemed to be marginal within the sample banks, which seemed to have a more qualitative and flexible approach and they would not refuse to finance a ship to their existing clients on the basis of its carbon intensity. As mentioned, a central characteristic of ship finance is the importance of the relationship with the regime shipowner, this characteristic has been simply reconfigured to accommodate growing landscape pressure, and has not been overruled by the need to finance low/zero-carbon ship assets.

To formally incorporate the shipowners' and/or the ships' environmental performance into a financial deal, many financiers interviewed have started to utilise various types of green finance, where the margin fluctuates depending on the operational efficiency of the ship financed or other environmental characteristics of the borrower or the ship (e.g. sustainability-linked loans or green bonds). This type of new instrument can be considered a financial innovation, which might allow the regime financiers to play an Enabler role. However, green finance in shipping suffers from the same criticisms as other industries. First, they only represent a small part of the bank activity: environmentally-linked bonds represent 5 % of released bond amount between 2019 and 2022 reported in Clarksons Shipping Intelligence Network (SIN), while $10.5bn of shipping environmentally-linked loans have been issued so far, i.e. roughly 4 % of the bank shipping debt portfolio. Second, those issuances are always released in agreement with the shipowners and several interviewees admitted that the effects on the margins are fairly small so far, making them only marginally more attractive from a commercial point of view. Third, there is no agreed definition of what a green shipping transaction is. In particular, less than 5 % of the green issuances reported in Clarksons SIN have been approved by the Climate Bond Initiative, the International Capital Market Association (ICMA) or the Loan Market Association (LMA), which casts doubts on how actually environmentally-friendly the remaining issuances truly are. Such transactions have been accused of green washing by some NGOs (Wiese Bockmann, 2022) but also by one of the shipping asset managers interviewed. Similar to other sectors, green finance in the shipping industry seems to constitute an incremental and symbiotic financial innovation as a response to financiers' landscape pressure to increase their legitimacy by visibly demonstrating an environmental contribution (Monk and Perkins, 2020). Green finance transactions are publicised in the press and companies' public reports so that the lender and the shipowner benefit from positive publicity. Their uptake since 2019 in new debt issued is shown in Figure 6.16. Considering that there were practically no green financial instruments for ship finance before 2019, this shows that there is some interest from both lenders and issuers towards this kind of instruments. All interviewed banks had already issued at least one green issuance, which suggests that the uptake covers a large range of banks rather than a few first movers (Figure 6.14a).

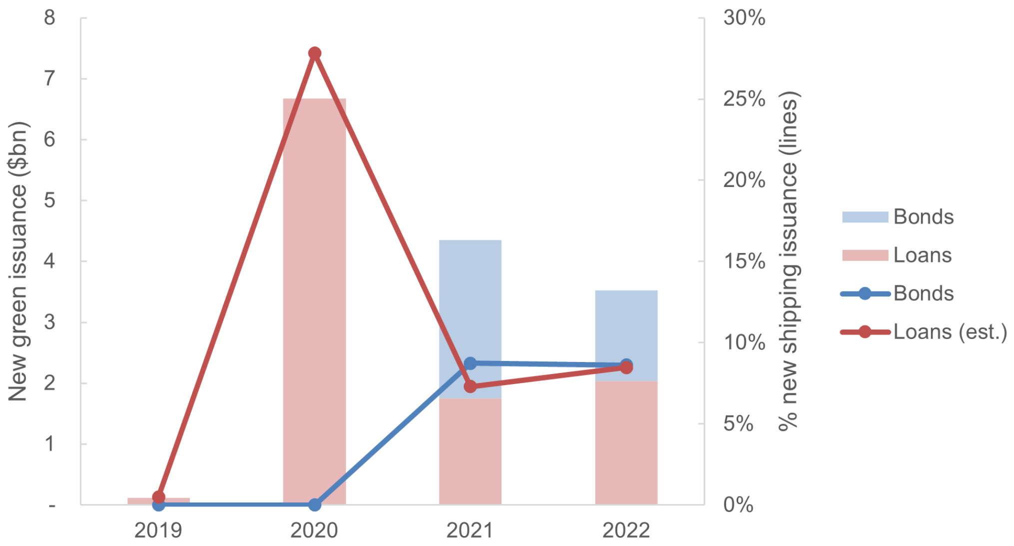

Figure 6.16: Issuance of green bonds and loans (Clarksons SIN, BRS Group 2019).

(a) Only bonds and loans reported in Clarksons SIN whose company sector is classified as shipowner or integrated cargo/shipping group are included.

(b) Green issuances cover a large range of bond and loan types which are often not approved by the Climate Bond Initiative (CBI), the International Capital Market Association (ICMA) or the Loan Market Association (LMA), so that the definition of what is “green” varies from issuance to issuance.

(c) New shipping loans amount is proxied as the new bank debt issued in 2019 (BRS Group, 2019) and is assumed to be constant in the following years in the absence of better source of information.

6.3 Discussion

After analysing the results in the previous section, this section will now summarise the main discoveries and examine how they compare to other studies (Section 6.3.1), consider their implications (Section 6.3.2) and limitations (Section 6.3.3).

6.3.1 Summary of results

This section looks at the quantitative results and qualitative results and finally explores how the qualitative case study helps explain the quantitative results.

6.3.1.1 Quantitative results

The[10] first quantitative phase provides several empirical insights. Shipping lenders were notably misaligned with the efforts of the shipping industry to decarbonise prior to the Paris Agreement when extending loans to shipowners. This study shows that they were not expecting transition risk.

However, the lenders' appetite for climate performance has increased after the Paris Agreement and there are signs that this positively impacted the pricing of the shipowners' climate performance. This increased appetite does not mean that borrowers are now expecting transition risks, as those are unlikely to be relevant to the short-term loans which they on average provide to borrower. Furthermore, this increased appetite is not sufficient though, as it does not lead to a differentiated margin based on the carbon intensity of the ship. Those, on the other hand, are often financed by longer-term loans (more than 7 years on average) and would be concerned by transition risks. So, although lenders pay attention to climate performances at a corporate level, they are not yet directly supporting lower-emission ships through a pricing mechanism.

Those results therefore further contribute to the existing literature which questions the relevance of the current metrics used by financiers to measure climate-related risks. Riedl (2020) and Thomä and Chenet (2017) argue that because they rely on backward-looking metrics, they are ill-suited to capture transition risks which have not materialised in the past, which instead would require forward-looking risk assessments. This analysis itself is limited in this regard, as both the CDP and the carbon intensity of the ship are backward-looking. For example, the carbon intensity of the ship does not include the possibility and expected cost of

[10] This section is based on the Section "discussion" of the study "Lower margins are tied to companies environmental performance rather than to low-carbon assets". I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

adopting cleaner technologies in the future, through retrofitting the ship for alternative fuels and energy efficiency measures, or the use of drop-in biofuel.

6.3.1.2 Qualitative results

The second phase of qualitative research provided additional empirical insights.

The findings suggest that the accumulation of socio-technical landscape pressure (existing and upcoming shipping and financial regulation, customer and shareholder pressure due to increased awareness of climate change) has caused lenders to partially and imperfectly alter their heuristics. The results show, in particular, that shipping financiers are confident that a supply-side shipping transition is underway, a trend that has developed in the last few years. This apparent increased belief in future transition risks, however, is ambiguous as regime financiers are more conservative about the speed of the transition than what would be required to attain a 1.5°C pathway and avoid the dangerous consequences of climate change. As a consequence, they are not particularly concerned about the risk of stranded assets on the fleet they have financed and continue to finance fossil-fuelled ships. The increased belief of an upcoming low-carbon transition confirms the theory and the findings of Geels and Ayoub (2023) on the UK offshore wind and electric vehicle industries, which show that stronger policies build confidence and spur investments in new technologies (feedback 3 in Figure 2 in Geels and Ayoub (2023)), but these findings are applicable to regime financiers (while Geels and Ayoub (2023) focusses on producing firms), and they further suggest that customer and shareholder pressures also lead to this effect. These results differ from those of Mitchell and Rehmatulla (2015), which show that regime financiers are not expecting stranded assets. These contradictory results may be the result of differences in timing: while the interviews for this chapter were conducted in 2021, and positive pricing of corporate climate performance is observed after 2015 only, Mitchell and Rehmatulla (2015) collected qualitative data supporting their conclusions before 2015. This suggests that the financiers' beliefs have evolved during the last decade, possibly as a consequence of the introduction of climate mitigation policies such as the IMO Strategy or the introduction of shipping into the EU ETS.

One heuristic which has been notably stable is the importance of the relationship with and the trust in the judgement of their existing clients, i.e. the incumbent shipowners who are part of the industry regime. Similar conclusions were drawn by Alexandridis et al. (2018), Gavalas and Syriopoulos (2015), and Mitroussi et al. (2016), but this chapter sheds further light on the consequences for shipping low-carbon transitions. The financial and industry socio-technical regimes appear strongly supportive of each other, and the majority of interviewees (and all commercial banks) expressed a desire to support regime incumbent shipowners, who form their customer base, in transitioning by adopting innovations (LNG or alternative fuelled carriers), i.e. to play a Loyal Enabler role. At the time of the interviews, there were few signs that they would want to support competitive innovations which would require supporting niche shipowners (Redirecting Enabler) or that they felt they should retreat from the sector (Winding Down). This suggests that regime financiers are more comfortable with supporting a socio-technical transition led by industry regime incumbents (i.e. a transformation or reconfiguration in Geels and Schot (2007)'s typology). Additionally, interviews with niche shipowners who receive funding from institutional investors revealed the emergence of a second type of financier, known as the Redirecting Enabler. These findings are at odds with those of Woodrow (2023), who survey a wide range of investors, including commercial banks, and show that they see shipowners as laggards in terms of ESG transparency and performance, awareness of ESG risks, and also find their commitments less credible than in other sectors. The survey shows that the majority of financiers, and in particular commercial banks, are considering divesting from the sector, which would correspond to a Winding Down behaviour. The discrepancy of those results with the findings found with most of the banks interviewed could be due to several factors. First, the scope of the work is different: Woodrow (2023)'s survey focuses on any ESG risk, with the perceived largest factor of risk being worker conditions and safety, while climate impact and technological disruptions only arrive in 7th and 8th position as the main factors of risks. This suggests that climate risks, while acknowledged by investors, are not their main concern, so that their critical view on shipowners might not be primarily linked to their risk in low-carbon transitions. Second, the data collection time is different: survey data were collected in September 2023, that is, after the adoption of the 2023 IMO Revised Strategy, which sets an ambition to a near 1.5°C trajectory (IMO MEPC, 2023). This might have created a strong shift in investors's expectations, which the literature shows can sometimes change quickly after an unexpected event (Antoniuk and Leirvik, 2021; Byrd and Cooperman, 2018; Kungl and Geels, 2018; Sen et al., 2017).

To adapt to the transition, some financiers who are early movers have started to implement stricter requirements. For instance, some now expect clients to have a credible plan for transitioning, repay loans more quickly, possess modern vessels, and/or ensure that low/zero carbon ships have a contract in place to shift the risk of transition onto the owner and charterer. As a result, the market might witness a consolidation trend toward top-tier owners who can afford to invest in transition plans and have a strong cash flow for research and development of greener fuels.

Table 6.5 summarises the results of this Chapter[11].

[11] This table is directly taken from the chapter "Exploring financiers' beliefs and behaviours at the outset of low-carbon transitions: a case study on shipping", section 4.3, whom I am the main author of. I have written the first draft of this section and it has been reviewed by the co-authors. The table has been slightly amended to integrate the quantitative results.

Table 6.5: Summary of the results of Chapter 6

Heuristics		Behaviours during transition
Beliefs of the transition	**Financial tools and instruments**	
· Most believe transition to low/zero-carbon shipping is happening. · But it will not be fast enough to be aligned with a 1.5-degree pathway. · Given above and tenor, financed ships are thought not to be at risk of being stranded	· Financiers have only started to consider environmental factors after the Paris Agreement · Currently measurement and pricing lies on corporate ESG score instead of asset/ships carbon intensity. The Poseidon Principles amplify this effect and does not lead to the direct pricing of carbon intensity into the loans spreads. · Measurement and reporting of ships' carbon intensity is based on proxies. · Ambiguous use of green finance (sustainability-linked, Poseidon-Principles-linked, Green Bonds Principles) · Willingness to transfer of risk onto the charterer	· Historically most can be classed as Inert (anticipate stability) · Many have ambition for becoming Loyal Enabler (anticipate and support the transition) · This varies by type of financier: traditional banks, due to the importance of the relationships with their existing clients, are more inclined to be Loyal Enabler. It is not clear yet whether alternative financiers and institutional investors will play a Loyal Enabler or enabling role. · Some face risk of Winding Down (incapable of operating in transition)

6.3.1.3 How the qualitative findings help explain the quantitative results

This last section explores how the qualitative case study data on financiers' beliefs and behaviour help explain why climate performance, as measured quantitatively, is priced in at the borrower, rather than at the asset level.

The quantitative phase found that loans margins did not to reflect the climate performance before 2015, neither of the borrower nor of the ships. The quantitative study reveals that lenders did not take into account the risk of transition. This can be explained from qualitative findings by the fact that traditional shipping lenders, which are part of the shipping financial regime, have been until recently *Inert* to climate risks and opportunities in the shipping industry. As a consequence, they did not consistently collect data on the climate performance of the borrower or of the ship until recently, and even less priced those into the margins. The lack of positive pricing and inertia could be attributed to the fact that the shipping industry had been sheltered from regulatory pressure to decarbonise for a long time, while other sectors (such as mobility and electricity generation) have already started their transition (Geels and Ayoub, 2023; Nijsse et al., 2023). Furthermore, cargo shipping, which constitutes the majority of the sector's capacity, is relatively far from consumer demand, making it difficult to create a business case aligned with decarbonisation before regulation (Poulsen et al., 2016). This makes it difficult for end-consumers to link their actions to climate-friendly choices related to how their goods are transported by sea.

However, the quantitative analysis suggests that shipowners with a better climate performance enjoy lower interest rates after the Paris Agreement. The direction of change is consistent with the qualitative findings: the findings from this Chapter suggest that shipping financiers are increasingly expecting, although ambiguously, the risk of stranded assets. This is a significant evolution since the findings of Mitchell and Rehmatulla (2015), who conducted interviews with various shipping financiers, including 4 lenders and 2 equity investors. They show that at the time of the data collection, most interviewed financiers were not expecting any stranded assets - half of them actually not being familiar with the concept. The contrast between their findings and the qualitative ones from this Chapter support the hypothesis of changing financiers attitudes.

This Chapter's qualitative findings only partly explain the positive pricing observed post Paris Agreement in the quantitative findings. They suggest that lenders have started to collect an increasing amount of data on the climate performance of the borrower and on the environmental characteristics of the ship, the former remaining more important. They also suggest that, for some lenders, the ESG data might start to be incorporated in the risk analysis, and therefore pricing. They also show that the margins are mostly determined by the competition between lenders for a few top-tier clients, which are perceived to be safer. As the climate performance and strategy of the borrower are increasingly scrutinised by lenders, climate performance might have an impact on the margins, through lenders competing for the large shipowners with strong ESG and climate performance. However, as the interviewees remained vague and ambiguous on how concretely climate performance translated into concrete decisions and/or pricing, it remains unclear what the channel towards this pricing is. There does not appear to be a consistent way of integrating climate risk, even at the corporate level, into investment decisions. In particular, climate performance is not included in the credit risk rating by most lenders.

The quantitative finding has found that the climate performance of the ships does not translate into lower margins, including after the Paris Agreement and from the Poseidon Principles signatories. This finding is validated by the qualitative data collection, which suggests that although data on ships' carbon intensity and occasionally risk of stranded assets are now collected, they are not formally incorporated into the process of investment decisions nor the pricing. Furthermore, this result should be seen in light of the qualitative findings that lenders first look at backward-looking characteristics of the borrower, such as financial strength (which is confirmed by the quantitative findings) and existing relationship with the bank, while they often give a lower importance to the asset. These results confirm those of Gavalas and Syriopoulos (2015), B. Lee and Aslam (2018), and Mitchell and

Rehmatulla (2015). In particular, in the quantitative dataset, the majority of shipping debt relies on the borrower as recourse. Consequently, risk analysis places greater emphasis on the significance of the borrower than on the importance of the asset. This might explain why climate performance at the corporate level rather than at the asset level has concrete effects. This might also explain why financiers seem more willing to play a Loyal Enabler role rather than a Redirecting Enabler one.

The fact that, at least at the time of the interviews, most financiers had the intention to become a Loyal Enabler might give an advantage to regime incumbents to undertake the transition and to symbiotic innovations, such as retrofit of existing assets and capital-intensive technologies (e.g. alternative fuels), should this intention translate into concrete actions. Such a transition would likely be a transformation or a reconfiguration, in Geels and Schot (2007)'s typology. On the other hand, this makes the success of niche innovations more difficult and suggests that niche players in shipping may need to seek alternative sources of finance, some of which are proposed by Schinas and Metzger (2019) and Schinas et al. (2018). Therefore, those results support Baresic (2020a) and Pettit et al. (2018)'s hypothesis that the industry is conservative to radical innovations and Baresic (2020a)'s argument that for a successful transition of shipping to occur, the participation of existing industry players, particularly shipowners, and the emergence of symbiotic innovations are likely to be essential. It further echoes the evidence from Mäkitie et al. (2022)'s survey of Norwegian shipowners, if they can be extrapolated to other geographical contexts, that incumbent (larger, older) shipowners are more likely to be first movers in the transition to low-carbon shipping. However, the fact that many financiers place the responsibility for the energy transition on the shipowners themselves could lead to a technology lock-in situation if financiers fail to investigate the associated climate risks. This is exemplified by certain banks supporting their clients' investments in LNG-fuelled ships. Another consequence is that niche shipowners are not expected to represent a large proportion of the fleet. However, as early adopters, they can exert pressure on established shipowners and help de-risk technologies that conservative shipowners are reluctant to embrace.

6.3.2 Implications

This chapter has two main theoretical implications. First, the contradictory expectations and behaviours highlighted above - belief in the upcoming transition but reservation on the speed, pricing of the climate performance at the corporate level but not at the asset level, lack of pricing of the asset-level climate performance in conventional loans but use of green instruments - support the AMH theory (S. Hall et al., 2017; Lo, 2004, 2012) that during periods of change and landscape pressure, financier heuristics evolve over time but are sticky and slow to adapt.

Furthermore, this section has shown the usefulness of the theoretical model proposed in Chapter 5 to understand the behaviour of financiers during socio-technical transitions. First, it looked at financiers as holders of agency and beliefs, rather than passive supporters of the industry regime. Second, the framework has been helpful in characterising the behaviour of financiers. It should not be understood as a single explanation of the world, but rather as a practical and useful tool to comprehend finance in times of social and technological change.

Moreover, the results of this section have a wide range of concrete implications.

The fact that financiers have the intention to become Loyal Enablers, while considering the assets they finance as secondary, is critical for two main reasons. First, in their view, the regime shipowner still remains responsible for investing in low-/zero-carbon assets. This leaves financiers exposed to the investment choices of the shipowner, potentially trapping them in assets that become obsolete if they are unable to transition their vessels from fossil fuels to a more competitive option. Given the lifespan of a ship (>20 years) and the average tenor of the observed loans (average 7.1 years for ship finance), the sustainability of the shipping loans in the lenders' portfolio could be at risk in the coming years if the transition risks become a reality. Second, lenders are not incentivising the uptake of carbon-emission ships by lowering the cost of debt. The fact that lenders price in the climate performance of the borrower means that they might be indirectly promoting low-carbon ships if shipowners with a higher climate performance were financing more carbon-efficient ships. However, there is no guarantee that this will happen. Indeed, companies that have a high climate performance might not necessarily allocate their investments towards low-carbon assets. Anecdotal evidence indicates that companies with high climate performance do not demonstrate a greater inclination to issue green bonds compared to companies with less environmentally friendly ratings (Immel et al., 2021). Furthermore, companies with higher environmental ratings are found to generate pollution levels similar to those of competitors with lower ratings (Amenc et al., 2023).

Our results highlight the potential, but also the limits, of voluntary initiatives from financiers to promote green investments, so that this chapter's analysis further contributes to the nascent evidence on the limited effectiveness of disclosure initiatives in changing investment decisions (Ameli, Kothari, and Grubb, 2021). Thus far, the Poseidon Principles have not succeeded in causing a decrease in the cost of debt associated with investments in low-carbon assets. This lack of success may be attributed to the recent implementation of the principles and the adverse effects of the Covid-19 pandemic on the shipping markets, which has resulted in a preference for companies with higher environmental ratings. The fact that lenders consider the environmental rating of the borrower implies that they may indirectly encourage the use of low-carbon ships if shipowners with higher environmental ratings were financing more carbon-efficient vessels. However, there is no guarantee that this outcome will occur.

Our results show that regime financiers have an ambiguous expectations regarding climate risks, and are not fully evaluating nor pricing in climate risks of their fleet into their activity. This implies that the transition to low-carbon shipping is not fully credible nor certain to them, despite the announced intention - but so far limited ambitious measures - of the IMO to reduce shipping emissions to net zero by 2050. This further implies that stronger regulation and enforcement action are needed to change investment decisions. Not only is the negative externality of shipping emissions not internalised, but market forces that regulators could have assumed were driving efficiency improvement over time (e.g. lower margins for low-carbon ships as a means to reduce operating costs), are not evidenced in practice for financiers. There is a sense among European banks that regulations are necessary to accurately assess climate risks, such as the EU taxonomy and differentiated capital requirements for green and brown assets, which suggests that further landscape development are needed for regime financiers to embrace the industry socio-technical transition. Several European banks have emphasised the need for regulation in financial reporting and capital requirements in order for banks to fulfil their role as a Loyal Enabler, as market competition between banks is hindering their ability to fully incentivise greener technologies. This demonstrates both the potential and limitations of voluntary initiatives by financial institutions to promote green investments. In addition, pilot projects carried out by commercial banks have been conducted in collaboration with the State, highlighting the importance of the State or international finance institutions in sharing financing risk through loan guarantees or financing support.

6.3.3 Limitations and future work

This chapter suffers from several limitations. First, concerning the quantitative analysis, there are various metrics to measure the climate performance of corporates and of ship assets, which are often only lightly correlated. To address this limitation, a sensitivity analysis of the results was carried out with alternative measures of environmental performance (see Appendix D.5). However, the existence of numerous instruments and the absence of coherence among them, particularly within the corporate side, highlights the insufficiency of suitable tools to evaluate the climate performance of borrowers and assets. This deficiency poses a potential hindrance to accurately pricing transition risks (F. Berg et al., 2022; SustainAbility, 2018).

Furthermore, the quantitative analysis conducted on the asset side specifically examines the senior secured loan. Although this is a typical scenario in the business, it may not accurately represent the entire industry. This is because the borrowers in this case are typically top-tier clients who possess a larger fleet compared to the industry average (see the analysis on sample bias in the Appendix D.3). Hence, it is possible that lenders factor in the risks associated with transitioning at the individual asset level when providing loans to smaller shipowners or in similar transactions.

However, the author believes that if lenders do not consider these risks for top-tier borrowers and in transactions where the connection between the loan and the asset is evident, they are unlikely to do so for other financing options.

Similarly, the sample of interviews is biased towards large European and US banks, who generally prefer to finance top-tier shipowners. Although other types of lenders have been included and those banks represent the majority of ship financing, it missed, in particular, most Asian financiers, such as leasing agencies, whose involvement in ship finance has increased dramatically over the last decade (Damyanova, 2018b). Employees from these institutions have been approached but did not respond to the demand for interviews. Overall, the two limitations mentioned in this paragraph means that the results are representative only of a certain segment of the financial regime, which is, however, fairly typical and represents to date the majority of external finance, in particular towards newbuilds. Further investigation of alternative lenders and their crucial role in financing the emergence phase of the transition could be conducted using a larger sample. Subsequent research could aim to investigate the perspectives of financiers who are diversified across different geographical locations and engage in various types of lending, such as financiers who focus on smaller ship-owners and/or alternative lending.

Furthermore, the partial discrepancy of the results from those of Woodrow (2023) calls for caution on the continued validity of the results to characterise the behaviour of financiers at the time of writing, particularly given that the data were collected before the adoption of the IMO 2023 Revised Strategy, which largely increased its intention to reduce shipping emissions. Keeping the possible differences of scope mentioned in the previous subsection in mind, the results of the Woodrow (2023)'s survey, if they held true for transition risks, suggest that investors' expectations of the transition has increased, so that they are now considering a Winding Down behaviour. This would open the door for a financial transition to happen alongside a transition of the shipping industry, with new sources of finance at least partially replacing existing financial actors. Testing for this hypothesis would require further research.

Chapter 7

Modelling financiers' expectations and stranded assets

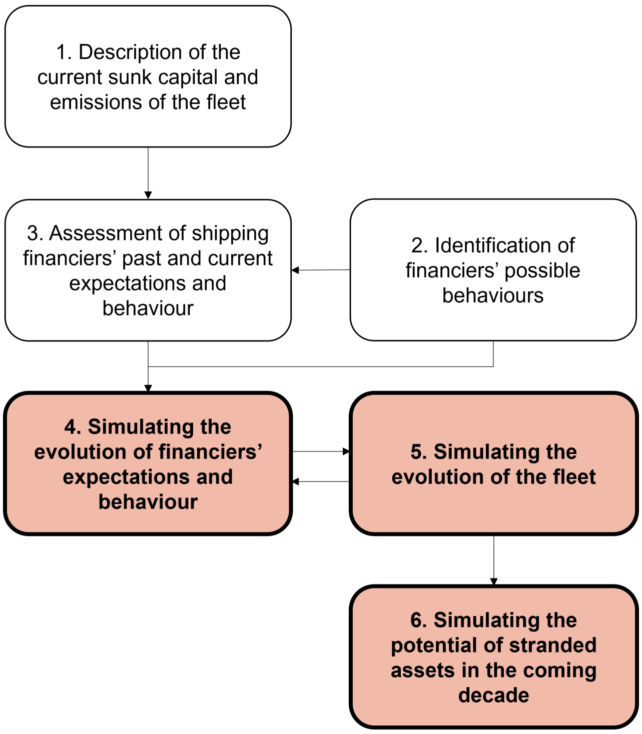

Figure 7.1: Sign-posting of chapter 7

This chapter conducts the final phase of the analysis, which is the simulation of the evolution of financiers' expectations and behaviour, the consequential evolution of the fleet; and, finally, of the resulting stranded assets (see Figure 7.1). Chapter 4 has provided an estimate of the risk of stranded assets based on the existing and ordered fleet (step 1 on Figure 7.1). This assessment, while helpful to get a sense of the misalignment between the capital sunk in current ships and the carbon budget implied by a 1.5° trajectory, was static and therefore ignored the evolution of the fleet after the date of analysis and the potential for retrofitting (which Bullock et al. (2020) does, for example). In particular, it ignored the impact of the financiers' behaviours, which have been investigated in Chapters 6 and 5 (steps 2 and 3 on on Figure 7.1), onto ship investment decisions and the evolution of the fleet (step 5 on Figure 7.1) and consequently on the potential for stranded assets (step 6 on Figure 7.1). Those elements are investigated in this Chapter, which aims to answer Research Question 4, i.e., to explain how financiers' expectations affect the amount of stranded assets during low-carbon transitions in shipping.

The first section of this chapter explains the research methods. The second section presents the results of the analysis. Section K in Appendix provides sensitivity checks to identify the robustness of the results. Finally, Section 7.3 explains the limitations of the methodology, details possible future work and presents the conclusions.

7.1 Research methods

Two exercises are carried out to model the effect of shipowners' expectations on stranded assets. Their structure and interactions are summarised schematically in Figure 7.2. In a first modelling exercise (left column), a shipping-land Stock-Flow-Consistent (SFC) model is used to model the interaction between financiers' beliefs, shipowners' investment decisions, and the cost of debt. There are several outputs from this exercise. The main one is the evolution of the cost of debt, which depends on whether or not shipowners anticipate the future carbon price or not. The costs of debt for green and conventional ships are differentiated because they carry different perceived risks for financiers. This output is used to characterise an "Enabler" versus an "Inert" behaviour, in line with the behaviours identified in Chapter 5. The model also projects investment decisions by shipowners and derives metrics such as shipowners' profits and non-performing loans. The second modelling exercise uses an amended version of the Global Transport Model (GloTraM), which is a bottom-up cost-optimisation model, to project the profits and investment decisions of shipowners, taking into account the differentiated Weighted Average Cost of Capital (WACC) obtained from the first modelling exercise. GloTraM provides much more granular results in terms of technology and ships' technical specification.

The interaction between the two models is twofold. First, none of the models can provide the full range of assumptions necessary to answer Research Question 4, so they are complementary in terms of input/output. In particular, the cost of debt from the land-shipping SFC model; and the initial capital cost of ships, their initial energy consumption and emissions, the initial fuel costs, and the shipping carbon price from GloTraM; are soft-linked from one to another. Second, by aligning the input between the two models and comparing their outputs, it is possible to manage the epistemic uncertainty by observing the implications of the choice of model on the results. In particular, both models provide estimates of investment decisions and profits, but they do so with fundamentally differing modelling paradigms: debt pricing and investment decisions in the SFC model are based on previous steps by linear or differential equations; shipowners and banks do not have perfect information on the future and do not make cost-optimal decisions. In GloTraM, shipowners use their myopic knowledge of the future carbon price to make cost-optimal decisions. Path-dependency is integrated exogenously in the model by adjusting the input (capital cost, WACC, fuel prices).

The next two sections describe in detail the two models. The land-shipping SFC model is fully described in Section 7.1.1 and in Appendix F. The main features of GloTraM with respect to this thesis and the amendments that have been added to GloTraM are described in Section 7.1.2.

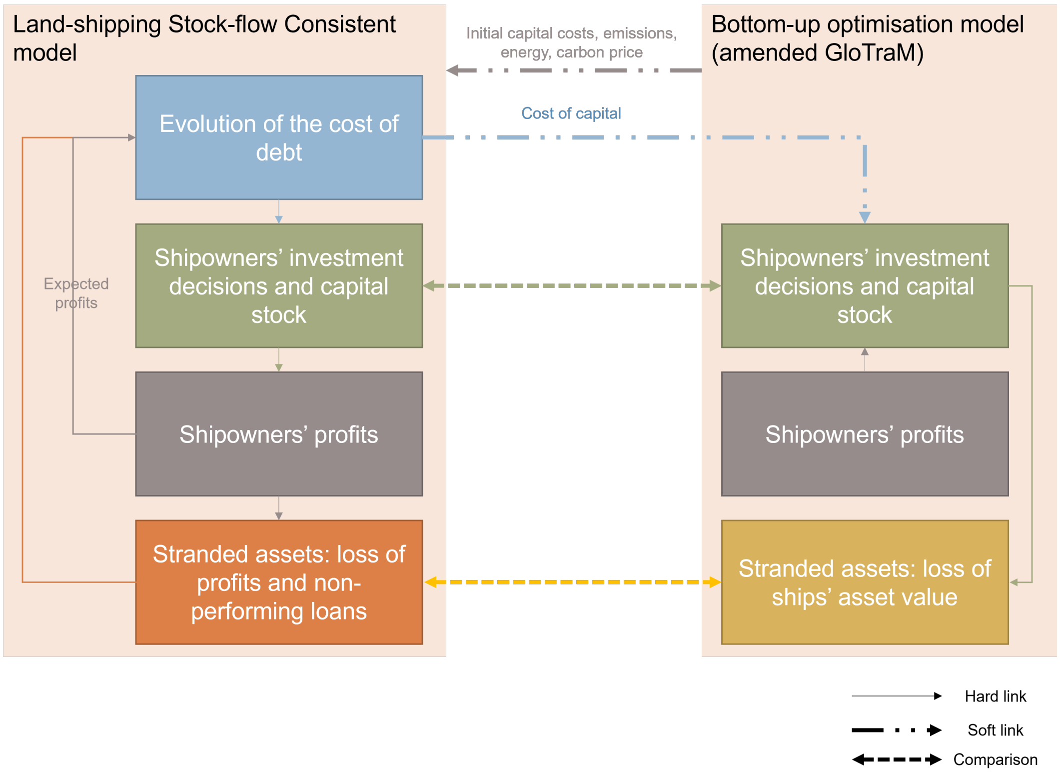

Figure 7.2: Overview of Q4 modelling approach

(a) The lines represent the input from one block to another.

7.1.1 Land-shipping SFC model : modelling financiers' expectations, fleet evolution and stranded paper

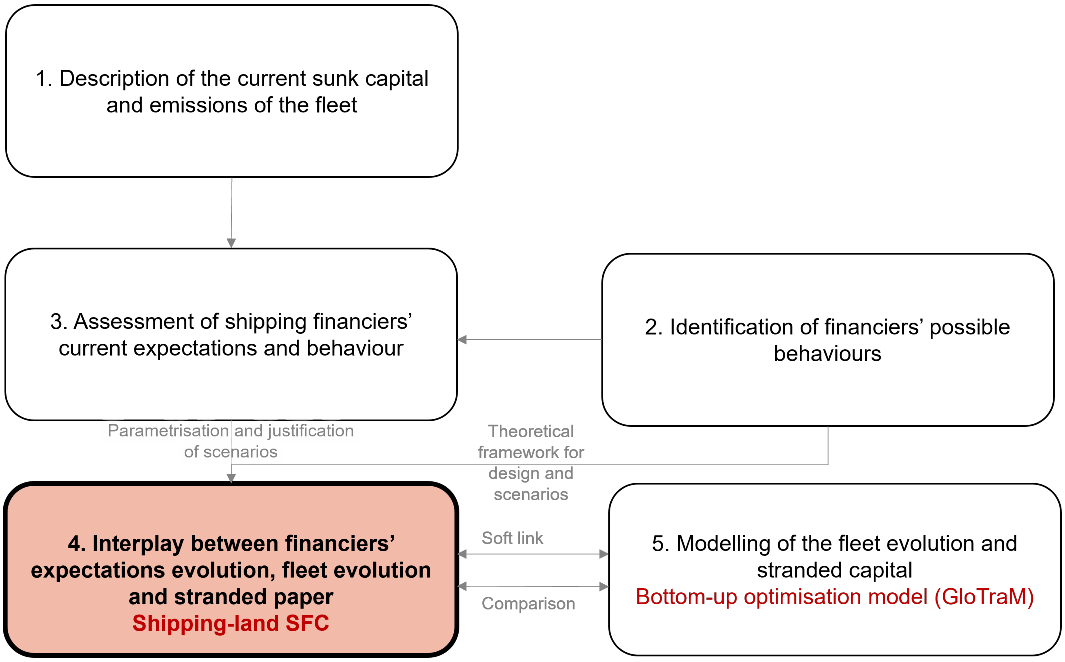

Figure 7.3: Sign-posting: Interplay between expectations evolution, fleet evolution and stranded paper

Let us first describe in more detail the land-shipping SFC model developed in this thesis. Where this method fits into the more general methodology is described in Figure 7.3.

7.1.1.1 Overview of the model

The land shipping SFC model is a hybrid between the following types:

- Stock-Flow Consistent: any positive stock and any flow from one agent is a negative stock of another, in line with accounting principles;
- Econometric: some economic and financial flows are represented by continuous functions whose parameters are, when possible, estimated with econometric techniques;
- System dynamics: some economic and financial flows are represented by differential equations.

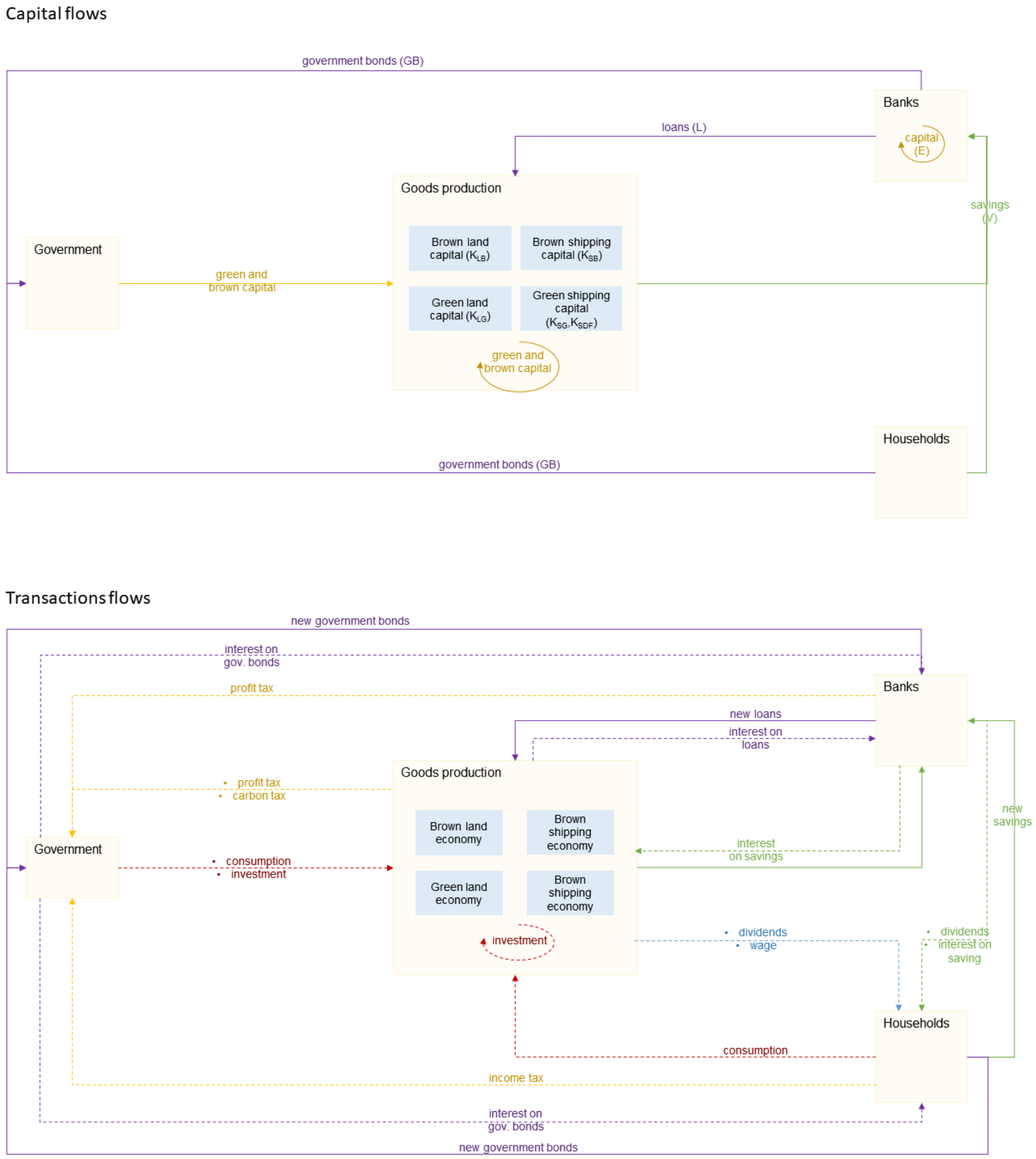

Figure 7.4: Schematic representation of the SFC model

(a) The Central Bank is not included for clarity as its role is limited in this model

The land-shipping SFC model is built from scratch, based on previous academic work. The general approach of the SFC models described in Godley and Lavoie (2007) serves as a basis for this model and was adapted to model the shipping sector (S) explicitly and more realistically . In particular, the goods production cost (in the case of shipping, the cost of moving cargo), emissions, and energy consumption have been modelled more precisely and calibrated onto a sample of shipping segments, i.e., bulk carriers, oil tankers, and container ships. On the other hand, the other sectors, which are not the focus of this thesis, have been modelled without extensive details in one general sector (L, land). Elements of the DEFINE model developed by Dafermos, 2012; Dafermos and Nikolaidi, 2021 related to investment decisions, energy efficiency, and emissions were used to model the firms (i.e., shipowners in the shipping sector). Elements of the SFC model from Dunz et al. (2021) related to the banking sector were also integrated; in particular, the differentiated cost of debt as a consequence of the financiers' expectations of future carbon prices, on the one hand, and as a consequence of the implementation of a green supporting factor, on the other.

The basic structure of the model is described in Figure 7.4, and in detail in the flows matrices in table F.1. There are 5 types of actors in this model:

- Firms invest in capital K^F which they use to produce goods Y. There are two main sectors : shipping S and land L. They can use green capital G, conventional B, or dual-fuel DF (in the case of shipping).
- Households collect income from working for firms WB and from dividends Div, consume goods produced by firms C^H, and provide government bonds to the government GB^H.
- Banks provide loans to firms L and bonds to the government GB^{Bk} in exchange for interest payments. They also keep savings from both firms and households V, against savings rates payments.
- The government collects taxes T from households, firms, and banks. It also collects a carbon tax CT that can be redistributed as subsidies Sub. The gov-

ernment also invests in capital that is used for goods production (K^{gov}) and provides public services (C^{gov}).

- The Central Bank provides advances to banks (A) and keeps part of their cash as compulsory reserves (high-powered money HPM)

In the following, *sc* is the source of capital and can take the value *gov*, government, or F, firm. s is the sector of activity and can take the value L (land sector), or S (shipping). c is the colour or type of technology and can take the value conventional (B), green (G) or dual-fuel (DF). t is the time step and corresponds to one year.

The full set of equations describing the state and the evolution of the stocks of those five actors are detailed in Appendix F. Most of those equations are proposed by Dafermos and Nikolaidi (2021), Dunz et al. (2021), and Godley and Lavoie (2007). For the sake of clarity, only the equations which differ from those papers, and the ones which are particularly relevant to research question 4, are detailed in the two coming sections, which cover equations on firms and banks respectively. The remaining equations are covered in Appendix F. Finally, Appendix H.1 explains how the model was initialised and calibrated.

7.1.1.2 Firms

As in M. Berg et al. (2015), the shipping and land sector exchange intermediate inputs, whose added values are therefore zero, that is, are not counted in Y. First, the land sector consumes shipping services to produce the final goods Y. This is called "shipping output" and is noted Yn^S in nominal value (equation 7.1). Because a large share of the shipping fleet and activity is dedicated to transporting fossil fuels, the share of shipping in total nominal output (sh^S) (before price effects) increases with the share of conventional energy in total energy (equation 7.2 and 7.1). Second, shipping requires several intermediate inputs from the land sector (suppliers S), namely fuel and other suppliers. These are added to the real land output (equation 7.4). The nominal output is adjusted for the prices P^s (equation 7.3).

$$Yn_t^S = sh_t^S Y_t \tag{7.1}$$

$$sh_t^S = sh_1 + sh_2 \frac{Y_{t-1}^{L,B} + Yn_{t-1}^{S,B}}{Y_{t-1}} \tag{7.2}$$

$$Y_t^s = Yn_t^s P_{t-1}^S \tag{7.3}$$

$$Y_L^t = Y_t + S_t^S \tag{7.4}$$

As discussed in the literature review in Chapter 2, there are several ways to model the choice of technology by asset investors in non-equilibrium top-down models :

- A linear function of comparative costs of technologies (as in Dafermos (2012), Dafermos and Nikolaidi (2021, 2022), Dafermos and Papatheodorou (2015), Dafermos et al. (2017, 2018), and Dunz et al. (2021), but none on shipping)
- Cost optimisation (Bas et al., 2017 on shipping, Monasterolo et al. (2018) and Ponta et al. (2018) on other sectors)
- Function of cost and knowledge of the technologies (Chica et al., 2023; Karslen et al., 2019; Rehmatulla et al., 2015 on shipping, Lamperti et al. (2018) and Mercure, Pollitt, Viñuales, et al. (2018) on other sectors)

.

The third approach is chosen for two main reasons. First, it fits best with the desired theoretical feature of "path-dependency", which was identified in Chapter 2. Second, it fits best the uptake of past technologies in shipping, namely Liquefied Natural Gas (LNG), with LNG dual-fuel ships being increasingly ordered following a convex curve in the last years despite higher gas prices (see Figure 7.6), electronic engine (see Figure 7.5) and Mewis Duct (Rehmatulla et al., 2015). Chica et al. (2023), Karslen et al. (2019), and Lamperti et al. (2018) are agent-based models so the approach is not directly compatible with this model, but Karslen et al. (2019) is partially calibrated according to the work of Rehmatulla et al.

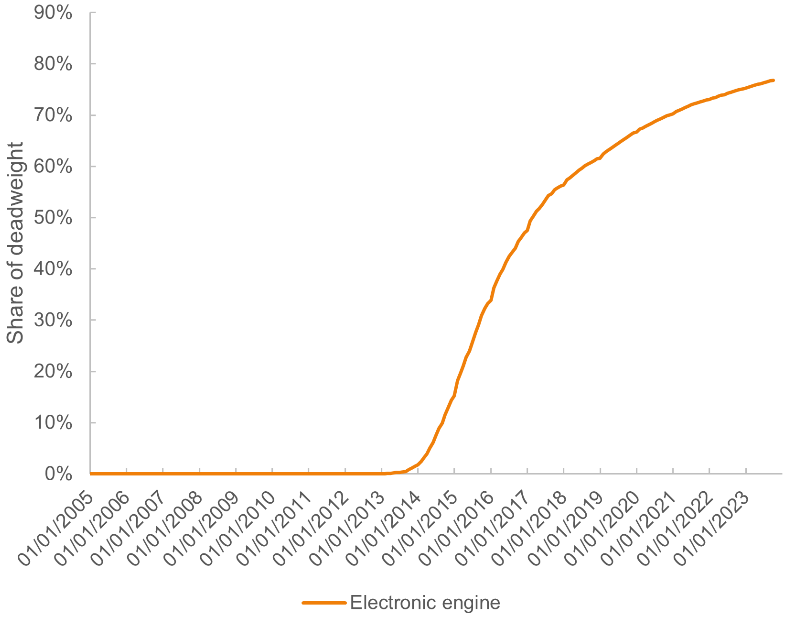

Figure 7.5: Adoption of Eco electronic engines (Clarksons Research, 2022b)

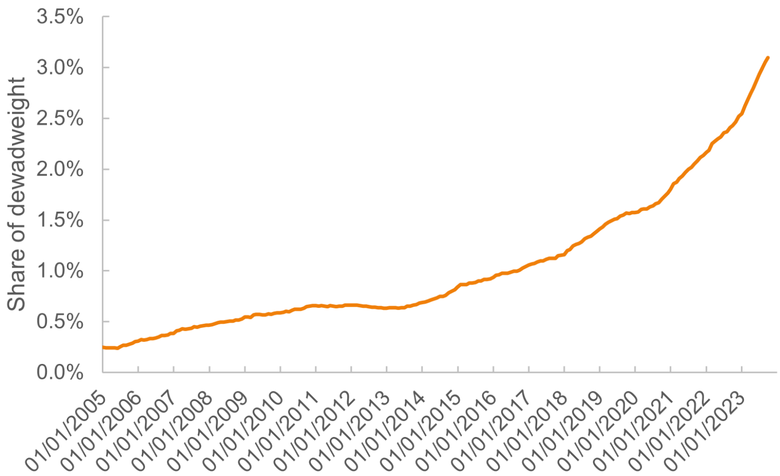

Figure 7.6: Adoption of LNG-capable ships (Clarksons Research, 2022b)

(2015) which uses the Bass curve, where change in the fraction of capital stock $f(x)/(1-F(x)) = p+qF(x)$, with $F'(x) = f(x)$ and p and q the coefficients of innovation and imitation, respectively. This approach is close to the one of Mercure, Pollitt, Viñuales, et al. (2018), but the latter ignores the innovation effect and takes into account the distribution of prices, which requires data that are not available for shipping, since most zero-/low-carbon technologies are not yet available for market. Here, an approach similar to that of Rehmatulla et al. (2015) is adopted, but factors in 1/ the fact that shipowners invest only in the most profitable known technology and 2/ $f(x)$ is constrained by the speed of fleet renewal. This latter point arises because, contrary to energy efficiency technologies which can be added to the existing fleet, here it is assumed that only newbuild vessels can use the alternative technology, i.e. retrofits to alternative fuels are not available to existing ships. This assumption is a limitation of the model which was made for simplicity and computational reasons, and is discussed in the limitations section (Section 7.3.3).

The Bass curve is rephrased with the notation of this thesis in equation 7.5, and assumes that alternative technologies only start to take up once they are more profitable than conventional. Θ is the share of colour in the existing capital and is used as a proxy for the ratio of existing capital, as capital is utilised equally. It is rearranged to incorporate the effect of fleet renewal (which includes replacing scrapped vessels and growing the fleet). Note that in the special case of technologies that can be retrofitted, as in Rehmatulla et al. (2015), $renewal = 1$. Let β be ethe share of colour in new investments. To obtain the final equation 7.7, β is further limited to 1, and it is assumed that $\beta_0 = p/renewal$ and $\beta_1 = q/renewal$ remain constant and the cases in shipping when green and dual-fuel ships are built are differentiated. As long as the cost of conventional is lower than the cost of green, dual-fuel ships (or nothing) are built rather than green. Once green becomes cheaper, it is assumed that only green ships are built. In practice, a marginal amount of green is kept before this point for computing purposes. Furthermore, given that green and dual-fuel ships have the same capital cost, the assumption of the breakdown between green and dual-fuel ships does not have any effect on the results.

$$\Theta_t^{s,G} - \Theta_{t-1}^{s,G} = \mathbb{1}_{tuc_{t-1}^G \leq tuc_{t-1}^B} (p + q\Theta_{t-1}^{s,G})\Theta_{t-1}^{s,B} \tag{7.5}$$

$$\begin{aligned}\beta_t^{s,G} &= \frac{\Theta_t^{s,G} - \Theta_{t-1}^{s,G}}{renewal} \times \mathbb{1}_{tuc_{t-1}^G \leq tuc_{t-1}^B} \\ &= (\frac{p}{renewal} + \frac{q}{renewal}\Theta_{t-1}^{s,G})\Theta_{t-1}^{s,B} \times \mathbb{1}_{tuc_{t-1}^G \leq tuc_{t-1}^B} \text{ with } renewal = \frac{I^s}{K^s}\end{aligned} \tag{7.6}$$

$$\beta_t^{s,c} = \begin{cases} max(\beta_0 + \beta_1(\Theta^{s,G} + \Theta^{s,DF}), 1)\Theta^{s,B}\mathbb{1}_{tuc_{t-1}^G \leq tuc_{t-1}^B}, \text{ if } \begin{cases} s = L; \text{ or} \\ s = S \text{ and } c = DF \text{ and } \mu^S = 0; \text{ or} \\ s = S \text{ and } c = G \text{ and } \mu^S = 1 \end{cases} \\ 1 - \sum_{c \in colours} \beta_t^{s,c}, \text{ if } c = B \\ 0, \text{ otherwise} \end{cases} \tag{7.7}$$

Let us go through the determination of μ, that is, when dual-fuel ships start using green fuel (equation 7.8). First, if they were already using green fuel in the previous time step, they would continue to use it, so there would be no back and forth. If this is not the case, shipping firms compare the cost of running on conventional compared to the cost of running on green if all dual-fuel ships moved to green. The former equals the levelised cost of conventional shipping plus the carbon price per unit of energy $lc_t^{S,B} + em_{t-1}^S ct^S$, with ct_t^s the carbon tax per amount of CO2. The latter equals the levelised cost of green shipping, minus the subsidy. The subsidy equals the total carbon tax collected $Em_{t-1}^{S,B} ct_t^S$, of which only a proportion is recycled into shipping subsidies (*ShareTaxRecycling*), divided by the total amount of green energy if dual-fuel ships run on green ($E_t^{S,DF} + E_t^{S,G}$). Because subsidies per unit of energy cannot exceed a certain share of the cost of green *maxSubsidyShareCost* (see Appendix F for explanation), this amount is capped by *maxSubsidyShareCost*. If running on conventional remains cheaper, then μ keeps the value 0. As dual-fuel is not allowed for the land sector, μ^L is always equal to 0 (equation 7.9) [1]

[1] It is worth noting that this calculation is similar to an Net-Present Value (NPV) calculation and

$$\mu_t^S = \begin{cases} 1, \text{if } \mu_{t-1}^S = 1 \\ 1, \text{if } lc_{t-1}^{S,B} + em_{t-1}^S ct_t^S \\ \qquad > max \begin{pmatrix} lc_{t-1}^{S,G} - \dfrac{ShareTaxRecycling \times Em_{t-1}^{S,B} ct_t^S}{E_{t-1}^{S,DF} + E_{t-1}^{S,G}}, \\ lc_{t-1}^{S,G}(1 - maxSubsidyShareCost) \end{pmatrix} \\ 0, \text{otherwise} \end{cases} \tag{7.8}$$

$$mu_t^L = 0 \tag{7.9}$$

The WACC is calculated as the weighted average of the cost of equity Ce, the cost of debt r and removing the income tax effect τ_F (equation 7.10), with $leverage$ the leverage of newbuilds. l^0 is assumed as a constant but can be increased by l^1 by a government policy to de-risk the green loans, in the form of loan guarantees, as suggested by Schinas et al. (2018).

$$wacc_t^{s,c} = r_{t-1}^{s,c}(1 - \tau_F) \times leverage_t^c + Ce(1 - leverage_t^c) \tag{7.10}$$

$$leverage_t^c = \begin{cases} l_0 + l_1, \text{ if } c \in DF, G \text{ and de-risking policy is implemented} \\ l_0, \text{ otherwise} \end{cases} \tag{7.11}$$

7.1.1.3 Banks

Let us now move to the main equations which govern the evolution of banks' behaviour (the full description of equations can be found in Appendix F).

The banks then set sector- and colour- specific interest rates $r_t^{s,c}$ depending on 4 elements (equation 7.12, in line with the approach proposed by Dunz et al. (2021)):

introduces a degree of profit optimisation in the model. There is a precedent for using NPV in an SFC model to represent decisions made by firms (Bovari et al., 2018; Monasterolo and Raberto, 2018) but it is at odds with the underlying non-equilibrium approach. Alternatively, μ could be modelled as a continuous function of differentiated prices, which could be calibrated on the use of LNG by LNG dual-fuel ships. However, this exercise is beyond the scope of this thesis - which is primarily concerned with investment decisions rather than operating ones - and does not affect the amount of stranded assets from a capital value approach.

- The base interest rate r^L
- The non-performing loan ratio $NPL_t^{s,c}/L_t^{s,c}$, which represents the considerations of firms' past economic performance (a proxy for credit score)
- The credit score is corrected by the additional expected future profits $\tilde{\pi}_t^{s,c}$ compared to last observed profits $\pi_{t-1}^{s,c}$. $\tilde{\pi}_t^{s,c}$ and corresponds to what Dunz et al. (2021) coined as "climate sentiments", which are called "expectations for future profits" here. This is the main novelty proposed by Dunz et al. (2021) and assumes that banks are not only backward-looking, but also forward-looking.
- The impact of macro-prudential policies that affect the risk weights for green firms, i.e., the Green Supporting Factor (GSF) or Brown Penalising Factor (BPF). When GSF is implemented, χ^G becomes lower and the interest rate decreases for green loans by $\kappa_2(\chi^G - \chi^B)$. Inversely, the implementation of a BPF leads to an increase in χ^B. Note that it is assumed that dual-fuel ships receive the same benefits as green ships.

$$
\begin{aligned}
r_t^{s,c} =& r_t^L \\
& + \kappa_1 \frac{NPL_t^{s,c}}{L_t^{s,c}} (1 - \frac{\tilde{\pi}_t^{s,c} - \pi_{t-1}^{s,c}}{\pi_{t-1}^{s,c}}) \\
& + \kappa_2 (\chi^G - \chi^B) \mathbb{1}_{c \in \{G,DF\}}
\end{aligned}
\tag{7.12}
$$

Banks' expectations are modelled as an implementation of the Dunz et al. (2021) proposal, which is summarised below. For more details, please refer to the article. In the scenario where banks are enablers (climate sentiments in Dunz et al. (2021) terminology), the nature of climate transition risks hinders their ability to possess perfect foresight. In a scenario where they anticipate the implementation of a carbon policy at a specific time point, they can only make informed estimations about future consequences, such as the impact it will have on firms' profits. Suppose that a bank at time t expects that a carbon tax will be implemented at time $t+q$

in the coming b years. Instead of waiting until $t+q$ to adjust the interest rate, it adjusts its interest rate already at time t. The expected future profits are modelled as follows (see Figure 7.7 for a graphical representation):

- Step 1: Past observed profits up to a years before generate a series of past observations $\Omega = [\pi_{t-a}, ..., \pi_{t-2}, \pi_{t-1}]$

- Step 2: A function f is fitted to Ω. Future backward-looking profits up to b years in the future are estimated using this logistic function $\hat{\Omega} = f([t, ..., t+b])$

- Step 3: $\hat{\Omega}$ is modified to incorporate the effect of the carbon tax, by adding the future change in profits ψ due to the implementation of the carbon tax. The vector Z is of length $b+1$ and its i-th element is equal to 0 if $i < q$ and $\psi^{s,c}$ if $i >= q$.

$$\hat{\Omega}^* = \hat{\Omega} + Z \tag{7.13}$$

- Step 4: Past observations Ω and predicted series $\hat{\Omega}^*$ are combined to create series $\bar{\Omega} = (\Omega, \hat{\Omega}^*)$.

- Step 5: A logistic function $\bar{f}$ is fitted onto $\bar{\Omega}$ and is used to predict $\tilde{\Omega} = \bar{f}([t, ..., t+b])$. The expected future profits are finally described in Equation 7.14.

$$\tilde{\pi}_t^{s,c} = \tilde{f}(t+1) \tag{7.14}$$

In the case of Inert banks, the expected future profits are simply equal to the last profits $\pi_{t-1}^{s,c}$.

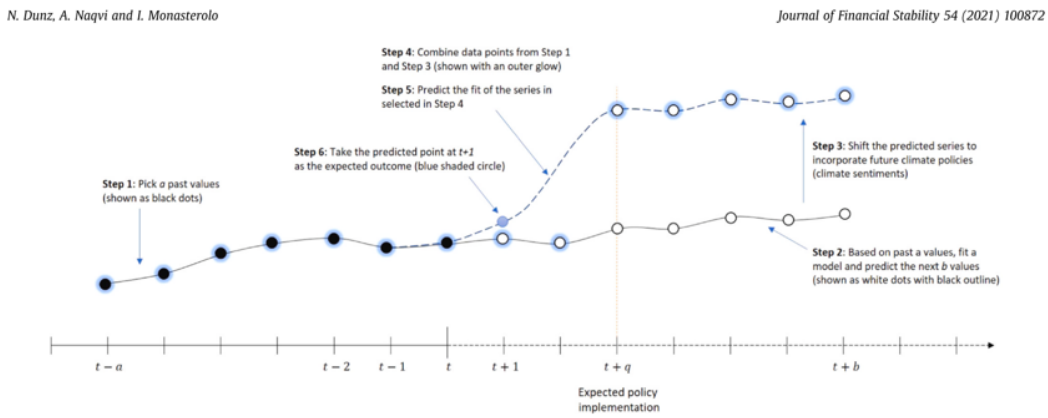

Figure 7.7: Overview of modelling of banks' expectations for future profits (from Dunz et al. (2021))

(a) The x-axis represents time, with current period at time t and implementation of future carbon tax at time t+q

7.1.2 Amended GloTraM: modelling fleet evolution and stranded capital via book loss

After detailing the structure and equations of the land-shipping model, this section now explains the second model used in this chapter, namely the extension of GloTraM. The integration of this method into the methodological approach of this thesis is summarised in Figure 7.8. GloTraM is an existing bottom-up optimisation model of the shipping fleet. The main existing features of the model related to this thesis are presented in Section 7.1.2.1. It was amended to integrate the effects of the lenders' expectations, which is described in Section 7.1.2.2. Furthermore, a post-processing module was built using its outputs to estimate the amount of stranded assets carried out by a fleet in various variants, where one parameter is changed to see its effect across all of the scenarios. To do so, a method was developed to estimate the second-hand value of the fleet, using the ships' specifications provided by GloTraM. It is detailed in Section 7.1.2.3. Of this value, the amount at risk of being stranded is further estimated using a modelling approach proposed in Section 7.1.2.4. Finally, in the appendices, Appendix G explains the bugs that were fixed, Appendix H.2 explains the input used to calibrate GloTraM, and Appendix B.4 validates some of the results.

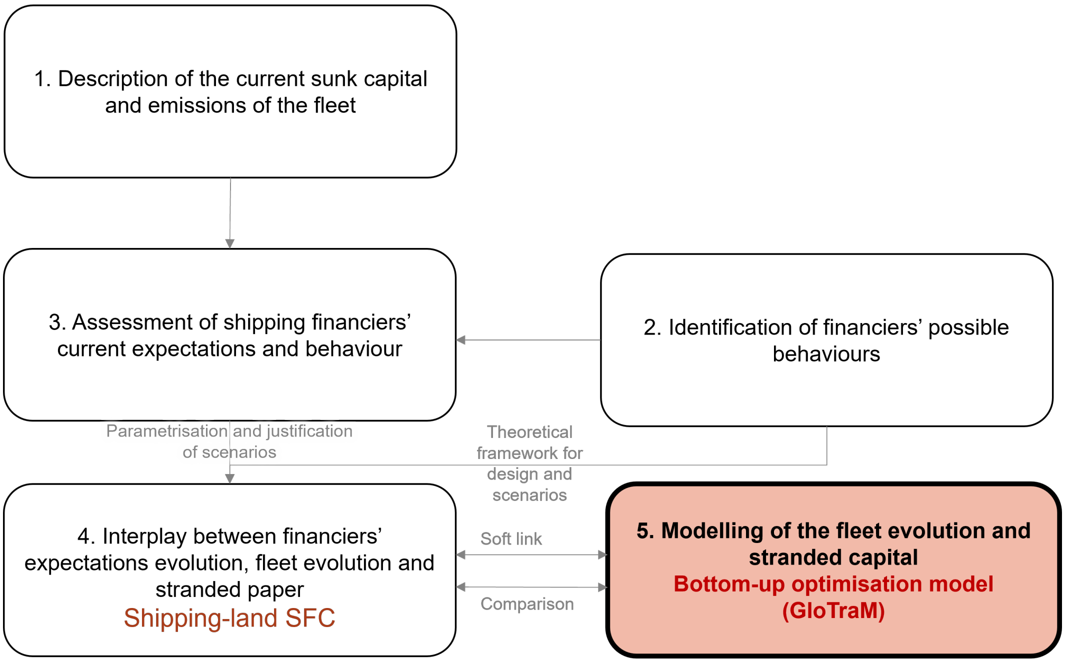

Figure 7.8: Sign-posting: modelling fleet evolution and stranded capital

7.1.2.1 Description of investment decisions in GloTraM

This section describes how GloTraM models investment decisions into new ships. A detailed description of how GloTraM works can be found in Raucci et al. (2017) and Smith et al. (2023).

GloTraM is a scenario-building tool that was originally developed for the international shipping sector to optimise agent's profit. Policymakers and stakeholders have used it to get insight into the processes and interactions within the shipping system (Smith et al., 2016, 2019b, 2022). The primary objective of GloTraM is to holistically analyse the global shipping system, incorporating data and modelling, to assess how the sector could change in response to various economic, technological, and environmental factors. GloTraM builds well-defined and manageable analysis blocks of the shipping system. These blocks capture complex interactions within the sector and interact with different modules and databases, as depicted in Figure 7.9. By connecting all components and considering the dynamics at a 'whole system' level, the model uses robust algorithms to evaluate different scenarios effectively. A notable feature of GloTraM is that it considers investment, techno-economic, and operational decisions for each ship class. Ship classes refer to different types, sizes, and age categories of ships. The model maximises the shipowner's profit for each specific ship class, taking into account various factors such as fuel prices, technological innovations like on-board carbon capture systems, and environmental regulations.

The ship evaluation module defines the characteristics of both existing and newbuild ships by optimising the combination of the following elements for profitability (represented by the Net Present Value, NPV) :

- Fuel choice for main engines,
- Operating speed, and
- Single and/or combination of CO2 abatement options.

These three elements offer different ways to optimise the NPV, and any change made within one element can impact the others. For example, combinations of engines and fuels influence factors such as specific fuel consumption, average emission factors, and costs. Similarly, variations in speed directly affect transportation work and fuel consumption. Before the simulation, the fuel and main engine options are established. In each time step, the model selects the characteristics and machinery/technology configuration of both existing and newbuild ships that result in the highest NPV while respecting regulations, thereby determining the most profitable option.

The model assumes that the shipowner is responsible for making investments in newbuilds or modifications to existing ships. To calculate the NPVs, the following steps are taken:

- Step 1: Calculation of annual transport costs during the assessment period, including fuel expenses and carbon prices. It is worth noting that future carbon prices over the assessment period are assumed to be equal to the carbon price at the same step, so shipowners do not expect any change in future carbon prices. This corresponds to a situation where shipowners are myopic about transition risks.

- Step 2: Calculation of annual voyage charter revenue, based on an assessment of $ / tonne of voyage income.

- Step 3: Calculation of annual revenue and costs of the shipowner. The latter includes, in particular, the investment cost in machinery, tanks, and energy efficiency devices. In the original version of GloTraM, it was calculated using a constant WACC.

- Step 4: Calculation of the NPV.

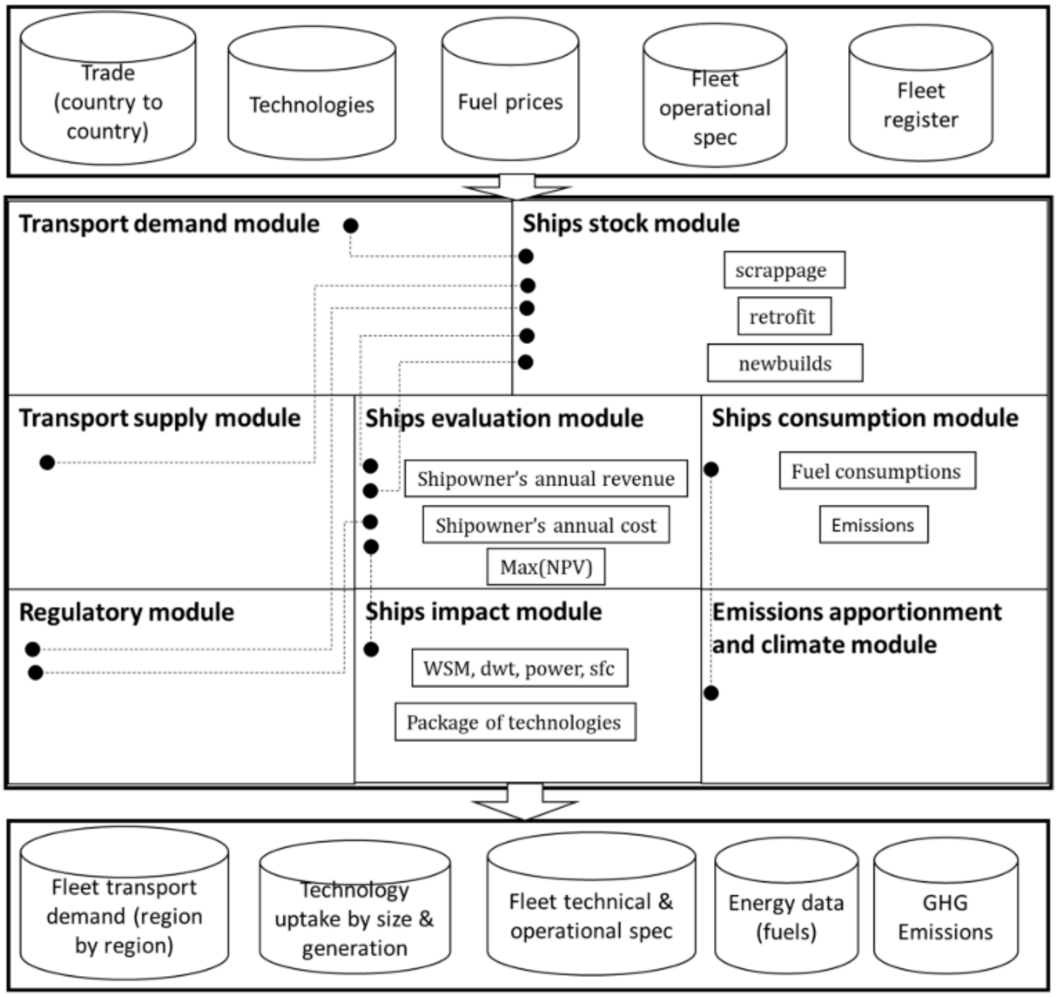

Figure 7.9: A conceptualisation of the GloTraM model framework. Taken from Smith et al. (2023)

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(a) Acronyms: WSM stands for Whole Ship Model, dwt for deadweight and sfc for specific fuel consumption.

7.1.2.2 WACC and investment decisions

This section describes how the modules modelling investment decisions in GloTraM were modified for the purpose of this thesis.

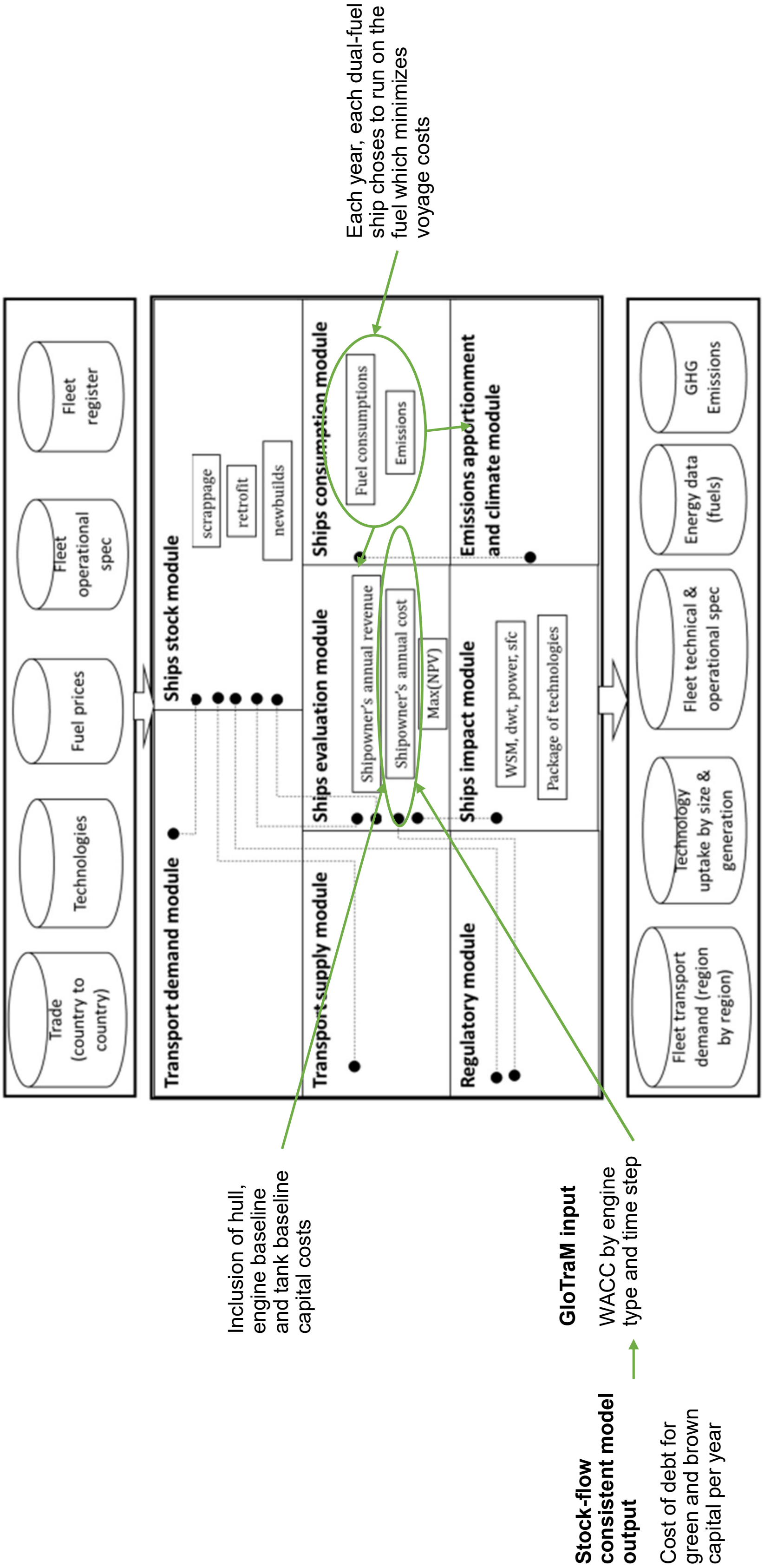
For the purpose of this thesis, the following elements were modified as in Figure 7.10:

- In step 3, the annual investment cost is now calculated using a WACC which is specific to the year of investment and the engine type. This allows the perceived risk by lenders of various technologies to be represented and is directly taken from the output of the SFC model described in the previous sub-section.

- In step 3, all engine and non-machinery costs are added so that investment cost represents the overall ship cost.

- In the original version of GloTraM, dual-fuel ships were limited to using the lowest emissions fuel, resulting in ships like methanol/LSHFO dual-fuel ships effectively only using methanol. This restriction was acceptable as long as there was no reason for shipowners to invest in dual-fuel ships, if not to use them with alternative fuels and to benefit from a reduced carbon tax. However, when differentiated WACC is allowed, shipowners might invest in a dual-fuel ship to benefit from a reduced annual capital cost, while still using it with LSHFO. The optimisation algorithm now considers two versions of dual-fuel ships: one where the shipowner selects the most profitable fuel each year to minimise voyage costs in a new preliminary step called step 0 (but the ship might then fail to pass some regulations, e.g., CII), and another one where they are forced to use the low-carbon fuel. The algorithm selects the most cost-effective one which respects regulations.

- Compliance to CII thresholds is imposed not only on existing ships but also on newbuilds, to ensure that new ships start operating while respecting regulations. CII is implemented as in Smith et al. (2023).


Trade (country to country)
Technologies
Fuel prices
Fleet operational spec
Fleet register
Transport demand module
Ships stock module
scrappage
retrofit
newbuilds
Transport supply module
Ships evaluation module
Shipowner's annual revenue
Shipowner's annual cost
Max(NPV)
Ships consumption module
Fuel consumptions
Emissions
Regulatory module
Ships impact module
WSM, dwt, power, sfc
Package of technologies
Emissions apportionment and climate module
Fleet transport demand (region by region)
Technology uptake by size & generation
Fleet technical & operational spec
Energy data (fuels)
GHG Emissions
Each year, each dual-fuel ship choses to run on the fuel which minimizes voyage costs
Inclusion of hull, engine baseline and tank baseline capital costs
GloTraM input
WACC by engine type and time step
Stock-flow consistent model output
Cost of debt for green and brown capital per year

Further details on how steps 0 and 3 are implemented are provided below. For details on how the steps are calculated, please refer to Raucci et al. (2017) and Smith et al. (2023).

In a preliminary step 0, the owner of a dual-fuel ship decides which fuel the ship will use. Single-fuel ships simply use the one fuel that is available to them. For dual-fuel ship, the fuel used is the one that minimises equation 7.15.

$$VC_i = em_i^{op} \times TC_{op} + em_i^{up} \times TC_{up} + FC_i \tag{7.15}$$

With VC_i the voyage cost of fuel i, em_i^{op} and em_i^{op} the operational and upstream emissions respectively per kWh of fuel used, FC_i the fuel cost expressed in \$/kWh.

In step 3, the annual cost incurred by the shipowner (C_{ow}) is now determined through the following equation:

$$C_{ow} = C_{base} + C_{\delta} \tag{7.16}$$

C_{base} represents the annual baseline cost, which comprises capital, brokerage, operating costs, ship maintenance, salaries, and other provisions. It was not modified from the initial version of GloTraM. It excludes voyage, port, and fuel costs, as these are assumed to be covered by the charterer, who pays the market time-charter day rate throughout the year (Raucci et al., 2017). Consequently, any surplus profits or losses for the shipowner are contingent on the disparity between the fuel cost savings transferred from charterers and the additional investment expenditure incurred.

The yearly capital expenditure is denoted as C_{δ}, which accounts for any capital expenses related to the selected retrofit or newbuild specification, including those required for a baseline specification. This differs from the previous version of GloTraM, where only costs that differed from the baseline specification were included. C_{δ} encompasses the capital costs associated with energy efficiency improvement (C_{eet}) as a difference from the standard hull cost; the main machinery cost (C_e) and the storage cost (C_s) as the capital expenses of the engine and fuel storage; C_h the standard hull capital cost; and the annualised fixed operating costs (C_{opa}). Capital expenses are transformed into annualised costs, as illustrated in equation 7.17, thus encompassing all these factors as part of the annual capital expenditure. $wacc$ and T are the interest rate and the pay-off period, respectively.

$$C_\delta = \frac{\frac{wacc(C_{eet}+C_e+C_s+C_h)}{1200}}{12(1-(1+wacc/1200))^{12T}} + C_{opa} \tag{7.17}$$

The cost of the baseline hull C_h was not included in the previous version of the model. It is now included and is a linear function of ship deadweight dwt for each ship type s:

$$C_h = a_s + b_s dwt \tag{7.18}$$

The coefficients a_s and b_s are specific to each ship type s (containers, bulk carriers and oil tankers) are fitted using a regression analysis detailed in Section 4.1.1.1.

While $wacc$ was a constant set for all time steps and all ship types in GloTraM's previous version, for the purpose of this thesis, $wacc$ is calculated for each engine type and time step as follows:

$$wacc = \begin{cases} (d_d - diff/2)leverage^G(1-\tau) + d_e(1-leverage^G) \\ \qquad \text{if the engine is able use a zero-/low-carbon fuel} \\ (d_d + diff/2)leverage^B(1-\tau) + d_e(1-leverage^B) \text{ otherwise} \end{cases} \tag{7.19}$$

The WACC is calculated as the average of the cost of debt and the cost of equity (constant d_e), weighted by the constant shares of each in total assets ($leverage$ and $1-leverage$, respectively) and corrected for tax rate τ. As in the land-shipping SFC model, under a de-risking policy, a public financial body (e.g. an Export Credit Agency) provides guarantees on loans provided to zero-/low-carbon ships only. This increases the leverage of the ship newbuild financing by l_1 and reduces the WACC, as suggested by Schinas et al. (2018). The cost of debt is different between ships that can use a zero-/low-carbon fuel (methanol, ammonia, and hydrogen) and those which cannot (e.g. single-fuel conventional ship). The constant standard cost of debt d_d is corrected for by the difference between the cost of debt of the conventional capital and the green capital $diff$ found by using the SFC model detailed in Section 7.1.1.

This approach rests on several assumptions:

- The cost of equity C_e does not reflect transition risks, whose underlying assumption is that equity investors are blind to climate risks. Equity investors can be external actors if the shipowner is listed, but for most of the shipowners, this is the shipowner itself. This assumption is consistent with the SFC model detailed in Section 7.1.1 and with the assumptions that shipowners are blind to climate risks, i.e., an Inert behaviour.

- The lenders adjust the pricing of the loans they provide with the risk they perceived rather than the rationing of the amount they lend, which leads to *leverage* being constant, unless a specific de-risking policy is implemented. The rationale and limitations of this approach are discussed in F.0.2.

Both of those assumptions can be relaxed and are worth investigating in future research: one could expect in the future that equity investors adjust their beliefs of transition risks; or that banks would refrain from financing certain types of ships, which might lead them to have a lower share of debt in their finance sources. However, including all effects conjointly would alter the clarity of the results, as a variation in the results might be due to the variation of any of those factors, and would not therefore allow the effect of the sole pricing of the lenders' beliefs of future climate risks to be disentangled, which is the objective of research question 4. This specification of the WACC should therefore be seen as a way to answer research question 4, i.e., what would happen if lenders started to price into the cost of debt the transition risks attached to the financed ships, rather than a realistic assessment of future evolution of the WACC.

7.1.2.3 Fleet valuation

This step is necessary to derive the maximum potential value at risk of being stranded in the fleet, as detailed in Section 7.1.2.4. How the value of the fleet is estimated is described in this section[2].

[2] This Section builds on the work done for Fricaudet, Taylor, and Smith (2022), although more efforts have been made for calibration and analysis have been carried out since then, so the results

As discussed in Chapter 4, Section 4.1.1.1, the newbuild and depreciated value of each ship can be estimated using parameters related to power (mcr), deadweight, fuel type, and ship type. Those parameters were estimated in Chapter 4, Section 4.1.1.1. Given that the dataset used to estimate the parameters contains many LNG-fuelled ships and a few methanol dual-fuel ships, the estimated parameters can theoretically be used to predict the value of each LSHFO single-fuel, and LNG and methanol dual-fuel ship from GloTraM output, using the ship specifications (MCR of main engine, deadweight, ship type, and fuel type) given in GloTraM output. However, for the other alternative fuels, in particular ammonia, there is no record of their newbuild prices in the WFR data. For those fuels, the newbuild value of each vessel can be calculated using the investment cost of each engine and tank rather than the estimated coefficient of regression. However, while the former approach covers market drivers, the latter only includes technology costs. The comparison may be biased between different types of alternative fuels if the market value is significantly impacted by other drivers, such as the limited capacity of the shipyard to build alternative-fuelled ships. As a result, all ships are valued by adding a technology capital expenditure of the engine and tank above the market price, excluding the interactions effects with the MCR and the fuel type, according to equation 7.21.

In equation 7.21, st is the storage capacity of bunker fuel bf, expressed in tonnes of fuel (the output of GloTraM). Note that all dual-fuel ships, apart from those powered by methanol, have two tanks, one for alternative fuel f, and one for LSHFO. As per Maersk Mc-Kinney Møller Center for Zero Carbon Shipping (2022a), it is assumed that methanol tanks can be used to store LSHFO. C is the cost per kW of the main engine (*main*), of the auxiliary engine (*aux*) or the cost per tonne of fuel of the storage tank (*storage*), and is an input to GloTraM. a_s and b_s are the coefficients of the intercept and interaction terms with the deadweight estimated with the model (3).

slightly differ

$$
\begin{aligned}
P^{new}_{mcr,dwt,st,f} = & a_s + b_s \times dwt \\
& + mcr^{main} \times C^{main}_f \\
& + mcr^{aux} \times C^{aux}_f \\
& + \sum_{bf inf, LSHFO} cap_{bf} \times C^{storage}_{bf}
\end{aligned}
\tag{7.20}
$$

(7.21)

The depreciated value is simply calculated as the linear depreciation of the newbuild value over the average lifetime until scrapping of the ship, and to the scrapping value. Using this method is subject to uncertainty, as the depreciation might not be linear and/or the end of economic life might happen before the time of scrapping, as previously discussed in Section 4.1.1.1 and in Appendix B.5. Given this uncertainty, the linear depreciation to the scrapping price at scrapping age is used as the central assumption, but the sensitivity of the results to the assumption on depreciation is tested by assuming a profile of 25 years for all ships.

7.1.2.4 Stranded assets

After explaining the methodology to estimate a fleet's second-hand value, this section[3] explains the methods to estimate the part of this value that could become stranded under various decarbonisation scenarios variants. Three variants are considered: one where drop-in fuels are available, one where drop-in fuels are not available but retrofitting is possible, and one where none of those are available. Further variants where different fuels become dominant (ammonia and methanol) are also considered

In the variant where drop-in fuels (e.g. biodiesel for conventional ships) are available at scale and competitively, no asset is stranded. In a variant where neither retrofitting nor drop-in fuel are available or cost competitive, the whole value of the

[3]This Section is directly taken from the report "Exploring methods for understanding stranded value : case study on LNG- capable ships" (Fricaudet, Taylor, and Smith (2022), Section 4.1 and Appendix A), whose main author is the thesis candidate who has designed the methodology and written the manuscript. Some sections of the text have been directly copy pasted below.

fleet is stranded.

In the variant where retrofitting is available, but no drop-in fuels, as zero-/low-carbon fuels (such as hydrogen, ammonia, and methanol) become increasingly mainstream, owners and operators of conventional ships are likely to face a choice of how to remain competitive with zero-/low-carbons newbuilds: between higher fuel costs (using drop-in fuels) or retrofitting (to a zero-/low-carbon design). The method assumes that retrofitting is the least costly option for compliance / competitiveness when the risk of stranded assets materialises (in this thesis, in the 2030s), especially for younger assets (e.g., 5-10 year old vessels). The costs of the options to remain competitive or in compliance are used to explore how the market could value conventional vessels relative to newbuild alternative-fuelled ones at a point in the future when policy and technology have clarified.

Conventional ships might unexpectedly lose value by competing with zero-/low-carbon newbuild ships; for the sake of the argument, let us assume for now that it is ammonia. For illustrative purposes, let us take the case of an investor who wants to acquire a 71,000 tonne deadweight bulk carrier with installed power of 7.1MW in 2030. She has the choice between buying a second-hand 8-year-old conventional ship and retrofitting it to ammonia, or ordering a newbuild ammonia dual-fuel ship. She can then run the former for its remaining 12 years or the latter for 20 years. For financing assumptions, its economic lifespan is assumed to be 20 years and its second-hand value depreciates to zero over 20 years[4]. The newbuild value of this illustrative ship can be estimated using the method detailed in 7.1.2.3 based on Clarkson's newbuild data: the newbuild value of the conventional ship is approximately \$ 27 m [5]. If the scrap of the ship is disregarded, in 2030, it is 8 years old and has depreciated to $(20-8)/20 = 60\%$ of its newbuild value, that is, \$ 16m. An ammonia dual-fuel newbuild of the same dimensions would be worth \$36m. Given a known price for an ammonia dual-fuel newbuild, what should she

[4] 20 is used for illustrative purpose here, but when modelling the full fleet, the average scrap age calculated from Clarkson's WFR is used as the expected lifespan. See Section 4.1.1.1 for the data used.

[5] All numbers have been rounded and the scrappage value of the ship is assumed to be 0 in this specific example for illustrative purposes; this was not the case when full results were computed.

be ready to pay for the 8-year-old conventional ship? There are several ways to quantify the answer to this question, but it is simply proposed here to take the value of the new ammonia dual-fuel ship depreciated to 8-years old, against which one needs to compare the second-hand value of a conventional ship including the cost of its retrofit to ammonia. As an ammonia-newbuild is worth around \$36m, the 8-years old equivalent should be worth $60\% \times 36 = \$22m$. To compare with this, the conventional ship investor would still need to pay \$14m to retrofit her ship from LSHFO to ammonia, so she should only pay $\$22 - 14m = \$8m$ for the conventional 8-year-old ship. As a result, the conventional ship has lost $(16-8)/16 = 50\%$ of its second-hand value (see Figure 7.11 for a schematic representation).

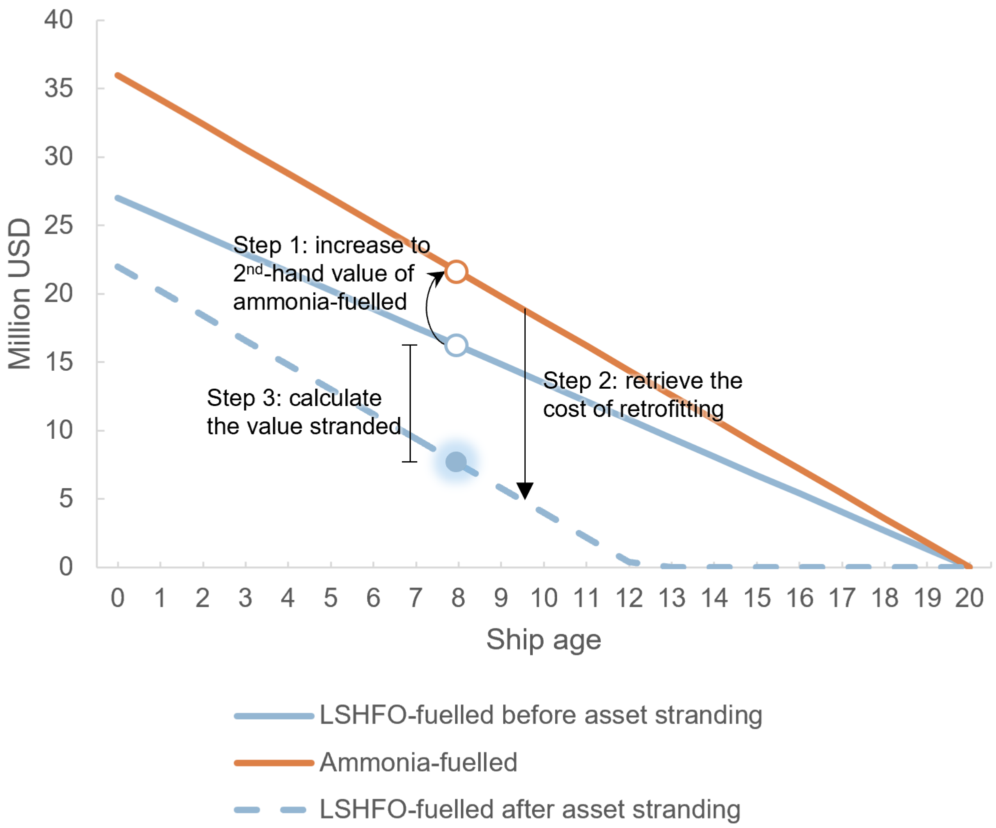


Figure 7.11: Illustration of the methods to estimate stranded capital via book loss

(a) The values plotted correspond to an illustrative 71,000 deadweight bulk carrier with 7.1MW installed power. For the sake of simplicity, in this specific example, the scrap value is assumed to be 0 and the expected lifetime 20 years.

The choice to use the value of the new ammonia dual-fuel ship depreciated to 8-year-old rests on the following underlying assumptions:

- The long-term average value of a second-hand ship is a function of its newbuild value; in other words, the newbuild and second-hand markets are linked through a linear relationship over the long run since new and second-hand ships are interchangeable (see Sections 4.1.1.1 and B.5 for a more in-depth justification of the assumption of linear depreciation). The validity of this simplification is supported by the interconnectness of the newbuilding and the second-hand ship markets - along the demolition and the freight markets - as attested in the literature (Stopford, 2009; Thalassinos and Politis, 2014; Tsolakis et al., 2003);

- The long-term average second-hand value eventually outweighs the short-term variations in the market prices of second-hand ships (e.g. short-term changes in freight rates, short-term impact of inflation or shipowners' expectations) which are ignored in this approach. More generally, this approach ignores the high short-term volatility of shipping second-hand prices, which is difficult to integrate in such long-term assessment, but corresponds to the typical accountancy and brokers' practice to depreciate ships down to scrap (Stopford, 2009);

- A retrofitted and a newbuild ammonia dual-fuel ship are substitutes on the market.

The intuition described in this illustrative can be formalised mathematically as follows:

$$V^{intrinsic}(f,dwt,mcr,s,age) = max(V^{second-hand}(g,dwt,mcr,s,age) - C^{retrofit}(g,mcr), V^{scrap}(dwt)) \quad (7.22)$$

$$(7.23)$$

With $V^{intrinsic}(f,dwt,mcr,s,age)$ the intrinsic value of a ship powered by fuel f, of deadweight dwt, main engine power mcr, ship type s and age age when in competition with newbuilds powered by a zero-/low-carbon fuel g;

$V^{second-hand}(g, dwt, s, age)$ the second-hand value of the ship of the same characteristics but powered by g; $C^{retrofit}(g, mcr)$ the cost of retrofitting to g and $V^{scrap}(dwt)$ the scrap value of the ship. The stranded value is the difference between the ships' second-hand value and the intrinsic value of the ship:

$$\begin{aligned} SA(f, dwt, mcr, s, age) = & V^{second-hand}(g, dwt, mcr, s, age) \\ & - V^{intrinsic}(f, dwt, mcr, s, age) \end{aligned} \tag{7.24}$$

The stranded value is calculated for each GloTraM cohort (ship type $\times$ ship size bin $\times$ build year) and is aggregated across the entire conventional fleet.

The cohorts built before the start year are grouped with a larger range than the model time step: for example, ships built between 2007 and 2014 are grouped under the 2014 generation. This creates bias in their estimate of age and depreciated value. Therefore, in post-processing, they are divided into sub-generations covering the same number of years as the time step.

7.2 Results

This section discusses the results[6] of the chapter to attempt to answer Research Question 4: how do the expectations of financiers of upcoming low-carbon transitions in shipping affect the amount of stranded assets? Various scenarios were run in the two models and are described in Section 7.2.1. The results of both models are discussed and compared along three topics, as in Figure 7.2: the evolution of the WACC, the investment decisions of the shipowners and the evolution of the fleet, and stranded assets. Those topics are discussed, respectively, in sections 7.2.2, 7.2.3 and 7.2.4.

[6] The presentation of the results slightly differ from the other Chapters due to the length of this Chapter and for readibility of the results. In particular, key findings are highlighted in bold in Sections 7.2.2 to 7.2.4

7.2.1 Scenarios

To explore the interactions between the financial system and stranded assets, a range of scenarios described in Table 7.12 are compared. First, two scenarios of potential behaviours (first line in Table 7.12), without any further financial policy, are considered :

- **Inert** financiers: lenders do not anticipate climate risk (i.e. upcoming carbon tax), are inert of landscape pressures and they react to its implementation only once it has effects on the liquidity of the firms. In this scenario, no lever is promoting the uptake of cleaner ships.

- **Enabler** financiers: lenders anticipate the implementation of the carbon tax 7 years before it is implemented and adjust their loan pricing accordingly. This could also represent a situation where financiers perceive and react to broader landscape pressures, as described in Chapter 6, such as change in customer or shareholder preferences towards more climate considerations. In adjusting their pricing, they support the niche technology - the modelling is however silent on whether this niche technology is being developed in protected niche and/or held by niche actors, or whether it is already being integrated by incumbent actors in the wider regime

		Behaviour	
		inert	enabler
Financial policy	none	Inert	Enabler
	de-risking	De-risking*	Enabler + de-risking
	Diff. capital requirements	GFS + BP*	*Not modelled*
	de-risking + diff. capital requirements	Combined financial policy	*Not modelled*

Core scenarios

Additional scenarios

* Scenarios only run in the land-shipping SFC model

Figure 7.12: Description of scenarios

(a) * Scenarios only run in the land-shipping SFC model

2 scenarios are built corresponding to possible financial policies implemented in isolation (1st column, 2nd and 3rd row in Table 7.12). Those represent external

landscape shocks to the regime financiers:

- **De-risking**: in order to support an early uptake of green technology, a public financial institution provides guarantees to loans used to finance green and dual-fuel technologies from 2023 to 2033. No guarantees are given to conventional loans. This leads to an increase in the leverage of the green investments, in line with Schinas et al. (2018), from 65 to 80%.

- **Green Supporting Factor and Brown Penalising Factor (GFS+BP)**: the regulator requires from 2023 onwards that banks use a lower risk weight on green and dual-fuel loans (usually called a ”Green Supporting Factor”) ($\chi^G = \chi^{DF} = 0.8$) and a higher risk weight on conventional loans (”Brown Penalising factor”) ($\chi^B = 1.2$).

As it will be seen from the results, none of the 4 scenarios described above are capable of generating a difference in WACC sufficient to bridge the gap between zero-/low-carbon and conventional ships. Therefore, two composite scenarios combining two of the levers described above are built to create a sufficient difference in WACC to drive an early uptake of zero-/low-carbon ships :

- **De-risking + Enabler**: in this scenario, a de-risking policy implemented by a public financial institution is assumed to drive an increase in expectations of the lenders, which adopt the behaviour ”Enabler”. This is in line with the findings from Geddes and Schmidt (2020) and Geddes et al. (2018), which state that the support of a public financial institution not only directly supports the low-carbon technologies, but creates a ”trust signaling” effect which makes the finance regime more supportive of the low-carbon niche technology. In this scenario, the de-risking policy therefore not only directly supports the green technology via the provision of guarantees, but also leads to a shift in financiers’ expectations, who become Enablers.

- **Combined Financial Policies**: both policies targeting the financial sector - de-risking and differentiated capital requirements - are implemented simultaneously.

Of the 6 scenarios built this way (2 pure behaviours, 2 isolated financial policies, 2 combination of levers), only 4 core scenarios are presented in the main body of the text (red fill in Table 7.12): the scenarios Inert, Enabler, De-risking + Enabler and Combined Financial Policies. The two additional scenarios were run in the land-shipping SFC model but the results are reported in Appendix J for better readability (blue fill in Table 7.12).

All scenarios consider the same shipping policy (i.e. shock in the industry landscape), that is, the short-term measures implemented in the 2020s following the implementation of a carbon price in 2030. This represents the realisation of a delayed decarbonisation scenario, where the regulator and the consumer do not take strong actions during the 2020s to tackle climate emissions, but start to price emissions strongly and suddenly in 2030. The existing IMO measures are modelled as in the existing GloTraM model (sulphur limits in Emission Control Area (ECA) zones, EEDI, CII; see Smith et al. (2023) for a detailed description on how this is done). They are not explicitly modelled in the SFC model, as this would require more technical details than the model allows, but the energy and carbon intensity of the fleet decrease over time and with the uptake of green technologies, which implicitly represents a pressure towards energy efficiency. The landscape policy shock is modelled as the minimum carbon price necessary to reduce emissions to a 1.5°C-aligned curve without differentiated WACC (660 $ / tonne of CO2 in 2030). This is calculated in GloTraM using the 1.5°C curve from Smith et al. (2023) scenario A in 2030 only. In neither GloTraM nor the SFC is it assumed that the revenue of the tax is redistributed as subsidies to green shipping, for consistency between the two models, as GloTraM does not allow for redistribution.

This carbon price is a modelling instrument rather than an actual policy recommendation, nor a realistic landscape development for several reasons. First, if this revenue were fully redistributed as subsidies to zero-/low-carbon shipping, a much lower carbon price would be necessary to bridge the gap between conventional and zero-/low-carbon ships. Second, a carbon price might take the form of an actual carbon market or a carbon tax, but it might also reflect a propensity of customers to pay a higher price for zero-/low-carbon shipping, for example. Many more options for shipping policy are available to the regulator to bring shipping into a 1.5°C trajectory, which is outside the scope of this thesis.

The differences in cost of debt in the 4 core scenarios (Inert, Enabler, and De-risking + Enabler and Combined Financial Policies) are derived from the land-shipping SFC model and then used as input to GloTraM. The carbon price is kept the same as in the original run, to be able to compare the resulting investment decisions and stranded assets, all things else equal. This means that some scenarios could show emissions by 2030 above or below the 1.5°C curve.

7.2.2 Financiers' expectations and behaviour (Land-Shipping SFC model)

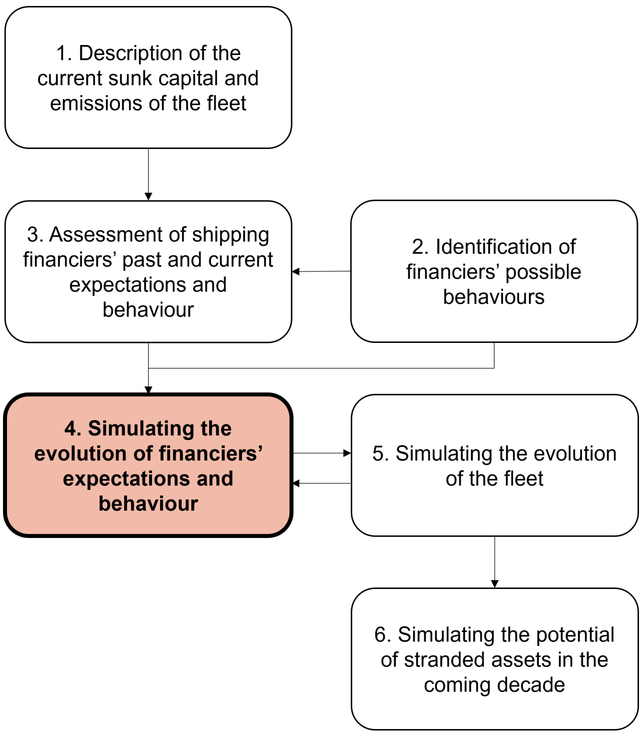


Figure 7.13: Sign-posting: simulating the evolution of financiers' expectations and behaviour

Let us first look at the evolution of the expectations of the financiers in the various scenarios (where those results fit in the analysis is plotted on 7.13), which represent the evolution of the financial socio-technical regime. As previously dis-

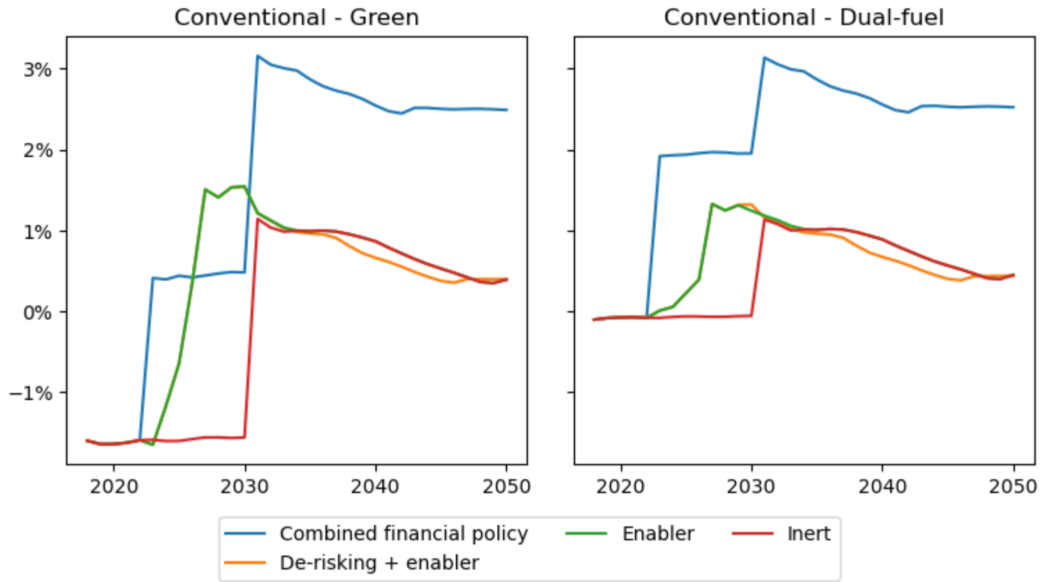


Figure 7.14: Difference in interest rates between shipping loans

(a) The Y-axis represents the difference between the interest rates of conventional ships and green ships (using green fuel only, left graph), and conventional ships and dual-fuel ships (using whichever fuel is cheaper, right graph). Read: in 2020, conventional ships can access loans with interest rates 1 percentage point *lower* than green ships.

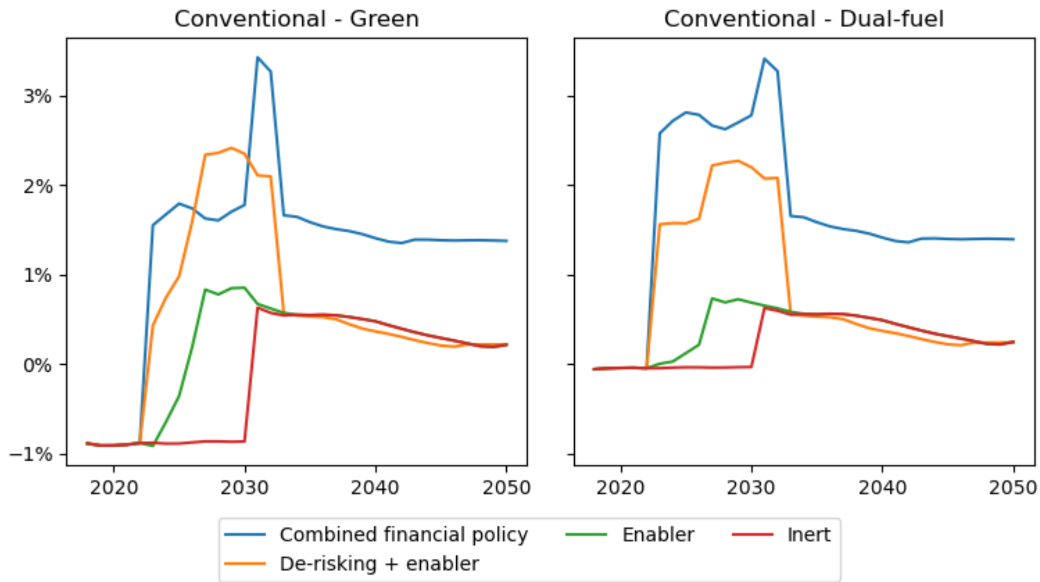


Figure 7.15: Difference in WACC between green and conventional ships

(a) The Y-axis represents the difference between the WACC of conventional ships and green ships (using green fuel only, left graph), and conventional ships and dual-fuel ships (using whichever fuel is cheaper, right graph).

cussed, financiers' expectations are represented in the cost of debt they require from shipowners. The evolution of the cost of debt and the WACC in the 4 core SFC-modelled scenarios are presented in figures 7.14a and 7.15a, respectively.

Lenders penalise green and dual-fuel ships in their pricing at the beginning of the period (Figure 7.14a) because green and dual-fuel ships are less profitable and therefore their owners are more likely to default than conventional ships (Figure I.1). Green ships, which by construction use zero-/low-emission fuel are largely penalised because they use more expensive zero-/low-carbon fuels and have higher initial capital cost, while conventional ships do not pay any carbon tax and remain compliant in the absence of carbon pricing (Figure 7.14a, left graph). This represents a situation where the financial socio-technical regime is fairly hampering the uptake of the niche technology. Dual-fuel ships are barely penalised however, as they are running on conventional fuel and therefore only slightly less profitable than conventional ships due to higher capital cost (Figure 7.14a, right graph).

If the financial socio-technical regime becomes enabler of the industry niche innovation, with lenders anticipating the upcoming 2030 carbon price, the cost of debt of zero-/low-carbon shipping can largely decrease compared to conventional shipping from 2023 onward, creating a two-tier finance market (Figure 7.14a). While Inert lenders continue to penalise dual-fuel and green ships up to 2030, Enabling lenders request higher interest rates to finance conventional ships, to cover for the risk of default arising from a carbon price of 660 $ / tonne in 2030 (Enabler and De-risking + Enabler scenarios). Conversely, they request lower interest rates from green and dual-fuel ships, as they anticipate growth in profits. This results in interest rates for green and dual-fuel ships being 1-1.5 percentage points below those of conventional ships in the few years preceding the implementation of the carbon price. On the other hand, Inert financiers continue to penalise green and dual-fuel ships until 2030 (Inert scenario).

After 2030, once transition risks are internalised by financiers, the interest rates are similarly favourable to green/dual-fuel technologies between the scenarios where financiers are enablers (Enabler, De-risking + Enabler) and the

Inert scenario. The interpretation of this situation is that the transition to the industry niche technology is sufficiently advanced, so that the financial regime overall become supportive of it. In all scenarios where financiers are Inert, interest rates on conventional (resp. green) ships increase (resp. decrease) to reflect the degraded (resp. improved) profitability of conventional (resp. green) ships. This corresponds to the sudden pricing of climate risks by lenders once they have materialised. Dual-fuel ships, on the other hand, had already a similar profitability to conventional ships before 2030, so that their interest rates do not see such a fall. However, in the two scenarios where financiers are Enablers, the interest rates do not vary much because transition risks were already priced in before 2030. From a modelling perspective, the driver of the interest rate, however, is different: before 2030, it is carried by the expected degraded/improved profits (equation 7.12, second term of the middle parenthesis), while after 2030, it is carried by the past non-performing loan ratio (first term of the same parenthesis). The interpretation is that if lenders are Enablers, they are not surprised by the implementation of a carbon price, and therefore they do not suddenly readjust their expectations and pricing.

Those effects are exogenous to GloTraM, as the WACC of various technologies is set as an input.

7.2.3 Evolution of the fleet

After looking at the evolution in the expectations of the financiers, this section now explains their consequences on the investment decisions of shipowners and therefore the evolution of the fleet (where this fits in the analysis is plotted in Figure 7.16). The results are first discussed for the land-shipping SFC and then for GloTraM.

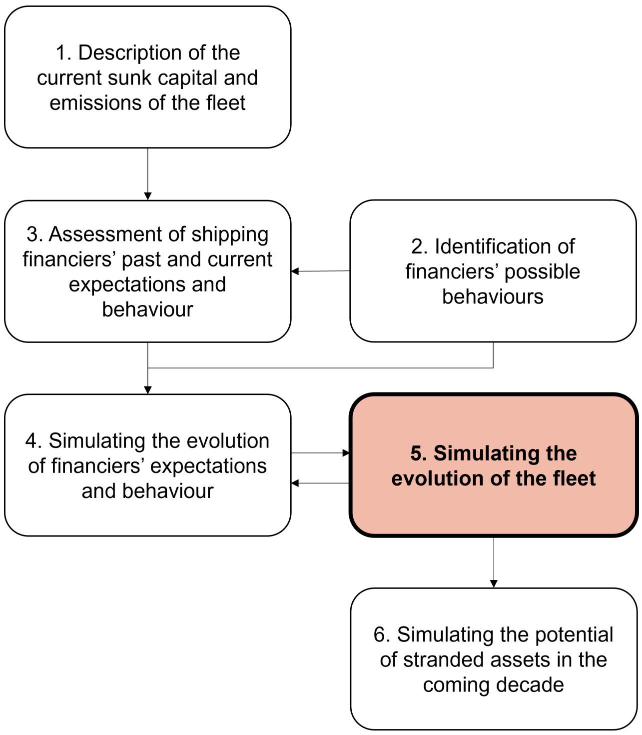


Figure 7.16: Sign-posting: simulating the evolution of the fleet

7.2.3.1 Land-shipping SFC model

The pricing of transition risk by financiers alone fails to make green and dual-fuel ships more competitive than conventional ships before 2030. The effect of the lenders' behaviours on the relative cost of green/dual-fuel over conventional shipping is plotted in Figure 7.17. Initially, both green shipping and dual-fuel shipping are more expensive than conventional shipping due to the higher investment cost for both (first row, Figure 7.17), and higher fuel cost for green shipping only (second row, Figure 7.17). A drop in the WACC between 2023 and 2030 in all but the Inert scenario leads to a slight decrease in the levelised cost of dual-fuel shipping (second row), which leads its relative profitability compared to conventional shipping to improve (third row). In the scenarios where only one lever is considered (Enabler, and the two additional scenarios GSF + BPF and De-risking reported in appendix J), the differentiated WACC fails to trigger significant dual-fuel investments before 2030. The lack of previous knowledge of the technology from shipowners means that they still represent the minority of new investments after then (Figure 7.18a, first column).

On the other hand, the difference in WACC is sufficiently large to drive shipowners in ordering dual-fuel ships before 2030 in the scenarios combining several levers (Combined Financial Policies and De-risking + Enabler on Figure 7.18a). The magnitude is at first quite small (6% and 1% of the fleet is dual-fuel in 2030 in the Combined Financial Policies and De-risking + Enabler scenarios, respectively (Figure 7.18a)). However, it triggers two learning effects: first, the imitation effect among shipowners becomes stronger as dual-fuel is added onto the fleet (Figure 7.18a, first column); second, dual-fuel, and therefore green, technology becomes cheaper as more ships are built (Figure 7.17, first row). This latter learning effect further reduces the total unit cost (Figure 7.17). This dynamic can be likened to the momentum building of a new technology in a protected niche, with learning effects and cost reduction meaning that the technology becomes closer to market - although the protected niche is not explicitly modelled here. As a result of those dynamics, De-risking + Enabling or the implementation of Combined Financial

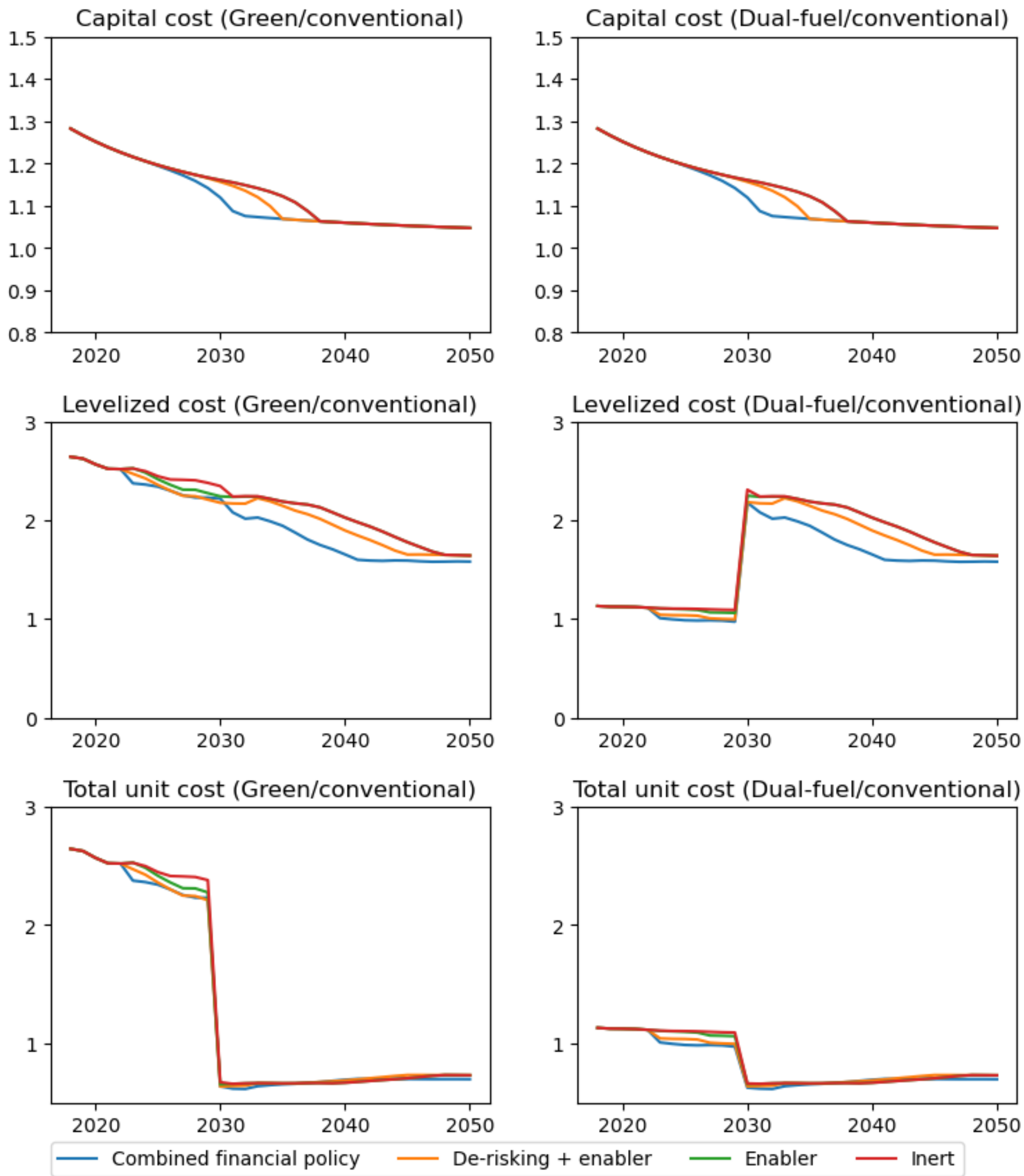


Figure 7.17: Relative cost of shipping technologies

(a) The Y-axis of the left graph corresponds to the ratio of green shipping cost over conventional shipping cost. The right graphs corresponds to the ratio of dual-fuel shipping cost over conventional shipping cost. For example, the capital cost of green is originally 1.3 times larger than the one of conventional (top left graph). Capital cost only includes the capital cost of the initial engine. Levelized cost includes both capital and operational cost but excludes carbon price. Total unit cost further includes the carbon price (see calculation details in Appendix F.0.1)

Policies somewhat reduce the share of conventional ships, although only slightly (99% and 93% respectively).

This early uptake has a long-lasting positive effect on the uptake of green ships after 2030, as imitation effects drive investments up, so that green ships represent 100% of newbuilds from 2033 onwards in the Combined Financial Policies scenario, and 2037 in the De-risking + Enabler scenario, compared to 2040 in the Inert and the Enabler scenarios. This suggests that if lenders fill the capital cost gap between dual-fuel ships and conventional ships, this has a long-lasting effect on the composition of the fleet. Finally, this uptake of green/dual-fuel shipping drives an improvement in energy efficiency of the fleet (3rd column on Figure 7.18a, details on the modelling approach can be found in Appendix F.0.1), which largely reduces the fuel consumption and reduces the cost of shipping for all types of fuels (4th column on Figure 7.18a).

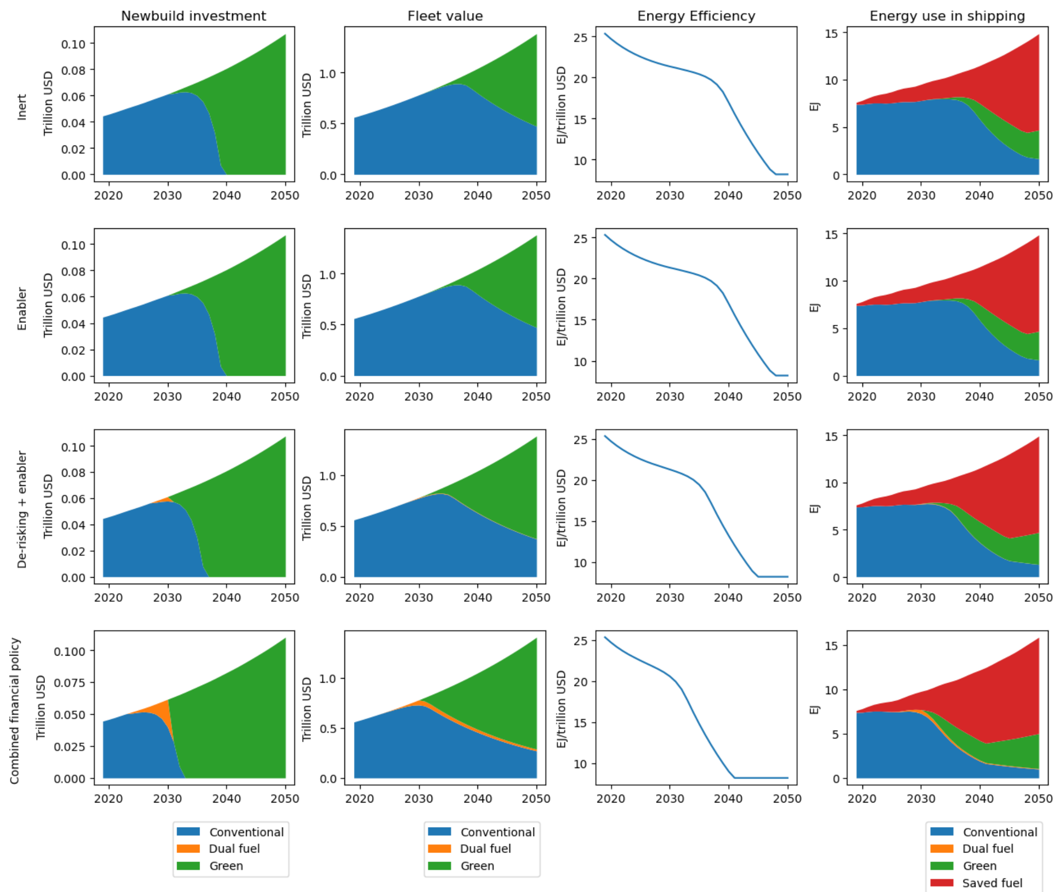


Figure 7.18: Investment in newbuilds, fleet composition, energy efficiency and fuel consumption, as modelled by the land-shipping SFC model

(a) The fuel saved represents the fuel which was not consumed because of the improvement of the energy efficiency of the fleet after 2050, by using energy efficiency technologies and reduced speed. It allows to compare the respective importance of energy efficiency and alternative fuels in the transition to low-carbon shipping. It was calculated post-processing by multiplying the energy intensity in 2018 with the transport work per year, and retrieved the energy use of that year.

7.2.3.2 Updated GloTraM

Let us now move to the evolution of the fleet projected by GloTraM.

A scenario with only one lever fails to bridge the gap between dual-fuel and conventional ships and therefore fail to trigger significant investments in the former (Inert and Enabler). As a consequence, in the Inert and Enabler scenarios, the absence of strong positive pricing (actually, negative pricing in the Inert scenario, positive but insufficient in the Enabler) towards zero-/low-carbon ships means that nearly all ships ordered are conventional. As a result, in 2030, most of the fleet value and deadweight is made of conventional ships (Figure 7.19).

However, the difference in the WACC significantly drives an uptake of methanol dual-fuel ships from 2022 onwards only when several levers are implemented (De-risking + Enabler and Combined Financial Policies). In the De-risking + Enabler and Combined Financial Policies scenarios, for most types and sizes of ships, methanol dual-fuel running on LSHFO becomes the cheapest option and therefore all new ships of those types and sizes are built as methanol dual-fuel ships[7] (Figure 7.19, first column). As a consequence, in 2030, only 50% of the fleet is conventional[8].

In all scenarios, all new ships ordered in 2030 are ammonia dual-fuel, because the carbon price now compensates for the increased fuel cost compared to LSHFO/MDO, and the difference in fuel cost between ammonia and methanol makes the former more economic (see Figure 7.19, first column). This does not vary across scenarios, because GloTraM assumes that shipowners have perfect information on the available technologies and therefore only order the most profitable design, i.e. ammonia dual fuel ships. Those newly ordered ammonia dual-fuel ships represent around a quarter of the value of the fleet in 2030. Furthermore, many existing ships are retrofitted to ammonia in 2030.

[7]Before 2030, ammonia and LNG dual-fuel ships are built in none of the scenarios considered, as their capital cost is higher than that of methanol.

[8]It is not worth it for dual-fuel ships to run on alternative fuel, so almost all of the fleet is operating with LSHFO and MDO and the difference in profitability only arises from the difference in annual capital costs and their ability to meet EEDI without further investments into energy efficiency technologies.

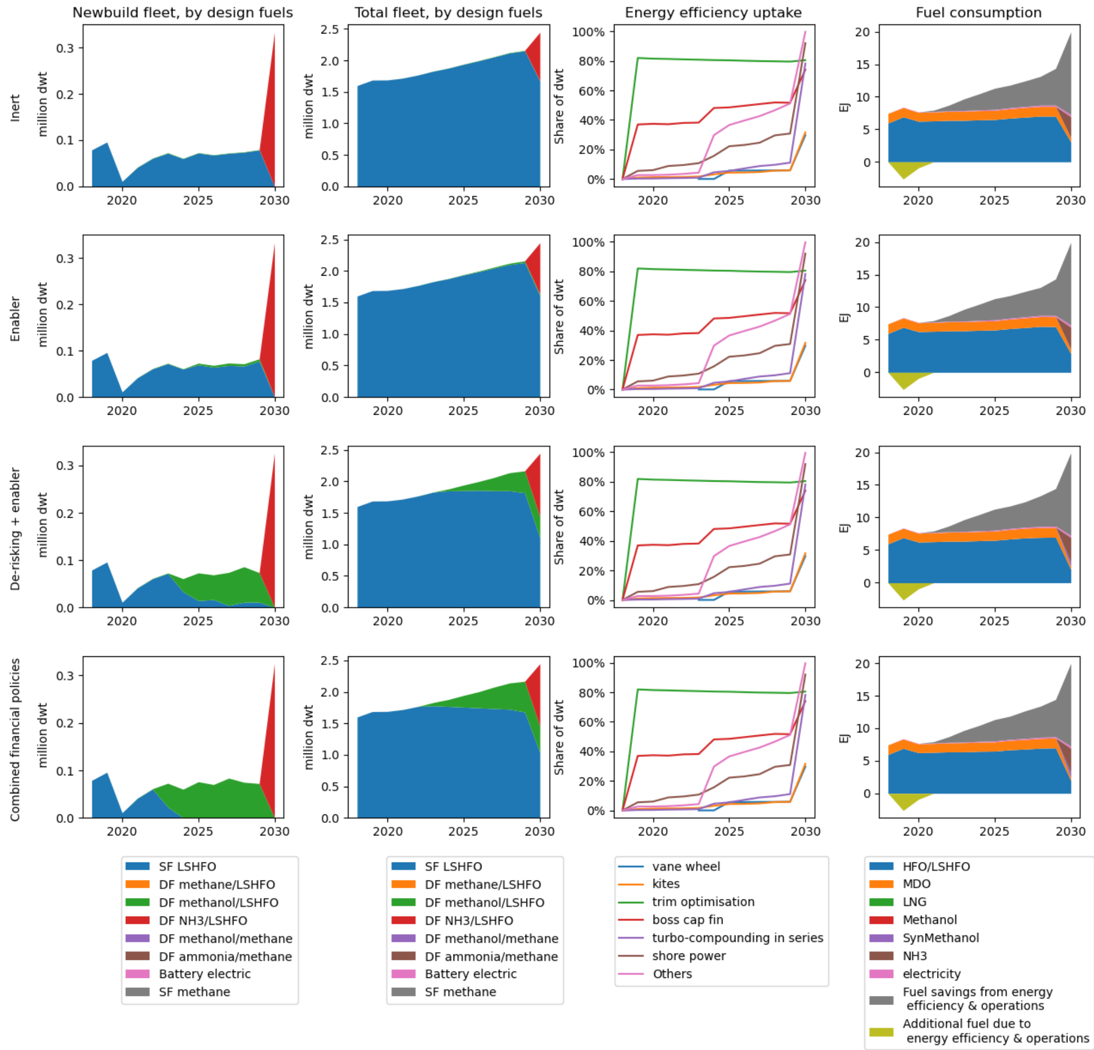


Figure 7.19: Fleet composition, energy efficiency technologies uptake and fuel consumption, as modelled by GloTraM

(a) SF: single fuel; DF: dual-fuel; HFO: Heavy Fuel Oil; LSHFO: Low-Sulphur Heavy Fuel Oil; MDO: Marine Diesel Oil; LNG: Liquefied Natural Gas; NH3: Ammonia

(b) The drop in newbuild investments in 2020 is due to the drop in shipping demand linked to the Covid pandemics.

(c) The implementation of a carbon price in 2030 leads ships to slow down in GloTraM, hence the need for fleet expansion and large newbuild investments in 2030.

(d) The fuel saved corresponds to the fuel which is not consumed, due to improvement in the energy efficiency of the fleet (speed and energy efficiency technologies) compared to 2018. It was calculated post-processing, by multiplying the energy intensity (MJ/tonne-mile) in 2018 per ship type and size with the transport work per year, and retrieved the energy use of that year. Negative savings (additional fuel due to energy efficiency & operations) in 2019 and 2020 are due to an increase in speed compared to 2018.

7.2.3.3 Comparison of the findings

Let us now discuss how the results of the two models compare to one another.

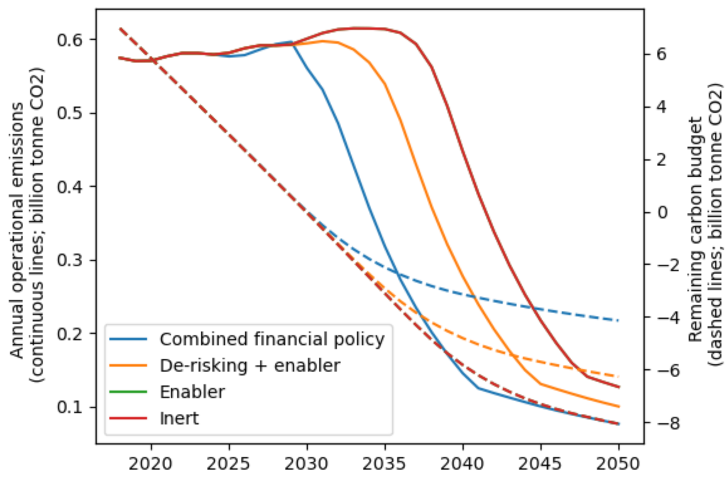


Figure 7.20: Emissions and remaining carbon budget, as modelled by the land-shipping SFC model

(a) Continuous lines correspond to the annual emissions on the left axis. Dotted lines correspond to the remaining carbon budget on the right axis

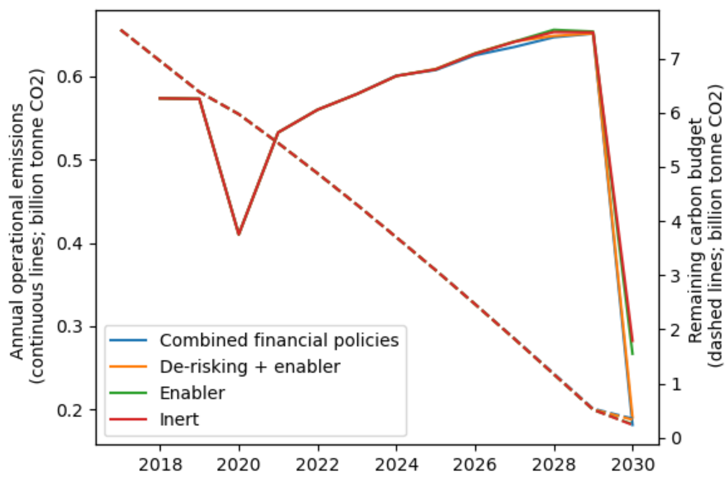


Figure 7.21: Emissions and remaining carbon budget, as modelled by GloTraM

(a) Continuous lines correspond to the annual emissions on the left axis. Dotted lines correspond to the remaining carbon budget on the right axis

First, in both models, **only when the difference in WACC is very large, above 1.5-2%, is this difference sufficient for dual-fuel ships to be more profitable to shipowners than conventional ships**. This difference could only be attained in the scenarios combining several levers (Combined Financial Policies, De-risking + Enabler). One interpretation of this is that the financial regime alone is unable to induce a socio-technical transition of the shipping industry regime. However, the support of the financial socio-technical regime, combined with further industry landscape pressures, can successively support a transition of the shipping industry regime.

Second, **in both models from 2030 onwards, ship ordering is mainly affected by the carbon price**, while the impact of the difference in WACC on new-build investments is now negligible. It leads to zero-/low-carbon shipping being more economic than conventional ones so that 1/ dual-fuel ships start running on the most carbon efficient fuel (Figure 7.18a, bottom right graph; Figure 7.19, fourth column) and 2/ zero-/low-carbon ships/green ships are now ordered. This latter effect differs significantly between GloTraM and the land-shipping SFC model.

Third, **the path-dependency effects modelled in the land-shipping SFC model and not in GloTraM means that the transition is much slower in the former, and that what happens in the 2020's has long-lasting effects on the transition up to 2050.** Whereas GloTraM finds a sudden uptake of methanol dual-fuel ships before 2030 in the combined levers scenarios, in the land-shipping SFC model, this uptake is fairly timid at first (Enabler + De-risking and Combined Financial Policies). Moreover, whereas GloTraM finds a sudden uptake of ammonia-fuelled ships in 2030 in all scenarios, the uptake of green fuels in the land-shipping SFC model is much slower in the scenarios where no early uptake of dual-fuel ships has happened. Furthermore, the difference in uptake by 2040 between the various scenarios in the land-shipping SFC model suggests that an early uptake of green shipping is necessary for a swift uptake once a carbon price is in place but also reduces cumulative emissions by around a fifth (12 to 25%). This timing is in line with the MLP theoretical framework however, where technological innovations take a long time to mature in niches, and, if successful, their uptake accelerate in a non linear fashion once they start replacing the regime technology.

Finally, **by 2030, in both models and all scenarios, the shipping carbon budget is used up or almost used up** (Figures 7.20a and 7.21a). This means that to respect the fair share of the 1.5°C carbon budget for shipping, all ships must then stop using fossil fuels, either by being replaced by cleaner ships, by using drop-in fuels, or because the demand for shipping is reduced. It should be noted that after 2030, the progressive uptake of alternative fuels in the land-shipping SFC model means that annual emissions do not drop as fast as in GloTraM (comparing figures 7.20a and 7.21a), especially in scenarios where the lending conditions have not allowed an early uptake of zero-/low-carbon ships in the 2020s.

This means that none of the scenarios of the land-shipping SFC model respects the 1.5°C curve (Figure 7.21a). This has qualitative implications for the unfolding of the transition: if a sudden uptake of zero-/low-carbon ships as modelled in GloTraM is unlikely in 2030 - as the results of the land-shipping SFC model suggest - more emphasis should be given to alternative ways of reducing GHG emissions, in particular improving the energy efficiency of the current fleet in the 2020s and/or reducing the amount of shipping transportation work. Even if a sudden uptake of zero-/low-carbon fuel is possible, in both models and in all scenarios, much of the gains in annual emissions are still a consequence of energy efficiency improvement of the fleet (see Figures 7.18a and 7.19).

7.2.4 Stranded assets

This section finally covers how investments made in the 2020s, as described in the previous section, translate into stranded assets in the land-shipping SFC model and in GloTraM respectively.

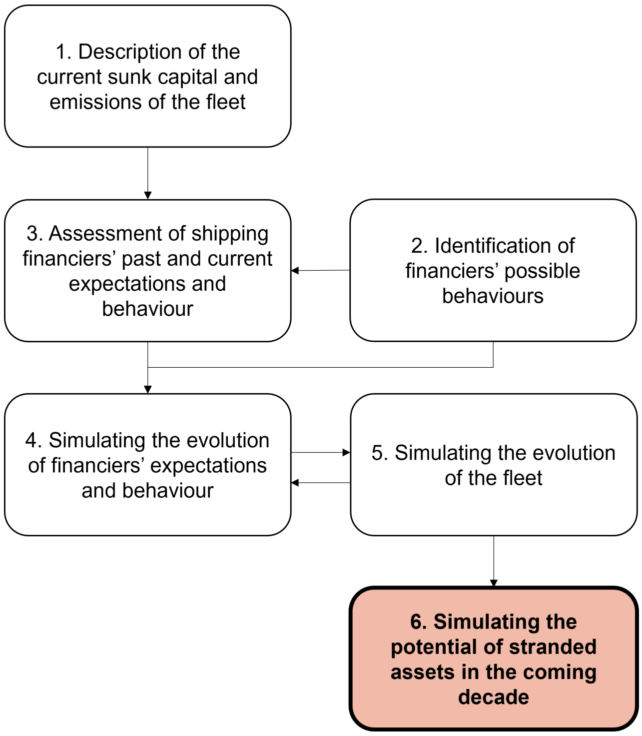


Figure 7.22: Sign-posting: simulating the potential of stranded assets in the coming decade

7.2.4.1 Land-shipping SFC model

Shortly after 2030, conventional ships face large foregone earning streams no matter the scenario (up to \$210 bn per year) (Figure 7.23)[9]. This is because the uptake of green ships in 2030 is at best small. It is worth noting that, in practice, it is unlikely that a shipowner would operate at such a loss for a long period of time. This suggests that companies are at a high risk of bankruptcy, or that shipping prices will increase more than the model suggests, so that part of those lost profits will be passed onto the consumer.

In all scenarios, the unprofitability of conventional ships cascades down to the banks through non-performing loans. If financiers are Inert, the model shows that out of the \$375bn conventional loans provided to the shipping sector (and therefore at risk of becoming stranded paper), up to \$42bn loans could default (Figure 7.23)[10]. Lozinskaia et al. (2017) find that banks generally save between 30% and 55% of the loan value in case of default; therefore, this would lead to stranded paper of \$19 to 29bn in the Inert scenario.

The combination of several levers significantly reduces foregone earning streams and non-performing loans in the mid and long-term when a differentiated WACC has allowed for an early uptake of dual-fuel ships (Enabler + De-risking and Combined Financial Policies, Figure 7.23), for two main reasons. First, the consequent faster uptake in the 2030s means that there are fewer conventional ships in 2035 and therefore a smaller amount of carbon tax is paid. Second, the uptake of green ships triggers an improvement in energy intensity for the entire fleet (third column, Figure 7.18a)), so that energy-efficient conventional ships pay less carbon tax per transport work and are therefore less unprofitable; thus defaulting less on

[9]Let us go through the drivers of those foregone earning streams. Green and dual-fuel ships use green fuel by then and start becoming price leaders: they set up the price above their normal mark-up cost as they are more economic than conventional ships. As a consequence, they enjoy fairly stable profits, while conventional ships face large carbon expenses and therefore losses, but cannot retrofit by construction of the model.

[10]It is worth noting that the amount of non-performing loans does not decrease immediately after 2030 by construction, as the model assumes that non-performing loans only default on interest payment so that non-performing loans do not clear up. As a result, the amount plotted should be understood as a cumulative amount rather than an annual one. In practice, it can be assumed that part of the non-performing portfolio will actually never be repaid.

their loans. This underscores the importance of energy efficiency in mitigating the risk of stranded assets.

An Enabling behaviour reduces the extent by which foregone earning streams cascade down to the financial regime actors into stranded paper, even when it does not have a significant impact on the amount of foregone earning streams. Part of the amount of non-performing portfolio is compensated by the increase in interest payments before and after 2030 (third row, first column, Figure 7.23). In the Inert and De-risking scenarios, this increase does not compensate for the amount of non-performing loans (second row, first column, Figure 7.23). However, in the scenarios where regime financiers are Enablers (Enabler, De-risking + Enabler scenarios), banks have collected a large amount of interest payments before 2030 as they have priced the risk of asset stranding into the cost of debt. This partly compensates for the non-performing loans they carry in 2030 (second row, first column, Figure 7.23). As such, in this scenario, non-performing loans are not fully unexpected, as they are priced into the cost of debt; so that foregone earning streams do not fully translate into stranded paper, i.e. the risk is not passed onto the banks.

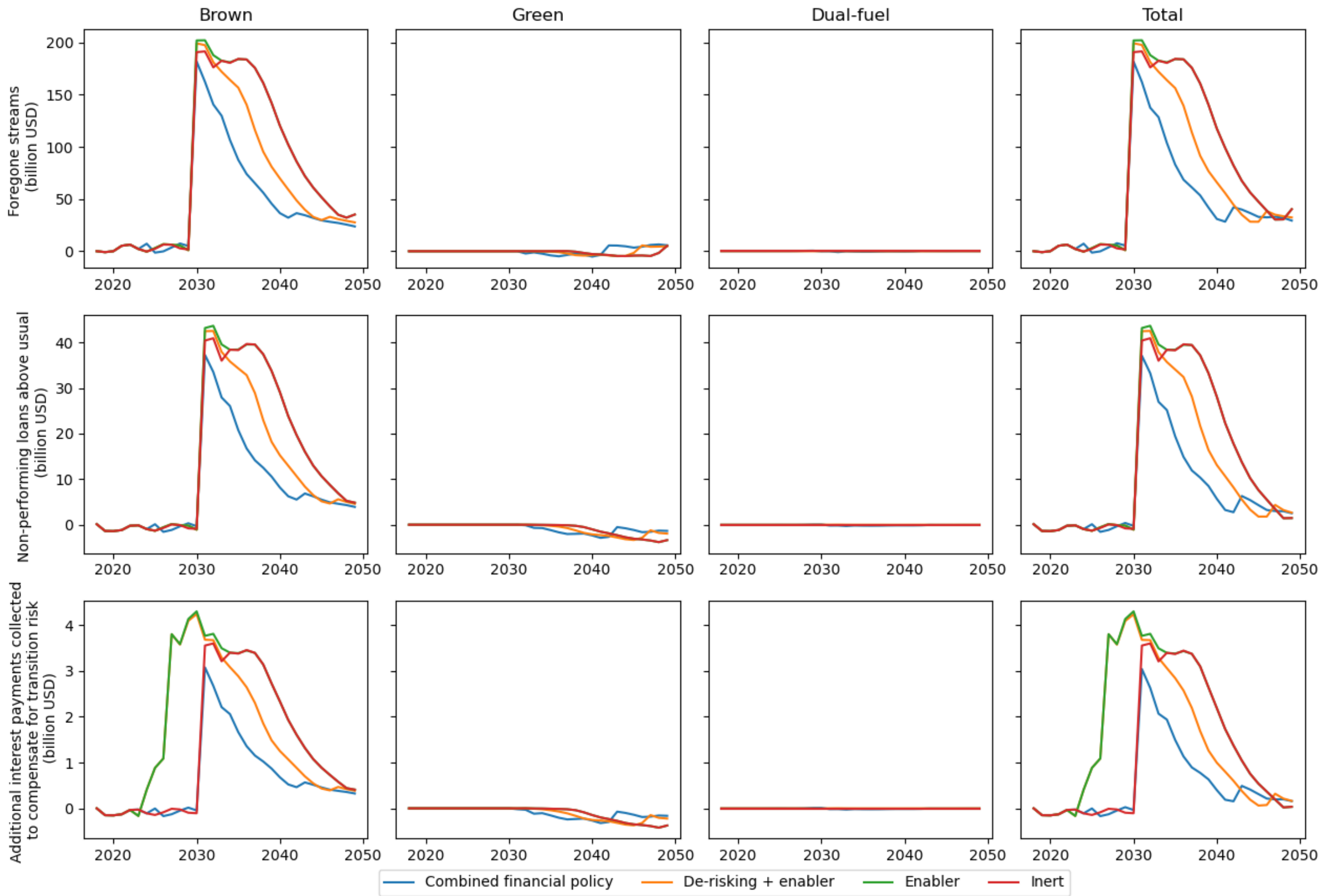


Figure 7.23: Stranded assets in the form of foregone earning streams, interest payments defaulted to banks and non-performing loans to banks, as modelled by the land-shipping SFC model

(a) Normal average profits are assumed to be 8.96% of output and normal non-performing loan is assumed to be 3.87% per year, which are their values at $t = 0$ in the model. The usual margin above the lending rate is 0.36%, which is the initial value in the model. The plotted value corresponds to the realised profits - normal average profits; non-performing loans above normal non-performing loans; and additional interest payments above normal interest payments.

(b) Additional interest payments do not include the effect of increased (resp. decreased) interest rates as a result of the differentiated CAR requirements, as those are compensated for by a decrease (resp. decrease) capacity to provide loans, hence a decreased (resp. increased) profitability.

7.2.4.2 Updated GloTraM

Let us now move to the stranded assets projected by GloTraM.

A large amount of capital might become stranded if fossil fuels cannot be used from 2030 onward, but the amount largely depends on the availability and competitiveness of drop-in fuels and retrofitting by then (Figure 7.24). In 2030, it is assumed that all fossil-fuel ships come under the economic pressure of moving to zero-/low-carbon solutions[11]. There are three variants, which are possible in all scenarios considered, by which they can do so:

- **If ships cannot be retrofitted and need to be replaced, up to $560bn of the fleet value is at risk of being stranded** (Retrofit impossible, Figure 7.24) . This worst-case variant might take place either because ships cannot retrofit either for economic (lack of finance, very high cost of retrofitting) or technological (e.g. moving to hydrogen, wind-dominated shipping, ships not having the space to allocate a larger tank, etc.) reasons; because shipyards do not have sufficient retrofitting capacity (see Lloyd's Register (2023) for a discussion on the topic); and/or because the transition unfolds due to a decrease in shipping demand. This variant corresponds typically to a socio-technical transition taking the form of substitution or de-alignment/re-alignment in Geels and Schot (2007)'s classification, where a competitive innovation replace the regime. This variant is consistent with the land-shipping SFC model and represents the maximum capital value at risk of being stranded in 2030.
- **If ships can be retrofitted to ammonia, and methanol dual-fuel ships continue being viable, a bit more than half of the value at risk is saved**, but the amount of book loss remains very high (”Retrofit available” in Figure 7.24) .
- **No capital is stranded if drop-in fuels are available at scale and economically competitive to the existing fleet** (e.g. bio-/e-methane and biodiesel).

[11] This assumption is in line with the results of GloTraM, which shows intense retrofitting activity in 2030; with the results from Lloyd's Register (2023), which finds that a large amount of the fleet is retrofitted to methanol or ammonia ; and with the findings plotted in Figures 7.21a, which shows that the carbon budget is nearly used up by 2030 even when annual emissions for 2030 fall dramatically. This does not mean that all ships retrofit at the same time, but all ships are assumed to be under the same economic pressure to do so, so that their value falls at the same time.

> However, if biomass availability is limited, these fuels are unlikely to compete with e-methanol or e-ammonia in particular, the latter being one of the most promising alternative fuels (IRENA, 2019b, 2021a; Longva et al., 2020; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021; Smith et al., 2019b). The last two variants correspond typically to a socio-technical transition taking the form of transformation in Geels and Schot (2007)'s classification, where a symbiotic innovation is integrated in the regime.

Based on this, if drop-in fuels are not available at scale, **a large share of the existing fleet is at risk of being stranded, no matter the investment decisions made in the 2020s** (Figure 7.24). This is because much of the fleet which becomes stranded capital is already built in 2022[12]; so investment decisions made afterwards, and consequently the behaviour of lenders, have a relatively milder, although still noticeable, effect on book loss in 2030 if retrofits are available.

However, when providing sufficiently cheaper lending conditions to green ships, lenders are able to reduce the maximum value at risk in 2030 compared to the Inert scenario by 15 to 39% (depending on the scenario and whether retrofitting is available), although they cannot eliminate the risk (scenarios De-risking + Enabler, and Combined Financial Policies, Figure 7.24). However, an Enabling behaviour alone does not have a large impact (scenario Enabler, Figure 7.24).

Furthermore, the results suggest that **the behaviour of lenders has a significant impact on the amount of cascading effects of stranded assets onto them**. The results of the interviews (see Chapter 6) show that lenders generally prefer to finance younger ships. This means that they might keep their distance with the generations built between 2006 and 2013 by 2030, especially if they are expecting the risk of stranded assets (Enabler scenario). Figure 7.25 shows the amount of stranded assets that affects banks if they only finance ships under 15 years old. The

[12]To understand in more detail those results, let us look at the breakdown of stranded assets by generation (Figure I.2 in Appendix). The years 2004 to 2009 have seen a large number of newbuilds being ordered, which means that ships built between 2006 and 2013 represent a large share of the 2030 fleet value despite their old age. This generation is approaching the end of its useful life in 2030, so it is not worth retrofitting, or when it is, the cost of retrofitting represents most of its second-hand value (see Figure I.3 in Appendix). This means that this generation is one of the most badly affected by stranded assets, in terms of share of stranded assets per second-hand value.

difference between the scenarios shown in Figure 7.25 suggests that the behaviour of lenders during the 2020s has a significant impact on the total amount of stranded capital covered by banks, that is, stranded paper.

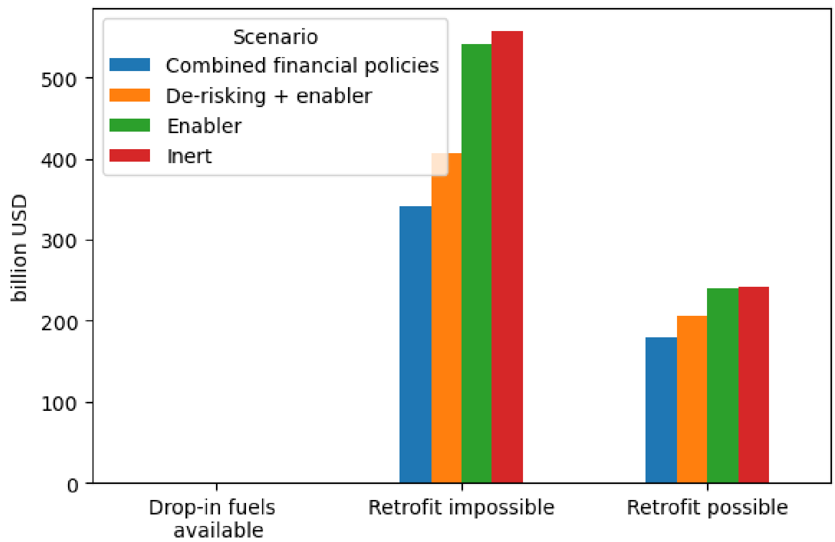


Figure 7.24: Stranded capital via book loss summary, as modelled by GloTraM

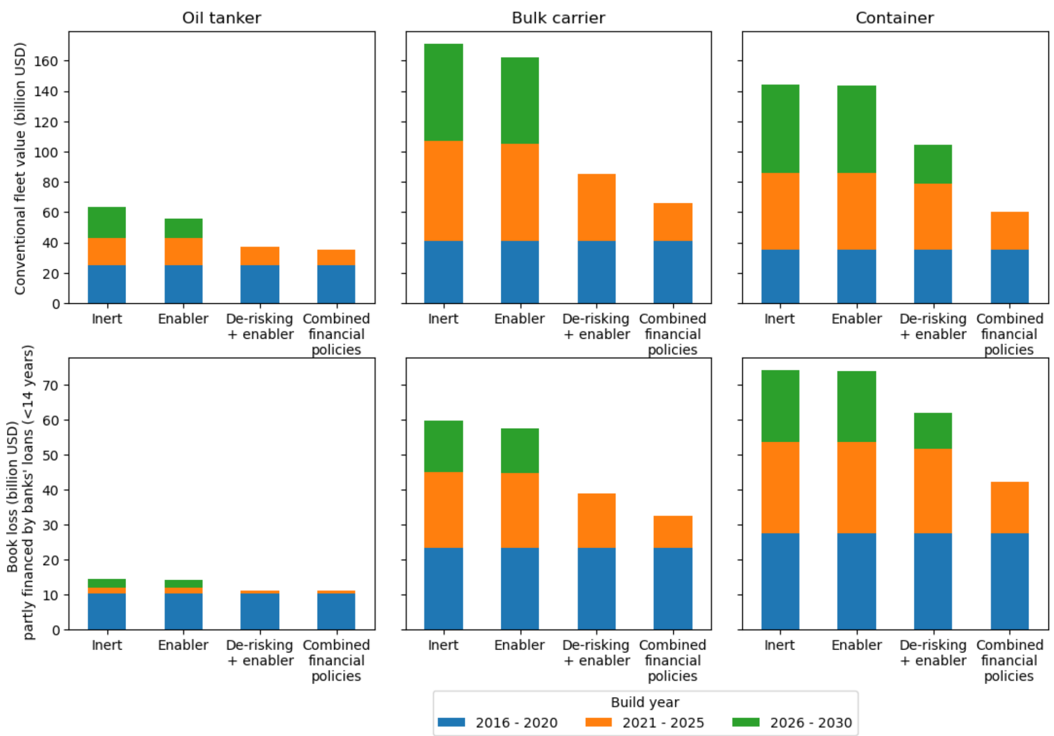


Figure 7.25: Conventional fleet value and book loss covered by loans by generation, as modelled by GloTraM

7.2.4.3 Comparison of the findings

Let us now discuss how the results compare to one another. The comparison of the results of the two models shown in Table 7.1 provides several insights.

First, **both models find that a large amount of capital is at risk of being stranded in 2030** ($557 to 780 billion of book loss in the Inert scenario[13]), **but their findings regarding the impact of financiers' behaviours on stranded assets differ in some scenario variants**. If the financial socio-technical regime is favourable to the future price leader in the 2020s (i.e., Combined Financial Policies and De-risking + Enabler scenarios; all variants of the land-shipping SFC model and variants where methanol is viable in GloTraM), both models also agree that they significantly reduce the amount of capital at risk - although the impact is much larger in GloTraM (Table 7.1). Their impact if methanol is not viable when in competition with ammonia is, however, not robust across models and assumptions: GloTraM finds that a supportive behaviour of financiers leads to an increased amount of stranded capital because methanol dual-fuel ships get built in the 2020s before becoming uneconomic (Figure K.5). This corresponds to a "Creative Self-Destruction" behaviour in Chapter 5's theoretical framework, where the financial socio-technical regime proactively supports an industry technology which does turn out to be successful in the transition. The land-shipping SFC model, on the other hand, because it ignores the competition between alternative zero-/low-emission fuels, finds that a supportive behaviour of financiers always reduced stranded assets (Table 7.1).

Second, **the comparison between the two models suggests that the land-shipping SFC model might be overestimating the amount of stranded assets.** First, book loss can be reduced by half if the fleet can retrofit, a finding that only GloTraM can show (Table 7.1). There is some uncertainty about the technological and economic feasibility of such retrofits, but the comparison between the models shows that the land-shipping SFC model might be overestimating the amount of

[13]The land-shipping SFC model finds a somewhat higher amount than GloTraM because it finds a slightly higher growth rate and because all new capital in 2030 is ammonia dual-fuel in GloTraM while only a minority is in the land-shipping SFC model.

Table 7.1: Summary of stranded assets results (billion USD)

Stranded	Retrofit	Scenario	Amended GloTraM	Land-shipping SFC
Book loss	False	Combined financial policies	340.4	728.8
		De-risking + enabler	406.6	772.1
		Enabler	541.2	778.4
		Inert	557.5	778.4
	True	Combined financial policies	178.9	
		De-risking + enabler	205.1	
		Enabler	238.7	
		Inert	241.3	
Paper	False	Combined financial policies	68.1	38.2
		De-risking + enabler	96.1	25.0
		Enabler	152.9	25.6
		Inert	159.8	41.5
	True	Combined financial policies	36.3	
		De-risking + enabler	47.4	
		Enabler	61.6	
		Inert	62.7	
Profits	False	Combined financial policies		1,354.9
		De-risking + enabler		1,904.0
		Enabler		2,441.1
		Inert		2,407.2

(a) All the variants presented assume that all low-/zero-carbon fuels are available (ammonia and methanol in practice), so that methanol dual-fuel ships are not stranded if ammonia becomes the dominant fuel.

(b) Stranded capital when retrofit is not available corresponds to the amount of conventional capital

(c) Stranded paper estimated in the land-shipping SFC model are the non-performing conventional loans above average in 2031, minus the additional interest payments collected from 2018 to 2030 to compensate for the risk of stranded assets. The usual nonperforming loans are assumed to be 3. 87% of the portfolio per year, which corresponds to the non-performing loan ratio $t = 0$ in the model. The usual margin above the lending rate and the pricing of the risk weight is 0.36%, which is the initial value in the model.

(d) Stranded paper as estimated in GloTraM corresponds to the book loss of ships younger than 14 years, times the leverage of conventional ships (65%). This assumes that banks only finance ships younger than 15 years old, but that they refinance the ships after the first loan and that the loans maturity is 7 years.

(e) Foregone earning streams are the conventional profits below average profits (8.96% of output), which are their values at $t = 0$ in the model. No foregone earning streams are estimated in GloTraM.

foregone streams if retrofit is available to ships. Second, the amount of foregone earning streams in the variant where ammonia is the dominant fuel exceeds the amount of book loss, estimated both in the land-shipping SFC model and in GloTraM (Table 7.1). This suggests that the shipowners might either default and the ships get scrapped, rather than operating for a long time at a loss; or that shipping prices might increase more than what the model suggests, which essentially consists of transferring part of the foregone earning streams onto the clients.

Third, **both models find that a large amount of stranded assets happening in the socio-technical regime could be passed onto lenders of the financial regime**: in the Inert scenario, around $41 to 162 billion in the variant where ammonia becomes the dominant fuel, and $6 to 160 billion in the variant where methanol does (Table 7.1). GloTraM finds a much larger amount of stranded paper, as it implicitly considers that all stranded capital covered by loans translates into losses for banks, while the land-shipping SFC model computes the non-performing loan ratio.

Finally, **both models suggest that financiers are significantly better off pricing climate risks**, but for different reasons. In both models, if financiers give sufficiently preferable financing conditions to the future price leader (i.e., Combined Financial Policies and De-risking + Enabler scenarios; all variants of the land-shipping SFC model and variants where methanol is viable in GloTraM), they reduce the amount of stranded paper by reducing the amount of finance to conventional ships. This reduces the amount of stranded assets from 15% (GloTraM, variant where retrofit is available) to 44% (land-shipping SFC model, foregone streams) (Table 7.1). The land-shipping SFC model identifies a further decrease in stranded paper in the accumulated interest payments in the 2020s in the Enabler scenarios, which compensate for the losses in 2030 and, therefore, significantly reduce the amount of stranded paper.

7.3 Discussion

Having examined the results in the preceding section, this section now summarises the main findings and compares them to other studies (Section 7.3.1), discusses their implications (Section 7.3.2) and limitations (Section 7.3.3).

7.3.1 Summary of results

This section has highlighted several empirical findings on the evolution in the cost of capital of various technologies, on their uptake, and on the materialisation of stranded assets. Those findings are summarised successively in this section and compared to the existing literature.

7.3.1.1 Evolution of the expectations and the cost of capital of various shipping technologies

First, the land-shipping SFC model has shown that, if the financial socio-technical regime becomes enablers of the transition to low-carbon shipping, the cost of debt and the cost of capital of zero-/low-carbon shipping can largely decrease compared to conventional shipping, creating a two-tier finance market. At the beginning of the period, the land-shipping SFC model predicts that the cost of debt for purely green shipping is 1.5 percentage points above the conventional one, and the cost of debt for dual-fuel shipping 0.1 percentage points. This gap could decrease to -1.3 percentage points by 2030, if financiers anticipate a strong mitigation of shipping carbon emissions by then. This validates fairly well with the evolution of the cost of debt in other industries which have started their low-carbon transitions earlier, which were reviewed in the previous section (Egli et al., 2018; Geels and Gregory, 2023; Kempa et al., 2021; Xiaoyan et al., 2023; Zhou et al., 2021). The fall in the cost of debt for green shipping is actually smaller than the one observed in particularly advanced transitions, such as the transition to renewable electricity generation in Germany and the UK (Egli et al., 2018; Geels and Gregory, 2023); so one could expect, in a best case scenario, an even larger gap in cost of capital. This also validates the projected evolution in the interest rates of conventional versus green capital modelled by Dunz et al. (2021), which finds a gap between green and conventional capital falling from 1 to -1 percentage points in the scenario where banks anticipate an upcoming carbon tax.

Similarly, the projected evolution in the cost of capital seems somewhat conservative compared to the existing literature. The land-shipping SFC model finds that, in 2018, conventional ships are characterised by a WACC nearly 1 percentage point lower than green ones (but similar WACC for dual-fuel ships). This gap increases to 0.8 percentage points in the Enabler scenario, and up to 2.3 percentage points if green investments are further de-risked (De-risking + Enabler scenario). In comparison, Bachner et al. (2019), using the empirical estimates in the cost of capital from Steffen (2020), assumes a gap between fossil power generation and renewables in Europe ranging from 2 to 9 percentage points (the cost of capital varying by technology and geography) in the central scenario, but finds that this gap could increase to 20-30 percentage points if investors fully priced in the risk of stranded assets and the potential for renewables (FFR scenario). Bachner et al. (2019)'s analysis concerns a sector much more advanced in the decarbonisation than international shipping (transition to renewable power production in Europe), which explains partly why the assumptions are much more bullish than the results presented here. In particular, the assumptions, which are already very ambitious for this sector, are unlikely to be realistic for the shipping sector in the short term, given that the carbon intensity of ships are not significantly priced into the cost of debt yet, as demonstrated in Chapter 6. However, their results suggest that the evolution in the cost of capital might be much stronger than what the land-shipping SFC finds, especially in the longer term, so those can be considered as conservative.

7.3.1.2 Evolution of the fleet

The Inert scenario up to 2029 corresponds to a scenario where the financial socio-technical regime does not provide any incentives to shipowners for investing in zero-/low-carbon technologies. In this scenario, both the land-shipping SFC model and GloTraM predict some, but limited, operational and technological energy efficiency gains; no uptake of alternative fuels; and, consequently, a slight increase in GHG emissions. Those findings are in line with those of Faber et al. (2020) and Halim et al. (2018), but slightly at odds with those of Longva et al. (2020), who find an uptake of LNG as a marine fuel in four business-as-usual scenarios out of six and which validates the recent large ordering of LNG-fuelled ships (Clarksons Research, 2022b). This discrepancy might be explained by the difference in fuel price assumption, as Longva et al. (2020) assumes that LNG is cheaper on a per GJ basis than LSHFO and MGO. On the other hand, LNG is not picked up by GloTraM in the absence of regulation as the most cost effective solution, because both fuel cost and investment costs are assumed to be higher than those of LSHFO-MGO. This development has little effect on the risk of stranded assets if zero-/low-carbon drop in fuels to LNG fuelled ships are not developed at scale and competitively, which is consistent with the findings of Korberg et al. (2021), Pavlenko et al. (2020), and Smith et al. (2021) (but still debated: see for example Campbell et al. (2023) and Law et al. (2021)), as LNG-fuelled ships are at least as much at risk of losing their value than LSHFO-fuelled ships (Fricaudet, Rehmatulla, and Smith, 2022).

No previous study has looked at the effect of differentiated WACC before a strong implementation of carbon tax in shipping, so the results of the other scenarios cannot be validated. However, findings in other industries show that a differentiated cost of capital between conventional and green technologies can indeed accelerate low-carbon transitions (or inversely decelerate), for example in the power sector in Europe (Dunz et al., 2021; Halstead et al., 2019; Polzin et al., 2021) and in Africa (Sweerts et al., 2019). Contrarily to Dunz et al. (2021), Halstead et al. (2019), and Polzin et al. (2021) but in line with Sweerts et al. (2019), this thesis finds that the pricing of climate risks by investors is not in itself able to influence investment decisions; so that a de-risking of investments in low-carbon solutions is needed. This might be because the studies mentioned above concern power generation technologies, whose costs are already close or even lower than their conventional competitors. All the studies mentioned above and this thesis show, however, that the cost of capital is able to influence the speed and the intensity of the transition, but is not the sole nor the main factor; with technology cost and availability and government intervention typically playing a large role (this is investigated in the sensitivity analysis, in Appendix K).

GloTraM finds a significant and sudden uptake of energy efficiency technologies (shore power, turbo-compounding, kites and vane wheel in particular) and of ammonia-fuelled ships in 2030, when a carbon tax is implemented. The speed of the uptake of alternative fuel when a strong decarbonisation is implemented is broadly in line with the findings from Bullock et al. (2020), Halim et al. (2018), IRENA (2021b), and Longva et al. (2020), although their findings on the fuel mix differ. Halim et al. (2018), IEA (2020), and IRENA (2021b) find a coexistence between biofuels, LNG and hydrogen-derived fuels in 2030, followed by a large uptake of ammonia/hydrogen by 2040, while Longva et al. (2020) find a large uptake of LNG and bio-MDO and no significant uptake of methanol or ammonia in 2030, the latter only picking up in most ”decarbonisation by 2040” scenarios after 2030. This uncertainty is managed in the sensitivity analysis by estimating stranded assets in variants of the scenarios where different fuels are available.

In contrast to the above, the uptake of green fuels in the land-shipping SFC model is much slower in the Inert scenario. The discrepancy in uptake between GloTraM and the above-reviewed cost-optimisation or simulation models; and the land-shipping SFC model suggests that the uptake of zero-/low-carbon ships might be slower than cost-optimisation suggests, due to the stickiness of investment decisions. In particular, the difference in uptake by 2040 between the various scenarios suggests that an early uptake of green shipping is necessary for a swift uptake once strong regulations are in place, which is in line with the theory of Baresic (2020b) using the MLP and the findings on a selected number of technologies in Bas et al. (2017), Chica et al. (2023), and Karslen et al. (2019), and consequently reduces cumulative emissions by around a fifth (12 to 25%). Path-dependency and imitation effects mean that a carbon tax alone is not able to drive the uptake of zero-/low-carbon fuels fast enough to fit into a 1.5°C curve. In line with the assumptions from the MLP framework, early support for the uptake of zero-/low-carbon ships through financial policy or demonstration projects in protected niches already in the 2020s is necessary to ensure a swift uptake of zero-/low-carbon fuels to replace the conventional socio-technical regime, and limit the lock-in and, therefore, stranded assets once carbon is priced in; especially in the case of a delayed transition.

Given this potential slow uptake of alternative fuels, and the short timing of the transition, it is unlikely that increased zero-/low-carbon fuel uptake alone will be sufficient for shipping to fit into a 1.5°C carbon budget. It is worth highlighting that, in both models and in all scenarios, much of the gains in annual emissions are a consequence of energy efficiency improvement of the fleet (see Figures 7.18a and 7.19). This budget can only be respected if shipping demand is reduced and/or if the energy efficiency of the fleet is strongly improved before 2030 through operational (speed reduction, supply chain optimisation) and technical (wind energy, energy efficiency technology) improvements, which is aligned with those of Bullock et al., 2020; Halim et al., 2018; Schwartz et al., 2020; Smith et al., 2023, who find that operational and technological energy efficiency plays a strong role – in fact, larger than alternative fuels – in the decarbonisation of shipping, in particular before 2030. Findings from the land-shipping SFC model show that an improvement in energy efficiency also reduces the cost of the transition (as smaller amounts of alternative fuels and carbon price must be paid) and significantly reduces foregone earning streams and stranded paper. This is because conventional ships have to pay a smaller amount of carbon tax per transport work, so that they are less unprofitable compared to green ships than if no energy efficiency improvements take place.

7.3.1.3 Risk of stranded assets

This PhD is the first to quantify the amount of stranded capital and paper in the shipping industry. The results from the two models highlight several noteworthy findings.

First, due to the long lifespans of ships, a large share of the existing fleet is at risk of being stranded, no matter the investment decisions made in the 2020s: in case of a delayed transition happening in the early 2030s, the amount of stranded capital could reach up to the full fleet value, if retrofit was uneconomic or unavailable, but can be reduced by around 50% if it is. This finding echoes those of Chapter 4 and of Bullock et al. (2020) and is consistent between the land-shipping SFC model and GloTraM. In particular, the intense newbuild activity carried out between 2008 and 2013 means that this generation will represent a large share of the fleet in 2030; given that it will be quite old by then (15-20 years old) and thus unlikely to be worth retrofitting, yet still younger than its scrapping age, this generation may lose most of its value in the event of the low-carbon transition.

For the fleet which will be built by 2030, the financial socio-technical regime is only able to significantly reduce the amount of book loss and foregone earning streams if it significantly influences investment decisions in the industry regime in the 2020s. Both models show that no weak lever considered (enabler role, differentiated capital requirements, de-risking policy) alone is sufficient to start the uptake of zero-/low-carbon ships, because only a large difference in WACC (around 2%) is enough for any significant uptake to happen. However, a combination of weak levers can create such a sufficiently differentiated WACC and therefore drive an early uptake of dual-fuel ships in the 2020s. If the financial regime, combined with those further financial landscape pressures, are able to drive this early uptake of dual-fuel ships and if those do not get stranded, then both models show a significant reduction in foregone earning streams (21-44%, depending on the scenario, model and variant), book loss (1 to 39%), and stranded paper (8 to 57%).

However, there is no guarantee that the financial regime would support the right ship design. If financiers expect the growth of a design which ends up being stranded, their behaviour can be characterised as creative self-destruction. Of course, it is not possible to know at the time of writing whether a specific design will become stranded, so the distinction between creative self-destruction and enabler is hypothetical at that point. Although the land-shipping SFC model is not able by construction to model a creative self-destruction behaviour, GloTraM further sheds some light on the risk of stranded assets for methanol dual-fuel ships. They are slightly more expensive than conventional ships, are available today to shipowners, and are therefore impacted by the behaviour of financiers– and the results show that the socio-technical regime is able to influence their uptake. Whether those will become stranded is an open question: methanol dual-fuel ship are less cost-effective on an operational basis than ammonia dual-fuel ships, but an early uptake might mean that they would set the price at least in the 2030s, while ammonia dual-fuel ships will likely be less mature.

Although the impact of financiers' behaviour on total stranded capital is limited by existing sunk capital and long lifespans of ships, financiers' expectations and behaviour have a large impact on stranded paper, i.e. losses which are passed onto the financial regime. This finding is consistent in both models and in line with the findings of of Dunz et al. (2021), but the mechanism behind this finding differs between the three approaches. Dunz et al. (2021) show that when lenders anticipate an upcoming carbon tax it reduces their exposure to conventional loans up to four years after its implementation, while additional interest payments are required by banks for providing conventional loans during the two years before the implementation of a carbon tax. The former mechanism only takes place in the land-shipping SFC and in GloTraM if further landscape pressure (a de-risking policy) is put in place. Analysis of the results in GloTraM shows that if financiers are wary of the generation mentioned above and refrain from financing them, and if they are able to drive an uptake of dual-fuel ships in the 2020s, the amount of stranded paper is greatly reduced. Findings from the land-shipping SFC model show that if lenders price in the transition risks into their interest rates (enabler behaviour), the additional interest payments partially compensate for the increase in non-performing loans in 2030.

Finally, the results from GloTraM suggest that retrofitting largely reduces, but does not eliminate, the risk of stranded assets. On the one hand, the fact that conventional ships cannot retrofit in the land-shipping SFC model means that they operate at a loss for a long time , which is unlikely to happen; thus, this is likely that the model overestimates the amount of stranded assets.

7.3.2 Implications

This chapter has several theoretical and methodological implications. First, the discrepancy between the uptake of alternative fuels in GloTraM and the land-shipping SFC model highlights the need for shipping models to integrate elements of path-dependency, in particular the stickiness of investment decisions and the cost of capital. Models that assume that investors and financiers will immediately choose the cost-effective option might underestimate the importance of an early but small uptake of niche technology to enable a future accelerated uptake to successfully replace the conventional regime. Second, largely based on the proposal of Dunz et al. (2021) in the power sector, it has proposed a methodological approach to endogenise the evolving expectations of shipping lenders of the upcoming transition to low-carbon shipping into the cost of debt and of capital. Finally, it has proposed an approach to translate qualitative findings of the MLP framework into modelling for the shipping industry.

This chapter also has several practical implications.

The most interesting result of this chapter is that very progressive and proactive private financiers are not able to impact investment decisions and reduce the amount of stranded capital on their own, but they can do so if further weak policy levers in the early days of the transition such as de-risking investments in zero-/low-carbon shipping are further implemented. This highlights the benefits, but also the limitations, of private initiatives such as the Poseidon Principles in shaping the transition, which is in line with the findings from Chapter 6.

Second, expectations of the upcoming transition still matter, even in the absence of such weak levers, as they impact the amount of stranded paper. This is clearly an incentive for external investors - in this case, shipping lenders - to price in the transition risks into their activities, as this significantly impacts their own losses down the line.

Finally, the results show that retrofitting (updated GloTraM results) and energy efficiency (land-shipping SFC model) greatly reduce, but do not eliminate, the risk of stranded assets. A key takeaway is, therefore, that, even before the fuel pathway to decarbonisation clarifies, new investments can already limit the amount of asset stranding by making sure they are retrofittable and as energy efficient as possible. Similarly, policies should already incentivise today the improvement of fleet efficiency.

7.3.3 Limitations and future work

Let us now discuss the limitations and future work that arise from the analysis carried out in this chapter. This section discusses the strengths and weaknesses of the approaches with respect to the desired features identified in the literature review, which are presented in Figure 7.2. Limitations shared by the two approaches are first discussed, before going through limitations which are specific to one type of modelling approach.

There are several limitations arising from the scope of this work which are common between the two approaches: on the scope regarding the financiers considered, on the mitigation measures implemented, and on the mitigation solutions and technologies.

Table 7.2: Summary of the limitations

		Land-shipping SFC	Amended GloTraM
Desired methodological features	Path-dependency	High : - endogenous learning effects - sunk investments - change in financiers' and shipowners' behaviour over time - but no limit in energy sources availability	Medium : - sunk investments - exogenous price depend on limited availability of biofuels - exogenous learning effects - exogenous change in financiers' behaviour over time
	Limited rationality	High : - imperfect and evolving beliefs and knowledge of both shipowners and lenders - rationality not assumed	Medium : - rationality constrained by shipowners' myopic foresight - exogenous expectations of external financiers
	Role of finance	High : - endogenous interactions of the shipping and financial actors - but only covers lenders	Medium : - exogenous differenciated cost of capital - no feedback effect towards bank
Coverage	Time	High : 2018-2050	Medium : 2018-2030
	Space	High: whole world shipping	
	Techno-economic detail	Low : - two fuel technologies - agregated energy efficiency	High : high differentiation with various technologies for energy efficiency and propulsion
	Sector coupling	High : hard link with land sector for fuel production and demand creation	Medium : exogenous assumptions on biofuels availability, fuel prices and shipping demand
	Shipping segment	High: 3 shipping segments covering 81% of the fleet deadweight	
Resolution	Time	High: 1 year time step	
	Space	Low: only one region	
	Techno-economic detail	Low	High

(a) For a discussion of the choice of features to be evaluated, please refer to Figure 2.5 in the literature review Section.

First, both modelling exercises place a large emphasis on the role of alternative fuels in shaping the low-carbon transition and somewhat downplay alternative solutions such as increase in energy efficiency and reduction in shipping activity (coverage of sector coupling and techno-economic detail, in Figure 7.2). Although energy efficiency technologies are modelled directly in GloTraM, and indirectly in the land-shipping SFC model, the WACC is only differentiated by fuel type and therefore ignores financiers' expectations and behaviour regarding the energy efficiency of vessels. As discussed in the results, energy efficiency plays a large role both in reducing emissions from shipping in the short- and mid-term and in reducing the risk of stranded assets, as more energy-efficient conventional ships are less unprofitable when a high carbon price is implemented. In fact, lenders may not want to finance energy efficiency retrofits because the investment amount is too small and because those ships are already financed by an existing loan using the vessel as collateral (Schinas et al., 2018). Although both of these issues can be addressed (Schinas et al., 2018), retrofitting is likely to be subject to lower leverage, so assuming a common WACC for retrofitting could overestimate the actual uptake of energy efficiency technologies. Alternatively, financiers become enablers of those technologies and facilitate their uptake, including on conventional ships - a situation which is ignored in this thesis. This work also mostly disregards the role of changes in shipping activity, either by optimising supply chains (X. T. Wang et al., 2021) or by reducing the demand for cargo transportation. The former is in particular ignored in this chapter. This approach to supply-side risk is therefore largely biased towards technology solutions. This focus is justified by the focus on the role of capital and cost of capital, which concerns largely technology, rather than demand reduction or operational factors.

Second, the geographic scope of the work was aggregated to one region in both models (geographic resolution in Figure 7.2). This is an issue, as different regions face different WACC (Egli et al., 2019a), which could facilitate or hinder investment in low carbon technologies and lead to a ”climate investment trap” in developing economies which have less access to capital, as Ameli, Dessens, et al. (2021), Ameli et al. (2023), and Rickman, Kothari, et al. (2022) shows for other industries. Therefore, this work ignores the potentially unequal access of some shipowners to cheap capital and thus the inequity of such a transition. Further work is needed to assess the differentiated risk of stranded assets and the differentiated capacity to take advantage of opportunities offered by the transition to zero-/low-carbon shipping by geography.

Third, both models are limited in the diversity of financiers they consider (role of finance and limited rationality in Figure 7.2). The focus of this chapter was on the impact of lenders' behaviour on investment decisions and stranded assets. The impact of the expectations and behaviour of other external financiers (e.g. equity investors, insurance) on shipowners was largely ignored, which makes the results somewhat conservative: should the cost of equity also reflect the variety of behaviour of other types of financier, the impact of the WACC would be larger. This limitation is a consequence of the scope of the analysis, and the choice to focus on one type of financier (banks). This choice is justified by the important role of banks in shipping finance, as was found in Chapter 6 and in the literature review (Section 2.1.1); and by the important role that private banks have played in financing the niche technology and driving financial learning, later attracting other investors (Rickman, Larosa, and Ameli, 2022). Furthermore, both models consider financiers and shipowners as a representative agents without considering their internal variety. This feature, which is part of the features of the non-equilibrium schools of thoughts identified by Hafner, Jones, Anger-Kraavi, and Pohl (2020) (see Figure 2.1d in Chapter 2) was not considered central to thesis (see discussion in Section 2.3.1) but further work might look at the effects of a variety of actors onto the unfolding of shipping low-carbon transition. In particular with regards to the MLP theoretical framework, it might be of interest to look at the effect of protected niche and niche actors (as opposed to regime actors) onto the unfolding of the shipping transition. While GloTraM is by construction quite limited to do so, there are a few examples in the literature of SFC-agent based models which could represent this variety. It would also be in theory possible to represent the effect of the development of new technologies developing in protected spaces by adjusting the innovation coefficient in the technology uptake function (equation 7.5). Such adjustment however would need to be justified by additional analysis, for example on historical shipping transitions.

The final limitation shared by the two models is that this work concerns the timing and mitigation instruments behind the low-carbon transition. This work considers the specific case of a delayed transition, in the form of the implementation of a carbon price by 2030. However, the implementation of strong mitigation measures to promote the transition to low-carbon shipping could occur earlier in the 2020s, for example if the mid-term measures currently discussed at the IMO are ambitious and implemented before 2030. This scope was adopted because it typically leads to the strongest risk of stranded assets but should be considered as a worst case rather than realistic scenario and might therefore overestimate the amount of stranded assets. Furthermore, in both models, the implementation of a carbon price is set as the main driver of decarbonisation. As discussed above, this price might not only represent a carbon tax/carbon market but also the readiness of customers to pay for low-carbon shipping. Although both a tax and higher prices for low-carbon shipping are currently being debated and might be implemented in the future, other mitigation instruments are possible: such as pilot projects, compulsory design requirements or a carbon intensity threshold. This issue is particularly salient for the land-shipping SFC model, as the short-term measures (CII, EEDI, EEXI) are not explicitly modelled. Furthermore, in none of the scenarios considered is the recycling of the carbon price considered, so effects of subsidies are ignored. Therefore, this work is not immune from criticism towards energy models, as the carbon price might be neither the most practical, nor the most optimal instrument behind decarbonisation (Rezai and van der Ploeg, 2017; Stiglitz, 2019).

After looking at the limitations common to both approaches, let us now look at what limitations were specific to the land-shipping SFC model, and to which extent they were compensated by the use of GloTraM. The land-shipping SFC model is mostly limited in its coverage and resolution, which stems partly from its underpinning assumptions as a top-down model, and partly from the lack of time and resources to code it.

First, the techno-economic coverage and resolution of the land-shipping SFC model are very limited and restricted to two technologies and dual-fuel (Figure 7.2). This lack of coverage was partly compensated by the use of GloTraM, which is able to highlight the most cost effective design in terms of energy efficiency technologies, speed and fuel options. The calibration of the land-shipping SFC model with regard to fuel availability, costs and the evolution of energy efficiency heavily relied on those outputs of GloTraM. However, in its current form it is unable to represent the interactions between various alternative technologies, either competing (e.g. alternative fuels) or complementary (e.g. energy efficiency technologies and fuels). This stems from its relatively low coverage of socio-technical detail and is partly due to the fact that it is a top-down model; but other works have proved that including more than one technology was manageable from a computational point of view (Chica et al., 2023; Knobloch et al., 2021), so an obvious extension of the model would be to simultaneously include several technology options. Equation 7.25 formalises this extension by providing the share of investment in colour c when in competition with a finite set of colour $k \in colours$. Finally, this model does not consider retrofitting as an option and therefore potentially overestimates the amount of stranded assets. This is partly compensated by the parallel use of GloTraM, which is capable of obtaining such results. Addressing this issue could be done by assuming that β is not constrained by the fleet renewal (equation 7.6) and therefore address the case where $\beta > 1$.

$$\beta^c = \sum_{k \in colours} (\beta^0 + \beta^1 \Theta^c) \mathbb{1}_{tuc^c < tuc^k} \Theta^k \tag{7.25}$$

Both the inclusion of competing technologies and the possibility of retrofitting are left for future work, and would allow the model to function without the need for GloTraM, which might be more practical than continuing with two soft linked models. Such an extended model would perform well in terms of macroeconomics dynamics and techno-economic coverage and resolution, at least from the fuel point of view of marine fuels - although the uptake of energy efficiency devices would still be crude.

Second, even though the land-shipping SFC model covers most of the fleet and emissions, there is no disaggregation in shipping segments (shipping segment resolution, Figure 7.2). While this is not too much of an issue to study supply-side risks, this lack of resolution makes it difficult to study demand-side risks. Although demand-side risks are modelled in the land-shipping SFC model (as the shipping demand is a function of conventional/polluting activity in the whole economy), because there is no disaggregation across shipping segments, it is not possible to look at the specific effects on fossil carriers; in particular, on oil tankers. As a consequence, the decrease in shipping demand consequential to the decarbonisation of the land sector is spread over all segments and relatively benign. Such work would build on the macro-economic capabilities of the land-shipping SFC model to endogenously represent the interaction between different sectors of the economy and is left for future work. Furthermore, although the interactions with the land sector, are already quite endogenised, the model would benefit from distinguishing, in the land sector between energy/fuel production and general goods production, as the behaviour of those two sectors matters to shipping but might be better represented in two different sectors. This might be particularly helpful in looking at investment decisions in fuel production and bunkering, and related stranded assets.

Let us now look at the limitations specific to GloTraM, and to which extent those are compensated by the conjoint use of the land-shipping SFC model.

First, the initial lack of consideration for financiers' behaviour is now partly compensated by the use of differentiated WACC obtained from the land-shipping SFC model, but the interconnectivity of the shipping and financial systems is limited as there is no feedback towards banks (role of finance and limited rationality in Figure 7.2). More concerningly, GloTraM ignores the effects of the rationality of the shipowners (limited rationality in Figure 7.2): they are assumed to have a perfect knowledge of all the existing solutions and choose the most profitable one. This approach is highly ambitious and ignores the learning and imitation effects of shipowners. However, this perfect knowledge is limited by a myopic foresight with a very short time horizon, as shipowners only know the current carbon price and ignore future carbon prices. This very short foresight makes the uptake of zero-/low-carbon ships before 2030 very conservative. Although this made it possible to identify the impact of sole lenders' expectations / behaviour onto investment decisions, it might be an unrealistic assumption and is worth further investigation.

Second, the performance of the model in terms of sector coupling is mixed (coverage of sector coupling in Figure 7.2). Input assumptions on biofuel availability, fuel production cost and shipping demand ensure coverage of interaction with other sectors. However, this link is exogenous and was only covered in one set of inputs due to time constraints. This is particularly a problem for studying demand-side risks: shipping demand aligns with SSP2-RCP2.6 and no further demand scenarios were considered. This is due to lack of time and scarcity of available datasets with a strong decrease in fossil use in the land sector (see, for example, Faber et al. (2020) and Sharmina et al. (2017)); most large-scale models assume a large use of carbon capture to justify long-lasting use of fossil fuels, especially oil (Grant et al., 2022). As a consequence, the work with GloTraM largely ignores demand-side risks. More research on the consequences of trade scenarios aligned with a temperature increase of 1.5 ° C is needed to investigate the potential for demand-side risk.

Chapter 8

General discussion and conclusion

The following chapter presents a general discussion and some concluding remarks. It first recaps the literature gaps which this thesis aimed to address and the research methods developed to answer those; going on to explain how the findings answer each research question. Then, the key findings under each research question are triangulated. It concludes by listing the key recommendations arising from this research.

8.1 Summary of literature gaps and research methods

As explained in the literature review, this thesis aimed to address five research gaps: one theoretical, three empirical and one methodological; as follows:

- Theoretical understanding of financiers' agency during socio-technical transitions.
- Understanding of the expectations of financiers about the upcoming shipping low-carbon transitions.
- Understanding of the pricing of transition risks by financiers at the asset level.
- Understanding how the expectations of financiers regarding an upcoming socio-technical transition impact its realisation.

- Incorporation of the expectations of financiers of an upcoming transition into energy modelling.

These literature gaps were addressed by investigating the steps described in Figures 8.1 and 8.2, using a variety of research methods. In Chapter 4, a static modelling exercise was performed to estimate the sunk capital in the current and ordered fleet and investigate how this capital compares with the limits imposed by the need to limit climate change to a 1.5° C increase. In particular, the committed emissions of the fleet were compared with the carbon transport budget; and the committed supply, with the demand for the transport of fossil cargo aligned with a 1.5°C temperature increase. The main results were elements of context of the scale of the issue of asset stranding in the shipping sector. Based on the findings from Section 2.1.3 in the literature review, Chapter 5 provides an extended theoretical framework to understand the evolution of expectations and the behaviour of financiers as socio-technical transitions unfold. This theoretical framework is used and tested in Chapter 6 to investigate the current expectations and behaviours of shipping financiers using a mixed methods approach. As a first step of this mixed methods approach, a quantitative econometric analysis is performed to investigate whether transition risks are priced into the loan spreads of shipping loans. As the second step, the results are explained using a qualitative case study; namely, the data collected from 12 interviews with shipping financiers. Finally, Chapter 7 conducts two modelling exercises to investigate the impacts of shipping financiers' expectations on the unfolding of a transition to low-carbon shipping (supply-side risk only). The models and scenarios are calibrated to the qualitative and mixed methods findings of Chapters 6 and 5. They simulate the evolution of the expectations of financiers, of the fleet and, finally, of the amount of stranded assets.

The next section summarises how those research methods answer the research questions set in the literature review.

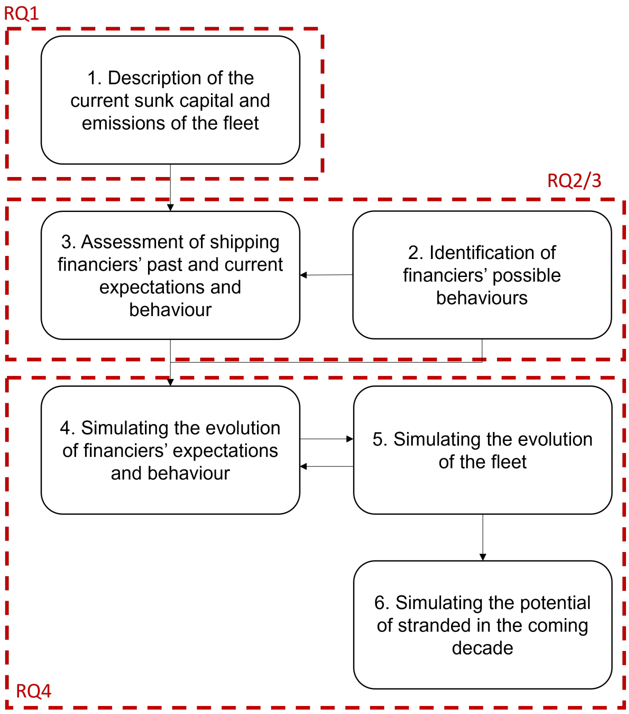


Figure 8.1: Overview of research questions (recap)

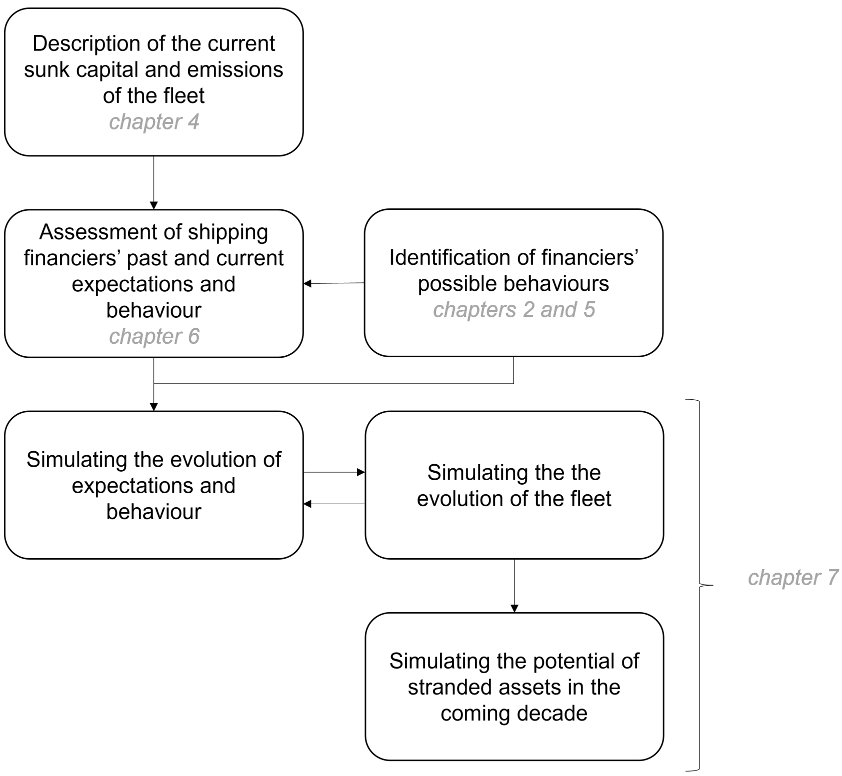


Figure 8.2: Research framework and structure of the thesis (recap)

8.2 Answering the research questions

Let us first consider successively how each research question was answered.

8.2.1 Research question 1

The first research question of this thesis was as follows: *What share of the existing sunk capital in ships is incompatible with land and shipping carbon budgets?*

Existing and ordered ships are set to emit 50% more CO2-equivalent than the carbon budget of the shipping aligned with a 1.5°C trajectory. This means that around 40% of the fleet (measured in deadweight and value) are incompatible with the shipping carbon budget and must either move to cleaner shipping technologies or stop operating earlier than the end of their expected lifetime in order to uphold the shipping carbon budget.

Existing and ordered oil and liquefied gas tankers are expected to be in oversupply if the demand for fossil fuels shipping aligns with a 1.5°C trajectory; with up to 30% of their fleets idled around 2030, even if no more ships are ordered after 2023. Given that the other sectors (bulk carriers, containerships) are not impacted by demand-side risk, only 8 to 9% of the profits and value of the entire fleet are at risk of stranding from demand-side risk.

8.2.2 Research question 2

The second research question was as follows: *"What are the current expectations of financiers regarding the upcoming shipping low-carbon transition?"*

After decades of inertia, shipping financiers are now expecting an upcoming transition to low-carbon shipping, although the shift in expectations was partial and imperfect at the time the data were collected: our qualitative findings show that financiers are not overly worried about the potential for their investments to become stranded assets, as they believe that the shift to a supply-side shipping transition is happening; although they are not as optimistic as would be necessary to reach a 1.5°C pathway. Therefore, they continue to finance fossil-fuelled ships. Furthermore, our quantitative findings show that banks are now providing cheaper loans to shipowners with higher climate performance, but not to less carbon-intensive ships.

Based on our qualitative findings, the partial and ambiguous shift in expectations regarding supply-side risks and the importance of the relationships and trust with their existing clients mean that financiers have the intention to play a Loyal Enabler role in the upcoming transition to low-carbon shipping. This new intention has some - although ambiguous - concrete impact on their behaviours. However, because of the weight of the financier-shipowner relationships and the trust in their clients' opinion, investors are at the mercy of shipowners' investment decisions, which could leave them stuck with assets that become stranded if they are unable to switch their ships from fossil fuels to a more cost-effective alternative.

8.2.3 Research question 3

Turning now to the third research question: *"How could the expectations of financiers of upcoming low-carbon transition in shipping evolve during this transition?"*

The extended MLP theoretical framework described in Chapter 5 proposes a range of five archetypal behaviours which the financiers could adopt in the future. First, financiers could not be expecting the upcoming low-carbon transitions and continue to finance conventional ships as they have in the past (Inert); or they could further anticipate a growth in conventional activity and push their clients to adopt a bullish investment strategy (Creative Self-Destruction). If they anticipate upcoming low-carbon transitions in shipping, they might expect the incumbent shipowners to lead this transition and support them in doing so (Loyal Enabler), or they might believe niche new entrant shipowners will develop and carry low-carbon innovations by replacing the incumbent shipowners and support them in doing so (Redirecting Enabler). Finally, they might believe the transition to be too risky or ill-suited to their preference and investors, and choose to divest from the sector all-together (Winding Down).

The results from Chapter 6 show that after being Inert over the past decade, an increasing amount of them have partially and ambiguously shifted their beliefs and now have the intention to become Loyal Enablers. If this trend were to strengthen and lead to concrete impacts, then one could expect shipping financiers to become strong Loyal Enablers and therefore help the current shipping incumbents drive the transition to low-carbon shipping. The results also hinted that a minority of financiers were tempted by a Winding Down behaviour. If this behaviour were to become dominant, then regime financiers might retreat altogether from the sector, leaving a finance gap which could either hinder capital-intensive "green" investment in the transition, or make room for new niche financiers to appear.

8.2.4 Research question 4

Finally, the fourth research question was: *"How do those expectations affect the amount of stranded assets?"*

To answer RQ4, this thesis has focused on supply-side risks only, as significant additional work was needed to address demand-side risks and those were left for future work. The summary of the results discussed below therefore only draw on an analysis of supply-side risks, and they might not be applicable to demand-side risks.

The results of Chapter 7 show that regardless of financiers' expectations and behaviour, a large amount of supply-side stranded assets could materialise should the shipping industry align with a 1.5°C trajectory. In case of a delayed transition happening in the early 2030s, the amount of stranded capital could reach up to the full fleet value, if retrofit was uneconomic or unavailable, but can be reduced by around 50% if it is. However, if lenders anticipate the future transition and asset stranding, they will be able to reduce (but not eliminate) the amount of supply-side stranded capital which they will bear, i.e., stranded papers, so that most of the stranded capital is borne by the shipowners and/or the customers.

However, a combination of Loyal Enablers and weak policy levers (e.g. differentiated capital requirements, de-risking of green loans by a State financier) leads to an early uptake of zero-/low-carbon ships in the 2020s which significantly accelerates the transition, reduces the amount of supply-side stranded capital and reduces cumulative emissions by around a fifth (12 to 25%). This is because a large delta in WACC (around 1.5-2%) is required to bridge the gap between conventional and dual-fuel ships, which financiers alone are not able to drive. This suggests that financiers' expectations alone are not sufficient to drive the transition and limit the amount of stranded capital, but can participate in it. Furthermore, Chapter 7 highlighted several other factors which have a large impact on the resulting stranded assets - e.g. importance of energy efficiency, retrofittability - so that financiers' expectations are one among several drivers of stranded assets.

8.3 How the findings relate to one another

Having summarised how the findings answer the research questions, this section now moves on to discuss how those findings echo each other. This thesis has used a variety of disciplines (transitions studies, macro-economics, techno-economics and neoclassical), theories (MLP, AMH and post-keynesian economics) and research methods (regression analysis, qualitative case study, SFC model and optimisation model). This section discusses what one can learn about transition risk and the way low-carbon transitions unfold by putting together these lenses. The findings address five key topics: the characterisation of financiers' expectations; the impact of financiers' behaviour on the shipping industry; the limitations of representing human behaviours in a quantitative model; the methodological considerations regarding the choice of model to represent a shipping low-carbon transition; and, finally, the need for financial regulation.

8.3.1 Characterising and explaining financiers' expectations

The juxtaposition of the techno-economics and transition studies lenses was helpful to characterise the expectations of stranded assets by highlighting the gap between where they currently lie and where they would if a 1.5-aligned decarbonisation scenario was fully certain. The answer to Research Question 2 (transition studies lens) shows that financiers' expectations of future supply-side stranded assets, although they have increased, are nowhere near the potential scale of the stranded assets highlighted in the findings of Research Question 1 (techno-economic lens). The qualitative findings of Research Question 2 have shown that financiers believe the transition is coming, but they believe that the conventional and LNG-fuelled ships they have financed are probably not at risk. This is in contradiction with the findings of Research Question 1, which shows that more than a third of the current and ordered fleet needs to either be retrofitted to low/zero-carbon technology and/or to transporting non-fossil commodities, or be scrapped before the end of their planned lifetime.

The transition studies lens, through the use of the AMH, is helpful to explain this gap. Research Question 2 qualitative results highlighted several reasons for this discrepancy: this might be because they anticipate a slower supply-side transition than the input of Research Question 1, suggesting that a 1.5°C transition is not fully credible to them, or an alternative credible scenario among others. It could also be because they have not grasped the strong implications of such a transition on the assets they finance. Finally, there might be a discrepancy between how risks are modelled by banks and how they are perceived. On the supply side, they anticipate in vague terms that some assets will become stranded, but that the ships they finance are not at risk, because they are more modern than the average and therefore will not be stranded. The results from Research Question 2's qualitative findings also suggest that some of them do not expect the stranded assets to translate into stranded paper on their own balance, because the tenors are too short - which is relevant for corporate financing, which is characterised by tenors of 2-3 years, but less so for ship financing, which usually has tenors above 7 years as highlighted in the quantitative results of Research Question 2.

Further developments in the financial and/or the shipping landscape and/or niche might be necessary to further increase the financiers' perceived likelihood of a low-carbon transition and therefore increase financiers' expectations of a strong decarbonisation of the shipping industry. For example, on the industry landscape side, the implementation of concrete measures (e.g. at the IMO, or by regional or national policy makers) or an increasing propensity of consumers to pay for low-carbon shipping might give stronger signals to the financial regime actors - and niche actors, although they were not the focus of this thesis. Further landscape evolution (e.g. an increased price of fossil fuels) might further play a role but are obviously difficult to anticipate. On the industry niche side, a sufficient momentum for shipping low-carbon technologies such as energy efficiency device or alternative fuels in protected niches might make the uptake of low-carbon shipping technologies more credible to the financiers. On the financial landscape side, further financial policies might be needed to shift the behaviour of the financiers, which are detailed below in Section 8.3.5. Finally, the build up of niche financial innovation, either carried by incumbent financial actors or by new niche entrants, might help the financial actors to measure the climate risks and adjust their behaviour, for example the development of new financial tools to measure climate performance or new financial instruments.

8.3.2 Understanding the impact of financiers' behaviour on the industry

Let us now move to the conjoint findings of RQ2/3/4, which use the lenses of transition studies, techno-economics and post-Keynesian economics, on the impact of financiers' behaviour on the unfolding of a shipping low-carbon transition. The findings reached by using the transition studies lens (RQ2/3) were helpful to inform the assumptions underpinning the scenarios modelled with macroeconomics and/or techno-economics lenses (RQ4). Likewise, the use of macro-economics and techno-economic models was helpful to understand, at an aggregate level, the implications of the findings obtained through the lens of transition studies, which are often context-specific and limited to the scope of the case study (e.g. Cairns et al. (2023), Falcone et al. (2018), S. Hall et al. (2017), and Pathania and Bose (2014), to cite a few). In this thesis, the findings from Research Questions 2 and 3 show that financiers have historically adopted an "Inert" behaviour, but that they have intentions to become "Loyal Enablers". Research Question 4 has investigated what this behaviour would translate into: the findings show that this intention alone fails to influence the supply-side transition significantly, but if further weak policy levers are implemented i.e. de-risking policy from a public investor or the implementation of differentiated capital requirements on green and conventional investments, a Loyal Enabler behaviour behaviour significantly impacts the materialisation of a low-carbon transition, with investments in dual-carbon ships happening before a carbon price is implemented. This early uptake somewhat impacts the amount of stranded capital.

Furthermore, the qualitative findings of RQ2/3 (transition studies lens) have not only helped inform the various scenarios (Inert versus Enabler), but have also established in which context those scenarios could unfold: as regime financiers were mostly found to support the regime incumbents, they are likely to support the low-carbon technology if it is carried by incumbent actors, and are more likely to adopt an inert or winding down behaviour behaviour if it is carried out by niche actors.

Such a hybrid approach is not completely new, but it is fairly unusual in the energy transition and modelling literature (McDowall, 2014). Furthermore, although this approach has been used with optimisation models (e.g. McDowall (2014) and van Sluisveld et al. (2020)), it is the first time to my knowledge that this was conducted with a post-Keynesian model. One further advantage of this approach is that it recognises the contested nature of the understanding of the low-carbon transitions, by actively engaging in a dialogue between two distinct methods (empirical mixed methods approach, and energy modelling) (McDowall, 2014).

8.3.3 Complexity of qualitative behaviours and limitations of modelling

The translation of RQ2/3 findings (transition studies lens) into RQ4 input (techno-economic and post-Keynesian economics lenses) has led to a narrowing of the rich qualitative findings into operational inputs which are more deterministic in nature, something which was already observed by van Sluisveld et al. (2020). The five behavioural archetypes identified in the findings of Research Question 3, which are already simplifications of reality, could not be fully translated into operational parameters; and only two (Inert and Enabler) were explicitly modelled. Although those two were chosen because they corresponded to the most likely findings of RQ2, this overview is helpful to highlight the model's blind spots and limitations of the modelling.

In particular, the qualitative results of Research Questions 2/3 (transition studies lens) have suggested the appearance of new financiers, which again concerned only a minority of the interviewees. If these trends strengthen over time, this suggests that a financial transition could take place in parallel with the industry transition, something which was not represented in the modelling exercises. Furthermore, the qualitative results of Research Questions 2 and 3 make a distinction between Loyal Enablers and Redirecting Enablers, concluding that the former is more likely at the time of the investigation. Research Question 4 fails to take into account this distinction and assumes that if financiers adopt an "Enabler" behaviour, they will automatically finance the successful developer of the low-carbon technologies. This scenario might hold true if the low-carbon shipping transition happens as a transformation led by incumbents supported by Loyal Enablers, a scenario which the findings from Research Question 2 hint towards - in particular, the quantitative findings from Research Question 2 suggest that financiers attach more importance to the borrower's environmental performance than the asset's, essentially trusting the borrower to make the right choice of ship.

Finally, those results have suggested that some financiers are tempted to adopt a "Winding Down" behaviour, although it was not the preferred option for most of them at the time of investigation. In particular, a strategy available to financiers, and which has been alluded to in the research findings of Research Question 2, is to reduce the tenors of their financing instruments in order to be able to retrieve faster from the sector if needed. This is equivalent to transferring part of the risk traditionally taken on by banks onto the shipowners, a behaviour which can be likened to a "Winding Down" behaviour. The work carried out to answer Research Question 4 (techno-economic and post-Keynesian economics) has not explicitly investigated the impact of such behaviour on the evolution of the fleet, which is an area for future work. However, RQ4 GloTraM results have shown that, if financiers refrain from financing new conventional fuelled ships from now onwards, their take of stranded paper would be significantly reduced; this suggest that financiers might benefit from such a behaviour.

This is particularly relevant given that the findings from Research Question 4 have shown that the extent to which financiers can impact the total amount of supply-side stranded capital is limited, as most of the stranded capital concerns existing and ordered ships today. This echoes the findings of Research Question 1, that is, that the current and ordered fleet already carries a large risk of stranded assets. Only if financiers refrain from financing older ships by 2030; they adopt a Loyal Enabler behaviour; and further weak policy levers are implemented; is the amount of supply-side stranded assets reduced compared to an Inert scenario. However, Research Question 4 shows that financiers' behaviour influences to which extent those risks are passed onto the banks, i.e. how much stranded paper happens. In particular, if financiers price into the cost of debt the future risk of supply-side stranded assets, the collected additional interest payments partly compensate for the increase in non-performing loans. Taken together, these findings suggest that it is in banks' and financial regulators' interest to price transition risks in the shipping industry; for the former, in order to reduce the stranded assets that they would bear; and, for the latter, in order to avoid financial instability and the transmission of the risk of stranded assets to the financial system.

It is inevitable that a modelling exercise, no matter how complex, would fail to represent the richness of human behaviours identified in the results of Research Questions 2 and 3. However, the results still highlight areas for future research. Given that the future evolution of financiers' behaviour is unknown, it might also be worth investigating how the transition unfolds depending on whether the incumbent financiers adopt a Redirecting Enabler or Loyal Enabler role; or whether they choose to retreat from the sector (Winding Down).

Despite those limitations, several features of the SFC land-shipping model show promise for capturing certain MLP dynamics. The SFC model developed in this thesis already incorporates notions of innovation and learning, resulting in a non-linear S-curve of technology uptake, which aligns well with the theoretical foundations and empirical findings of the MLP framework. Although the concept of a protected niche was not modelled, some non-equilibrium models have proposed approaches to it that could be integrated into the current framework (e.g. Walrave and Raven (2016)). The model already represents rationality based on heuristics, a concept commonly used in MLP (see Section 2.2.3.2 for a discussion). While the current model represents only one agent per type – financier, shipowner, and government – a few other SFC models have been adapted to agent-based models (e.g. Lamperti et al. (2021)), allowing for more complex representation of diversified agents. One could imagine building at least two agents, such as niche and regime actors, to represent some of the MLP dynamics. However, adding these elements introduces a trade-off between model complexity and result clarity, particularly if additional granularity is introduced to the techno-economic inputs.

8.3.4 Methodological considerations

The use of a macro-economic lens and a techno-economic lens is helpful to grasp the complexity of the unfolding of a shipping low-carbon transition, as both strands are limited methodologically in the way they represent features of this transition. A more detailed discussion is available in Chapter 7 but, as a summary, the main strength of the post-Keynesian model developed for this thesis lies in representing path-dependency and the role of finance in low-carbon transitions, even as it lacks many techno-economic details which are necessary to fully grasp the potential technological direction of the transition. In particular, in this case it failed to account for the various types of fuel available and the potential for retrofit. It is worth noting that such limitations could theoretically be addressed with further time and work, but they are very common in the current state of post-Keynesian economic research (e.g. Dafermos and Nikolaidi (2022), Dunz et al. (2021), Hafner et al. (2021), and Lamperti et al. (2021), to cite a few, only account for two technologies; Mercure, Pollitt, Edwards, et al. (2018) provides an interesting example of a study which has tried to address this limitation).

On the other hand, techno-economic models are limited in the way they can represent path-dependency and the role of finance. Such limitations seem harder to address, as they are embodied in the assumptions of the models and could only be partially fixed in this thesis on an ad-hoc basis by manually changing the exogenous input assumptions; in this particular case, the evolution in the cost of capital. Those assumptions need to be rigorously justified, which many studies fail to do (see Lonergan et al. (2023) for a review). In this particular thesis, the qualitative findings through the lenses of the MLP and the outputs of the SFC model (post-Keynesian lens) were used as input, which highlights the benefits of using those two models jointly; but this is likely to be impractical for most applications.

8.3.5 Financial policies

Finally, the answers to Research Questions 2 and 4 suggest, for different reasons and based on different methods, that financiers and private initiatives alone are unable to drive the transition and/or reduce the amount of supply-side stranded assets and call for public intervention to regulate the finance sector, not solely on the emitters' side. On one hand, several European banks interviewed to answer Research Question 2 have stated that financial reporting regulations and capital requirements are essential for banks to act as Loyal Enablers, as the competition between banks stops them from completely promoting greener technologies. On the other hand, findings related to Research Question 4 show that both financial policy levers and financiers' pricing of transition risks are necessary to drive an early uptake of low-/zero-emission ships in the 2020s. Given that this finding has been reached using two different theoretical lenses, the use of multi-disciplinary comparison here is not strictly necessary, but it is reassuring in its validation of the findings.

8.4 Recommendations

A number of recommendations can be derived from those results. These can be divided between recommendations for academic researc; for the industry, and for policy.

8.4.1 Recommendations for future research

Regarding implications for future research, this thesis has shown that financiers are not perfectly rational agents; and that their behaviour can have an influence on how low-carbon transitions unfold. Researchers might want to consider the agency of financiers, as they have the ability to lock in the energy system or accelerate investments, rather than assuming they will passively finance any investment in the new technologies. In particular, the results have shown that they do not have perfect and internally consistent beliefs about the future and do not expect a 1.5°C transition to unfold. Furthermore, those expectations are path dependent; that is, they evolve partially over time but do adjust to changes in the landscape. In that regard, the results validate the theory of the Adaptive Market Hypothesis. Those empirical findings have implications for socio-technical transition research and for the modelling of low-carbon transitions.

First, in line with the suggestion of Naidoo (2020), this thesis has demonstrated the importance of considering the active role of financiers in socio-technical transitions research, rather than assuming that finance is a passive and exogenous force. In particular, this thesis has argued that financiers are agents which can themselves be understood across the three levels of the MLP: incumbent financiers are part of the regime and share with other regime stakeholders knowledge and formal and informal norms; and rely on existing infrastructure. However, niche financial innovations can emerge and disrupt the financial regime as well as industry innovations. A specificity of the financial regime and niche, however, is that they potentially spread across several industry regimes, if they are providing finance to various industries - which is the case of most of the financiers considered in this thesis, in particular under Research Question 2.

Second, the results have several methodological implications for the modelling of low-carbon transitions. Unrealistically assuming that financiers have perfect future beliefs means that energy models might overestimate the access of new technologies to capital and the speed of the transition; and ignore the large risk of stranded assets. This research has experimented with two ways of integrating such expectations into the modelling exercise: by endogenously changing the inputted cost of capital in an optimisation model; and by building an SFC model integrating in detail the shipping sector. The results have shown that the choice of model has a large impact on the results, so that particular care in selecting one approach over the other should be justified. Both approaches have their strengths and weaknesses and, at least for this thesis, were building on each others' outputs for their own input.

Third, this thesis has shown the importance of considering the difference in access to capital depending on the expectations of the transitions by financiers; but several other areas of differentiation are also worth considering. In particular, industry players in various countries likely have a differentiated access and cost of capital, depending on their perceived country risk (Ameli, Dessens, et al., 2021; Ameli et al., 2023; Damodaran, 2022; Egli et al., 2024; Lonergan et al., 2023; Polzin et al., 2021). This perceived risk is highly correlated with the level of per-capita income (Ameli et al., 2023; Sweerts et al., 2019) and the vulnerability to climate change (Ameli et al., 2023). Ignoring such effects means that models likely over-estimate the potential uptake of low-carbon technologies in those countries and therefore the potential speed of the transitions, and underestimate the potential technological inequity of such transitions.

Finally, future research, in particular modelling, should especially pay attention to the path-dependency and lock-in elements of transitions; as knowledge accumulation, access of some actors to resources - in this case, financial resources -, sticky beliefs and learning effects mean that the way transitions unfold might be sub-optimal from a techno-economic perspective, take longer than expected to build up, and be subject to unforeseen accelerations. This research has shown that non-equilibrium models - and, in this particular case, SFC models - are well-suited to represent those dynamics in the shipping industry at least, while optimisation models can be adapted but are inherently more limited. Related to the point on geography made above, there might be path-dependent interactions between technology maturity and geography on the cost of capital: if technology learning (including by financiers, not only by industry players) is not fully transferable from one geography to the other, this would mean that, for a transition to happen across the world, technology uptake and its associated finance needs to happen in various parts of the world if the rapid uptake in the later part of the S-curve is to take place evenly across geography. The results of RQ4 have highlighted the importance of such early uptake on the unfolding of the transition, but have not investigated the interaction with geography. This is a potential area for future research.

8.4.2 Recommendations for the industry

Turning to the recommendations to the industry and, in particular, to financiers, a key implication from all the research questions is that financial institutions and shipowners should evaluate the climate risk of their fleet and, if this evaluation finds that this risk is significant and that a decarbonisation scenario is a credible scenario, consider the value for the vessels in their portfolio to be climate resilient and for their customers have a reliable transition plan (e.g. by investing in ships that are ready for future fuels and can be operated with low-/zero-carbon fuel, and by avoiding investments in LNG that have expensive fuel substitutes). The results from Research Question 4 show that the ability to retrofit ships and increased energy efficiency largely reduce, although they do not eliminate, the risk of stranded assets. Although future low-carbon technologies are not clear, new investments can, therefore, already limit the amount of asset stranding by making sure that new ships are retrofittable and as energy efficient as possible.

Given that a large amount of capital is at risk, investors and financiers might benefit from assessing the risk of stranded assets; if found credible, from pricing those risks when investing in new ships; and from taking a view of the risks attached to the assets themselves, not solely to the borrower. This might mean adjusting the pricing, reducing the tenors of the loans, or divesting from certain types of ship and of shipowners. The results from Research Question 4 show that those expectations do have an impact on the amount of stranded paper, and to some extent on the amount of stranded capital if combined with weak policy levers.

8.4.3 Recommendations for policymakers

Finally, the findings of this thesis have several implications for policymakers.

First, the findings of all research questions underscore the need for early policy signalling, as the absence of clear and credible commitments allows for the continued construction of ships misaligned with decarbonisation trajectories, contributing to a growing pool of potential stranded assets. These investments exacerbate technology lock-in and increase the overall cost of the transition. The fact that landscape pressures (Paris Agreement, IMO announcements) have led to a shift in financiers' expectations and behaviour suggests that, whilst waiting for the implementation of policy solutions, there is an advantage in having clear signals to decarbonise international shipping in line with the Paris Agreement temperature goals from organisations such as the IMO. Even if no policy is implemented immediately, as expectations of lenders influence investment decisions, a pre-commitment of policy makers would nudge private investors towards low-carbon technologies. The recent development in the IMO, which has seen the adoption of a near 1.5°C objective (IMO MEPC, 2023), goes in the right direction in this regard; but more concrete measures are needed to ensure that the commitment to meet this trajectory is credible to investors.

Second, the results from Research Questions 1 and 4 suggest that policymakers should consider the role of existing non-aligned ships during the low-carbon transition, contemplating whether mandates for retrofitting, under-utilisation or scrapping should be imposed, all of which require careful consideration.

Finally, the results from Research Questions 2 and 4 further reinforce the argument for strengthening disclosure initiatives and intensifying monitoring efforts or implementing more interventionist policies to regulate the financial sector; not solely focused on the emitters' (here, shipowners') side. Early weak policy levers, if coupled with proactive financiers, have the potential to significantly impact the unfolding of the transition before strong industry policies such as the implementation of a carbon price. Several policy options are available to regulators, ranging from mandating lenders to assess and disclose emissions financed according to industry standards, through imposing taxes on financial actors based on the emission intensity of their portfolios (Donnelly et al., 2023), to adjusting capital adequacy requirements for carbon efficient (intensive) portfolios via a green supporting factor or implementing green monetary easing policies (Campiglio and van der Ploeg, 2022; Dafermos and Nikolaidi, 2021; Dunz et al., 2021). When possible, for example in project finance or with the use of collateral, such regulations should not only cover companies' emissions but also the assets being financed. Furthermore, direct support from a public financial body can compensate for the lack of support from existing lenders to finance cleaner assets, for example through the provision of guarantees (Schinas et al., 2018). Export credit facilities are already commonly combined with senior-secured loans in the shipping industry to reduce the cost of capital, and could be used specifically to facilitate the uptake of cleaner technologies (Schinas et al., 2018). Direct support for public financial institutions not only supports low carbon technologies, but also creates a signalling effect of trust that encourages existing lenders to support new technologies (Geddes and Schmidt, 2020; Geddes et al., 2018).

8.5 Concluding remarks

The results of this thesis hopefully broaden the understanding of the agency and the role of financiers during low-carbon transitions. Taken together, the findings stress the scale of the risk of stranded assets in the shipping industry, should the world economy decarbonise, and how inconsistent financiers expectations are with those risks. They also suggested that financiers have a valuable role to play in the upcoming low-carbon transitions, although they cannot drive the transition alone. In particular, the findings from the various research questions suggest that private initiatives and financiers' proactive role alone are not sufficient to drive the shipping transitions and reduce the amount of stranded assets; hence the need for climate policies to regulate the financial sector. The results directly investigate the impact of public financial support in de-risking investments into cleaner technologies and creating a trust signal to shift financiers' expectations; and the impact of differentiated capital requirements. However, further options are available to regulators, such as requiring lenders to assess and reveal the emissions related to their financing activities in line with industry standards; and imposing taxes on financial institutions based on the carbon intensity of their portfolios in order to link the cost of debt to the environmental performance of the borrower and the asset. This would encourage the financial system to contribute to the shift to a low-carbon economy.

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Appendix A

Mapping of ship types

Table A.1: Mapping between IMO and Clarksons WFR ship types

IMO type	Clarksons type
Bulk carrier	Bulk/Oil Carrier
Bulk carrier	Nickel Carrier
Bulk carrier	Aggregate Carrier
Bulk carrier	Salt Carrier
Bulk carrier	Gypsum Carrier
Bulk carrier	Bulk and Caustic Soda Carrier
Bulk carrier	Miscellaneous Dry Bulk
Bulk carrier	Chip Carrier
Bulk carrier	Forest Product Carrier
Bulk carrier	Ore Carrier
Bulk carrier	Aggregates Carrier
Bulk carrier	Limestone Carrier
Bulk carrier	Ore/Oil Carrier
Bulk carrier	Bulk Carrier
Bulk carrier	Cement Carrier
Bulk carrier	Urea Carrier
Chemical tanker	Ore and Sulphuric Acid Carrier
Chemical tanker	Phosphoric Acid Carrier
Chemical tanker	Methanol Carrier

IMO type	Clarksons type
Chemical tanker	Chemical and Oil Carrier
Chemical tanker	Chemical Bulk Tanker
Chemical tanker	Sulphuric Acid Carrier
Chemical tanker	Chemical Unknown Carrier
Chemical tanker	Bulk/Chemical and Oil Carrier
Chemical tanker	Molten Sulphur Carrier
Chemical tanker	Edible Oil Carrier
Chemical tanker	Chem Parcel Tanker
Container	Fully Cellular Container
Cruise	Cruise Ship
Ferry-RoPax	Ro-Ro Freight/Passenger
Ferry-RoPax	Reefer/Pass./Ro-Ro
Ferry-RoPax	Reefer/Ro-Ro Cargo
Ferry-RoPax	Pass./Car Catamaran Vessel
Ferry-RoPax	Pass./Car Ferry
Ferry-RoPax	Passenger/Cargo Vessel
Ferry-pax only	Passenger Vessel
Ferry-pax only	Passenger Catamaran Vessel
Ferry-pax only	Air Cushion Ferry
Ferry-pax only	Passenger/Trimaran
General Cargo	Pulp Carrier
General Cargo	Fish Feed Carrier
General Cargo	Palletised Cargo Carrier
General Cargo	Open Hatch Carrier
General Cargo	Transport (Heavy Lift)
General Cargo	Slurry Carrier
General Cargo	Deck Cargo Carrier
General Cargo	Livestock Carrier
General Cargo	Heavy Lift Cargo Vessel
General Cargo	General Cargo
General Cargo	Multi-Purpose/Heavy Lift Cargo

IMO type	Clarksons type
General Cargo	Barge Carrier
Liquefied gas tanker	Oil and Liquid Gas Carrier
Liquefied gas tanker	LCO2 Carrier
Liquefied gas tanker	LCO2/LPG Carrier
Liquefied gas tanker	CO2 Carrier
Liquefied gas tanker	CNG Carrier
Liquefied gas tanker	Liquid Hydrogen Carrier
Liquefied gas tanker	Ammonia/LPG
Liquefied gas tanker	Ethane/LPG
Liquefied gas tanker	Ethylene/LPG
Liquefied gas tanker	LPG Carrier
Liquefied gas tanker	LNG and Oil Bunkering Vessel
Liquefied gas tanker	LNG/FPSO
Liquefied gas tanker	LNG Bunkering Vessel
Liquefied gas tanker	LNG/Ethylene/LPG
Liquefied gas tanker	LNG/Regasification
Liquefied gas tanker	LNG Carrier
Miscellaneous - other	Armory Vessel
Miscellaneous - other	Search and Rescue
Miscellaneous - other	Patrol Vessel
Miscellaneous - other	Rocket Salvage Ship
Miscellaneous - other	Rocket Launch and Recovery Ship
Miscellaneous - other	Electricity Generating Vessel
Miscellaneous - other	Miscellaneous Cargo
Miscellaneous - other	Anti-Pollution Vessel
Offshore	Service Operations Vessel
Offshore	PSV/Supply 3-4,000 DWT
Offshore	Oilfield Pollution Control
Offshore	AHTS 4-8,000 BHP
Offshore	PSV/Supply ¡2,000 DWT
Offshore	PSV/Supply 2-3,000 DWT

IMO type	Clarksons type
Offshore	ERRV
Offshore	AHTS 12-16,000 BHP
Offshore	AHT
Offshore	Gravel/Stone Discharge
Offshore	Supply Tender
Offshore	Bucket Ladder Dredger
Offshore	Miscellaneous Offshore Service
Offshore	AHTS ¡4,000 BHP
Offshore	Seismic Support
Offshore	Construction Service Operations Vsl
Offshore	Crew/Supply
Offshore	Offshore Crew Tender
Offshore	Hydrographic Survey
Offshore	Well Stimulation
Offshore	Dredgers (Stone Dumping, Fallpipe)
Offshore	FPSO
Offshore	Seismic Survey
Offshore	Cable, Umbilicals and FP/Flowline Lay
Offshore	Drillship
Offshore	Crew Boat
Offshore	ROV/Submersible Support
Offshore	Cylindrical Floating Prod. Unit
Offshore	Diving Support
Offshore	Multi-Purpose Support
Offshore	PSV/Supply 4,000 DWT+
Offshore	FSO
Offshore	Backhoe/Dipper/Grab Dredger
Offshore	Semi-Submersible Heavy Lift
Offshore	LPG/FSO
Offshore	FSU
Offshore	FPDSO

IMO type	Clarksons type
Offshore	FSRU
Offshore	Extended Well Test Vessel
Offshore	LNG/FSU
Offshore	Accommodation Vessel
Offshore	Derrick/Lay Vessel
Offshore	LPG/FPSO
Offshore	Pipe Layer
Oil tanker	Methanol Bunkering Tanker
Oil tanker	Shuttle Tanker
Oil tanker	Oil Transfer Vessel
Oil tanker	Slop Reception Vessel
Oil tanker	Products/Multi-Purpose Cargo
Oil tanker	Asphalt and Bitumen Carrier
Oil tanker	Product Carrier
Oil tanker	Tanker
Other liquids tanker	Fruit Juice Carrier
Other liquids tanker	Wine Carrier
Other liquids tanker	Water Carrier
Refrigerated bulk	Reefer Fish Carrier
Refrigerated bulk	Reefer
Refrigerated bulk	Reefer/General Cargo
Refrigerated bulk	Reefer/Pallets Carrier
Ro-Ro	Product Carrier/Ro-Ro
Ro-Ro	Ro-Ro/Lo-Lo
Ro-Ro	Ro-Ro
Ro-Ro	Ro-Ro/Container
Ro-Ro	Landing Craft
Service - other	Heavy Lift/Crane Ship
Service - other	Special Equipment Dredger
Service - other	Standby Safety/Guard
Service - other	Multi-Purpose

IMO type	Clarksons type
Service - other	Work/Repair Vessel
Service - other	Pilot Vessel
Service - other	Pile Driving Vessel
Service - other	Barge Unloading Dredger
Service - other	Crew Tender
Service - other	Suction Hopper Dredger
Service - other	Other Dredger
Service - other	Utility/Workboat
Service - other	Waste Disposal Carrier
Service - other	Salvage Vessel
Service - other	Buoy/Lighthouse Tender
Service - other	Crew/Fast Supply
Service - other	Oil Bunkering Tanker
Service - other	Oceanographic Survey
Service - other	Floating Production Unit
Service - other	Geophysical Survey
Service - other	Cable Layer (Fibre Optic)
Service - other	Research Vessel
Service - other	AHTS ¿16,000 BHP
Service - other	AHTS 8-12,000 BHP
Service - other	Oil Recovery Tanker
Service - other	Floating Crane
Service - other	Trailing Suction Hopper Dredger
Service - other	Maintenance
Service - other	Dredger (Unspecified)
Service - other	Training Ship
Service - other	Marine Research
Service - other	Cutter Suction/Bucket Wheel Dredger
Service - other	Log Tipping Ship
Service - other	Mining Vessel
Service - other	Icebreaker

IMO type	Clarksons type
Service - other	Transshipment Vessel
Service - other	Hospital Vessel
Service - other	Suction Dredger
Service - tug	Ocean-going Salvage Tug
Service - tug	Fire-fighting Tug
Service - tug	Tug, Anchor Hoy
Service - tug	Tug
Service - tug	Ocean-going Tug
Vehicle	Pure Car Carrier
Yacht	Sailing Vessel
Yacht	Exhibition Vessel
Yacht	Theatre Vessel

Appendix B

Ships' valuation method (Chapters 4 7

B.1 Average age at scrapping

Table B.1: Average age at scrapping, by ship type and size

	Size bin	Av. scrapping age	Min.	Max.	Unit
Ship type					
Bulk carrier	1	39	0	9,999	dwt
Bulk carrier	2	33	10,000	34,999	dwt
Bulk carrier	3	29	35,000	59,999	dwt
Bulk carrier	4	28	60,000	99,999	dwt
Bulk carrier	5	22	100,000	199,999	dwt
Bulk carrier	6	27	200,000	1,000,000	dwt
Chemical tanker	1	31	0	4,999	dwt
Chemical tanker	2	29	5,000	9,999	dwt
Chemical tanker	3	25	10,000	19,999	dwt
Chemical tanker	4	25	20,000	39,999	dwt
Chemical tanker	5	23	40,000	1,000,000	dwt
Container	1	27	0	999	teu
Container	2	26	1,000	1,999	teu
Container	3	29	2,000	2,999	teu

	Size bin	Av. scrapping age	Min.	Max.	Unit
Container	4	25	3,000	4,999	teu
Container	5	20	5,000	7,999	teu
Container	6	22	8,000	11,999	teu
Container	7	25	12,000	14,499	teu
Container	8	25	14,500	19,999	teu
Container	9	25	20,000	1,000,000	teu
Cruise	1	17	0	1,999	gt
Cruise	2	57	2,000	9,999	gt
Cruise	3	39	10,000	59,999	gt
Cruise	4	29	60,000	99,999	gt
Cruise	5	35	100,000	149,999	gt
Cruise	6	35	150,000	1,000,000	gt
Ferry-RoPax	1	42	0	1,999	gt
Ferry-RoPax	2	37	2,000	4,999	gt
Ferry-RoPax	3	44	5,000	9,999	gt
Ferry-RoPax	4	36	10,000	19,999	gt
Ferry-RoPax	5	32	20,000	1,000,000	gt
Ferry-pax only	1	37	0	299	gt
Ferry-pax only	2	40	300	999	gt
Ferry-pax only	3	48	1,000	1,999	gt
Ferry-pax only	4	46	2,000	1,000,000	gt
General Cargo	1	40	0	4,999	dwt
General Cargo	2	33	5,000	9,999	dwt
General Cargo	3	30	10,000	19,999	dwt
General Cargo	4	27	20,000	1,000,000	dwt
Liquefied gas tanker	1	33	0	49,999	cbm
Liquefied gas tanker	2	34	50,000	99,999	cbm
Liquefied gas tanker	3	38	100,000	199,999	cbm
Liquefied gas tanker	4	35	200,000	1,000,000	cbm
Miscellaneous - other	1	33	0	1,000,000	gt
Offshore	1	32	0	1,000,000	gt

	Size bin	Av. scrapping age	Min.	Max.	Unit
Oil tanker	1	36	0	4,999	dwt
Oil tanker	2	31	5,000	9,999	dwt
Oil tanker	3	35	10,000	19,999	dwt
Oil tanker	4	25	20,000	59,999	dwt
Oil tanker	5	22	60,000	79,999	dwt
Oil tanker	6	22	80,000	119,999	dwt
Oil tanker	7	23	120,000	199,999	dwt
Oil tanker	8	23	200,000	1,000,000	dwt
Other liquids tanker	1	52	0	999	dwt
Other liquids tanker	2	52	1,000	1,000,000	dwt
Refrigerated bulk	1	34	0	1,999	dwt
Refrigerated bulk	2	38	2,000	5,999	dwt
Refrigerated bulk	3	35	6,000	9,999	dwt
Refrigerated bulk	4	34	10,000	1,000,000	dwt
Ro-Ro	1	38	0	4,999	dwt
Ro-Ro	2	31	5,000	9,999	dwt
Ro-Ro	3	26	10,000	14,999	dwt
Ro-Ro	4	35	15,000	1,000,000	dwt
Service - other	1	36	0	1,000,000	gt
Service - tug	1	47	0	1,000,000	gt
Vehicle	1	29	0	29,999	gt
Vehicle	2	24	30,000	49,999	gt
Vehicle	3	22	50,000	1,000,000	gt
Yacht	1	56	0	1,000,000	dwt

B.2 Regression analysis of ships' newbuild price

This appendix details the results of the regression analysis of ships' newbuild price, whose estimated parameters are used to estimate ships' value in Chapters 4 and 7.

The[1] regression model is summarised on Equation B.1, with P^{new} the newbuild price of a ship of main engine MCR mcr, deadweight dwt, which uses fuel type f, whose shipping segment is s and which was built in year t. a are the regression coefficients, and $\mathbb{1}_x$ the dummy that takes the value 1 is the categorical variable equal to x, 0 otherwise. ε is the residual error.

$$\begin{aligned} P^{new}_{mcr,dwt,f,s,t} = \sum_{s \in shiptypes} & a^1_s \times dwt \times \mathbb{1}_s \\ & + \sum_{f \in fuels} a^2_f \times mcr \times \mathbb{1}_f \\ & + \sum_{s \in shiptypes} a^3_{s,t} \times \mathbb{1}_s \mathbb{1}_t \\ & + \varepsilon \end{aligned} \tag{B.1}$$

The regression variables are summarised in Table B.2. The dataset includes 4,457 newbuild prices, corresponding to the recorded newbuild prices in WFR since 2009. Although it covers a wide range of ship segments, bulk carriers cover most of the data points and some shipping segments include a few data points, casting doubt on the reliability of the results for those segments. The average size of the ship is around 100,000 deadweight (the average for the entire fleet is around 70,000) and a 25 MW engine, and it was built for an average of \$88 million. Not surprisingly, the vast majority of ships built are HFO-fuelled, although 10% are LNG-fuelled, and a few transactions now include methanol-fuelled. The model is fitted using an ordinary least squares regression analysis and the results are shown inTable B.3. Model (1) includes all shipping segments but no time fixed effects. The R2 of the model is 94%, which shows that it predicts most of the variation in the prices of new ships. The engine size (MCR) has a statistically and economically significant impact on the price of the ship, and LNG and methanol are more expensive than

[1]This section is based on the Section ”Fleet valuation” of the study ”Fossil fuel carriers and the risk of stranded assets”. I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

Table B.2: Summary statistics of the dataset used for the regression of ship newbuild value

	count	mean	sd
Price	4457	88138732	1.1e+08
Deadweight	4457	101094	79929.8
Main engine MCR	4457	25185	19221.5
Built year	4457	2015	4.7
Observations	4457		

	frequency	Percentage
Bulk carrier	1573	35
Chemical tanker	347	8
Container	1126	25
Cruise	55	1
Ferry-RoPax	30	1
General Cargo	3	0
Liquefied gas tanker	484	11
Miscellaneous - other	86	2
Offshore	19	0
Oil tanker	589	13
Other liquids tanker	3	0
Ro-Ro	68	2
Service - other	2	0
Vehicle	72	2
Total	4457	100

	frequency	Percentage
HFO	3996	90
LNG	433	10
Methanol	28	1
Total	4457	100

HFO, which is in line with expectations. Positive coefficients on ship segment × deadweight terms show that increased size leads to a higher newbuild price for all shipping segments, apart from the notable exception of containers, which has a counter-intuitive sign. The magnitude of the coefficient suggests that some types of ships are more expensive by deadweight than others. Not surprisingly, cruises, ferries, and offshore are the most expensive, while tankers and bulk carriers are the cheapest. Overall, apart from containers, the results broadly fit what could be expected.

To study the sensitivity of the fuel price to short-term variations, the model is re-estimated by adding interaction dummies for each shipping segment and each year (model (2)). Adding time × shipping segment dummies slightly increases the R2 of the model to 96% (model (2)), suggesting that short-term market variations have a statistically significant impact on the newbuild prices of the ships, but this effect is relatively weak compared to the effects of the ship's design parameters. However, omitting those might bias the results if they cover omitted variables variation (omitted variable bias). To test for this hypothesis, a Wald test is conducted to test for the joint significance of the time × shipping segment dummies. The Wald test rejects the null hypothesis that the coefficients of these dummy variables are jointly equal to zero. Therefore, those dummies should be kept in the model.

Most of the coefficients maintain their degree of significance and sign after including them, but several interaction terms between sectors and deadweight are affected. In particular, the coefficient for containers becomes statistically and economically positive. This suggests that those sectors have been impacted by omitted variables that could bias the results over the period. For some sectors, the coefficient becomes negative, which is counter-intuitive (other liquids tankers, Ro-Ro, vehicles, and chemical tankers). For the many shipping segments which have few observations, the small amount of variation in the deadweight of those segments casts doubt on the robustness of the results and raises issues of collinearity. To further test the robustness of the results, the model is therefore further estimated by using an alternative sample. The value of ships might be further affected by ship specifications which are not covered in the dataset, for example, additional onboard equipment or chemical tank coating. Omitting those variations could significantly bias the results. Shipping segments which are least standardised, such as cruise, ferries of offshore are most likely to suffer from this omitted variable bias, while this might be less likely for standardised shipping segments. Restricting the regression to those shipping segments also has the advantage that because they are more widely covered in the dataset, collinearity issues mentioned above are less likely to arise. Model (3) therefore runs the model, but by only including bulk carriers, containers, oil tankers, and liquefied gas tankers. The results are similar to those of model (2), which gives confidence in the robustness of the results. It is, however, noteworthy that the coefficient for containers × deadweight increases, although it remains significantly positive.

Second, the value of ships ordered but not yet built could reflect the particular period during which they were ordered, that is, the Covid pandemics and the large profits on most ship segments, but particularly for containers. To control for those effects, only ships that were built at the time when the data were collected, i.e. before 2023, were included. The results in model (4) again do not differ significantly from those of models (2) and (3), although the coefficient of containers increases again. This is counter-intuitive, as one could have expected that containerships in particular would have become more expensive in the later period, all things being held equal. The robustness analysis gives confidence that the model adequately predicts ship's newbuild value for bulk carriers, liquefied gas tankers and oil tankers. However, the coefficient in the deadweight of the containers is more uncertain and could range between $113 to $480/ deadweight.

B.3 Top-down validation of the valuation method

The[2] valuation method used in Chapter 4 was validated against the total fleet value estimated by Clarksons in 2019, 2021 and 2023 (Clarksons Research, 2019, 2021, 2023). The methods behind the Clarksons estimates are not fully public, so it is not possible to trace the root of the differences between the two estimates. Only the sectors whose valuations are available by Clarksons SIN are plotted in Figure B.1. Overall, the two estimates validate well with one another. However, while this article estimates are fairly stable in time and only slightly increase due to the growth in the fleet, Clarksons estimates show large variations from one year to another (e.g. containers in 2021, oil tankers in 2023). As a result, there are significant differences for some years and some segments, for example bulk carriers in 2019, containers

[2]This section is based on the additional materials of the study "Fossil fuel carriers and the risk of stranded assets". I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

Table B.3: Results of the regression of newbuild prices

	(1) All	(2) All	(3) Sample	(4) Sample 2009-2022
HFO × Main engine MCR	1956.9*** (0.000)	1721.5*** (0.000)	1172.2*** (0.000)	759.7*** (0.000)
LNG × Main engine MCR	2712.1*** (0.000)	2258.2*** (0.000)	1830.9*** (0.000)	2556.8*** (0.000)
Methanol × Main engine MCR	3041.4*** (0.000)	2337.4*** (0.000)	1786.7*** (0.000)	
Bulk carrier × Deadweight	100.7*** (0.000)	136.8*** (0.000)	173.3*** (0.000)	201.3*** (0.000)
Chemical tanker × Deadweight	264.8*** (0.000)	-124.1 (0.525)		
Container × Deadweight	-31.31 (0.185)	113.3*** (0.000)	292.1*** (0.000)	479.8*** (0.000)
Cruise × Deadweight	54359.9*** (0.000)	46990.0*** (0.000)		
Ferry-RoPax × Deadweight	12346.2*** (0.000)	12889.1*** (0.000)		
General Cargo × Deadweight	699.5** (0.019)	934.2** (0.039)		
Liquefied gas tanker × Deadweight	1143.5*** (0.000)	1601.3*** (0.000)	1768.1*** (0.000)	1425.2*** (0.000)
Miscellaneous - other × Deadweight	177.3* (0.065)	200.3 (0.656)		
Offshore × Deadweight	6924.8*** (0.000)	5860.4*** (0.000)		
Oil tanker × Deadweight	143.0*** (0.000)	102.0*** (0.000)	144.8*** (0.000)	180.7*** (0.000)
Other liquids tanker × Deadweight	106.8 (0.839)	-901.0 (0.585)		
Ro-Ro × Deadweight	677.5*** (0.000)	-56.63 (0.832)		
Service - other × Deadweight	1861.2** (0.024)	2146.3 (0.230)		
Vehicle × Deadweight	1692.0*** (0.000)	-2586.0*** (0.000)		
Ship type x Year FE	No	Yes	Yes	Yes
R-squared	0.937	0.959	0.930	0.923
Observations	4457	4457	3772	3292

p-values in parentheses
* $p<0.10$, ** $p<0.05$, *** $p<0.01$

in 2021 and oil tankers in 2023. Those differences can likely be explained by the difference in methodology: while the current approaches model long-term intrinsic fleet value, Clarksons models short-term market value and likely follows the ship second-hand market value, which this method fully ignores. Factors such as the large increase in ship price due to the Covid pandemics that were recently observed on the fleet (Osler, 2021) are not taken into account in this valuation method.

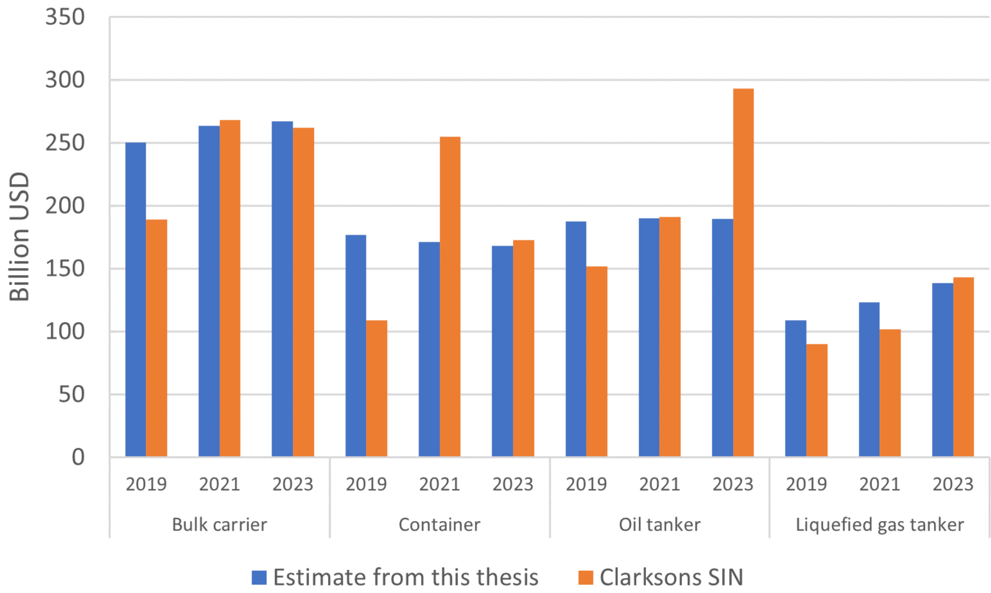


Figure B.1: Validation of the fleet valuation method

B.4 Bottom-up validation of the valuation method used in GloTraM

This section validates the estimates of the newbuild value in Chapter 4 (called ”interpolation from regression coefficients” here) and in Chapter 7 (called ”updated GloTraM”) on the case study of a bulk carrier of 53,000 deadweight, with a main engine of capacity of 7.5MW. This ship was chosen because it is also estimated in Lagemann et al. (2023), and because it is a relatively common model. The estimated value of the newbuild is compared to the value observed in the WFR database for those ship specification; to the predicted value from the regression analysis; and to the estimated value of Lagemann et al. (2023) in Figure B.2. The results show that the initial GloTraM investment is much lower than the ship value. This is not surprising given that it only includes components which vary depending on the engine and fuel type. The estimates interpolated from the regression coefficients and from GloTraM validate fairly well with the observed LSHFO value and the estimates from Lagemann et al. (2023), although they are slightly lower. This suggests that the estimates of fleet value and therefore value at risk are slightly conservative.

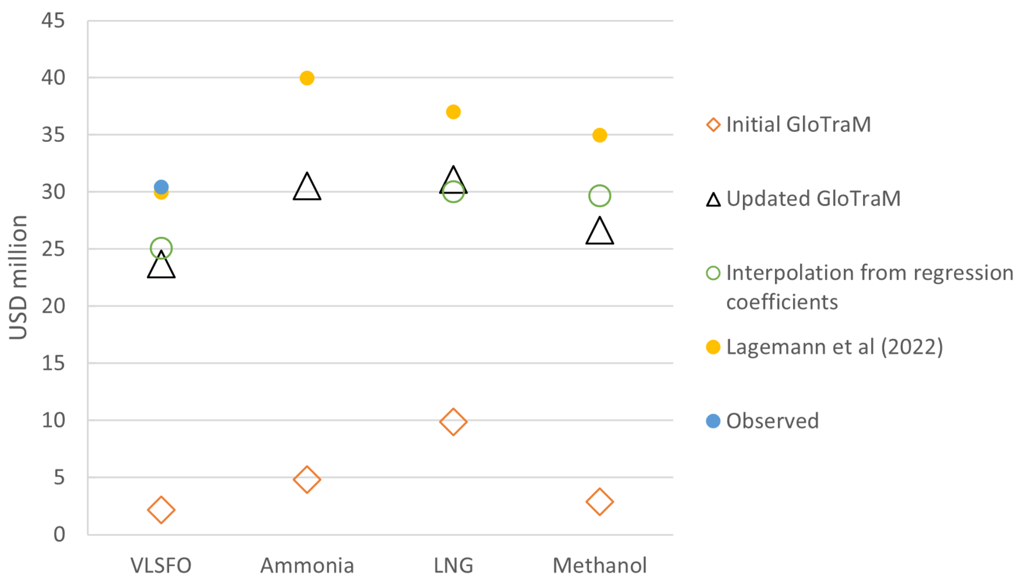


Figure B.2: Validation of the newbuild valuation method on the case of a 53,000 deadweight, 7.5MW MCR bulk carrier

(a) Observed corresponds to the average price of 53,000 deadweight bulk carriers observed. They were built on average in 2011, at a time when the bulk carriers ship prices were still strong, and have on average an MCR of 9,960, which is higher than the case study. This might explain why they are above the case study estimates. There is no observed LNG, ammonia or methanol-fuelled ship of roughly those specifications

B.5 Validation of linear depreciation and scrapping age

This[3] appendix discusses two assumptions made to estimate the value of each ship in Chapters 4 and 7, namely that ships depreciate linearly, and that they depreciate

[3]This section is based on the additional materials of the study ”Fossil fuel carriers and the risk of stranded assets”. I am the main author of the paper and have drafted the first version of this section, which have been reviewed by the other co-authors. Sections of text have been copy-pasted, although it had been modified to better fit the format of the thesis.

to their age of scrapping.

Regarding the first assumption, as a sense check, let us look at the sale value of second-hand ships from Clarksons (Figure B.3). From Figure B.3, it appears that the linear depreciation and exponential depreciation curves are very similar for bulk carriers, oil tankers, and containers and that the latter barely improve the fitness of the data (R^2 does not increase much from the linear to the exponential trend line). This does not change when including only one year of the sample. Only for the liquefied gas tanker does the exponential curve do a significantly better job than the linear curve, but the sample is quite small and they are not included in the segments modelled in Chapter 7. These plots give some confidence that using a linear depreciation as opposed to a convex depreciation is not obviously and largely overestimating the long-term value of the fleet.

Turning now to the second assumption, i.e. that ships' end of economic lifetime corresponds to their scrapping age, let us look at the point at which the linear curve intersects the scraping value (yellow curve) in Figure B.3. This point is around 22 years old for oil tankers, compared to 23 years of scrap age on average for oil tankers (average weighted by the share of deadweight per size bin); 30 years old for bulk carriers, compared to 27 years average scrap age ; 31 years for containers, compared to 23 years of scrap age. This comparison suggests that there is no strong argument to not use scrapping age as the depreciation profile. Those findings are indicative and should be taken with caution for two main reasons. First, as previously discussed, second-hand value is driven by many factors including, but not only, age, and those are beyond the scope of this article. Second, sales data are only available for the period 2020-2023 which is characterised by high shipping prices and likely lower depreciation than usual.

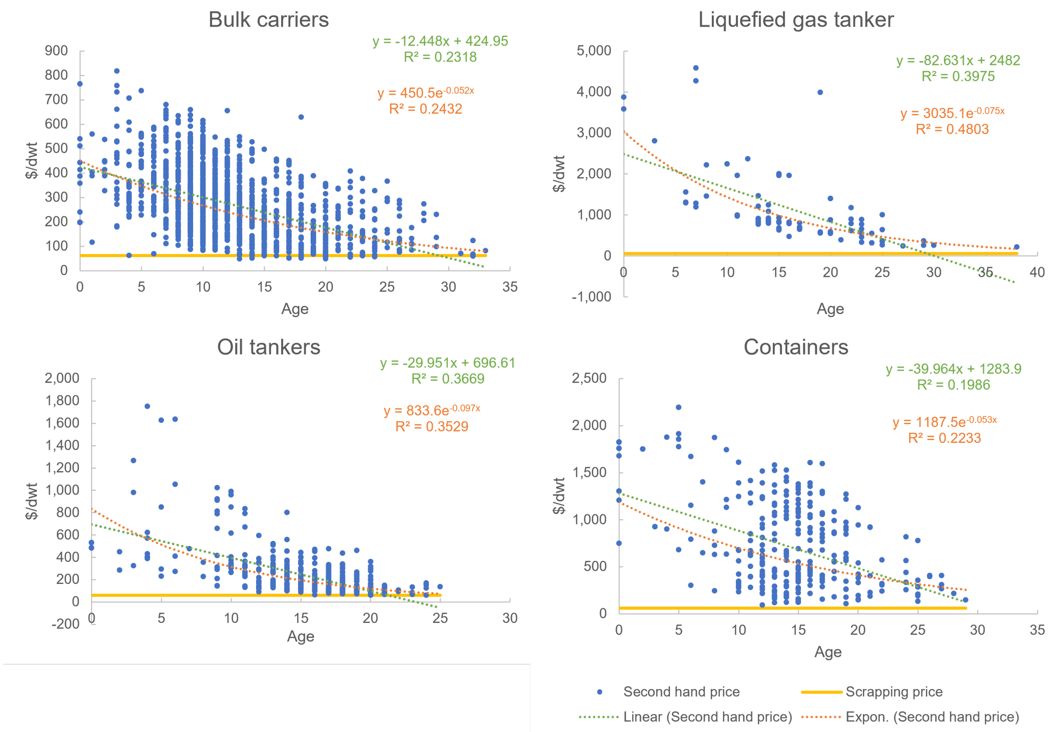


Figure B.3: Depreciation and second-hand ship prices. Data from Clarksons Research (2023)

(a) The y-axis corresponds to the sale price of the ship divided by its deadweight. The x-axis corresponds to the age of the vessel when it was sold. Linear and exponential trend lines are plotted.

Appendix C

Utilisation and price of shipping (Chapters 4 7

Table C.1: Utilisation and price of shipping for bulk carriers, containers, oil tankers and liquefied gas tankers

	Utilisation	Price of shipping ($/tonne-mile)
Ship type		
Container	0.3128	0.0184
Bulk carrier	0.4957	0.0026
Oil tanker	0.3656	0.0044
Liquefied gas tanker	0.2762	0.0119

Appendix D

Regression of shipping loans margins (Chapter 6)

D.1 Regression detailed results

Table D.1: Results of the regression analysis of loans margins, environmental performance and the Paris Agreement. Central model.

	(1) sample2	(2) sample2	(3) sample2	(4) sample2	(5) sample3	(6) sample3	(7) sample3	(8) sample3	(9) sample1	(10) sample1	(11) sample1	(12) sample1	(13) sample1	(14) sample1
CDP score	-3.305	0.429			-3.189	1.086								
	(0.569)	(0.933)			(0.584)	(0.833)								
Post 2015 dummy=1 × CDP score		-35.33**				-48.87***								
		(0.028)				(0.009)								
Refinitiv environmental score			-0.234	-0.209			-0.0909	-0.0156						
			(0.475)	(0.557)			(0.811)	(0.971)						
Post 2015 dummy=1 × Refinitiv environmental score				-0.171				-0.561						
				(0.709)				(0.296)						
Relative EIV									-3.159	-55.42				
									(0.930)	(0.231)				
Post 2015 dummy=1 × Relative EIV										142.5				
										(0.116)				
AER											-21.59	-58.49		
											(0.274)	(0.202)		
Post 2015 dummy=1 × AER												47.71		
												(0.343)		
Energy saving technologies													-5.759	14.89

	(1) sample2	(2) sample2	(3) sample2	(4) sample2	(5) sample3	(6) sample3	(7) sample3	(8) sample3	(9) sample1	(10) sample1	(11) sample1	(12) sample1	(13) sample1	(14) sample1
													(0.825)	(0.698)
Post 2015 dummy=1 × Energy saving technologies														-50.87
														(0.338)
Loan amount	6.810	4.549	-7.574	-7.568	8.453	5.172	-5.420	-5.064						
	(0.517)	(0.603)	(0.182)	(0.183)	(0.437)	(0.534)	(0.377)	(0.409)						
Tranche amount	-5.369	-5.583	-2.803	-2.759	-3.943	-3.789	-2.140	-1.958	7.467	6.808	7.404	7.096	12.28	12.63
	(0.372)	(0.341)	(0.315)	(0.331)	(0.520)	(0.525)	(0.496)	(0.552)	(0.239)	(0.202)	(0.228)	(0.214)	(0.175)	(0.165)
Number of lenders	3.092	2.315	1.461	1.554	2.084	2.984	0.693	0.989	0.0136	-2.204	2.308	0.477	-2.193	-1.484
	(0.804)	(0.844)	(0.869)	(0.861)	(0.871)	(0.807)	(0.941)	(0.917)	(0.999)	(0.821)	(0.803)	(0.963)	(0.843)	(0.893)
Maturity	28.58***	27.04***	15.66**	15.51**	26.63***	24.38**	14.27**	13.60**	-29.27	-33.99	-33.98	-38.08*	21.72	19.72
	(0.004)	(0.007)	(0.021)	(0.024)	(0.006)	(0.010)	(0.032)	(0.044)	(0.152)	(0.114)	(0.122)	(0.081)	(0.376)	(0.403)
Firm size	-20.36	-17.79	-8.644	-8.395	-22.69	-21.32	-12.60	-12.43	-43.54***	-36.87***	-42.28***	-38.24***	-48.27***	-50.89***
	(0.142)	(0.178)	(0.213)	(0.228)	(0.119)	(0.111)	(0.114)	(0.119)	(0.001)	(0.005)	(0.002)	(0.006)	(0.000)	(0.000)
Leverage	21.02	24.91	38.81***	38.50***	23.86	27.38	37.09***	36.06***	37.34	88.61*	33.73	52.41	8.351	-2.541
	(0.390)	(0.291)	(0.002)	(0.002)	(0.341)	(0.242)	(0.003)	(0.005)	(0.467)	(0.073)	(0.499)	(0.258)	(0.877)	(0.966)
Profitability	74.92	61.78	-270.2**	-266.6**	129.4	119.0	-355.5**	-349.3**	-120.9	-146.9	-115.9	-108.7	-146.4	-139.7
	(0.716)	(0.756)	(0.037)	(0.044)	(0.513)	(0.525)	(0.016)	(0.019)	(0.224)	(0.132)	(0.226)	(0.280)	(0.164)	(0.198)
Collateral=1	117.4**	113.5**	80.37***	81.15***	117.2**	112.1**	79.92***	81.40***	33.71**	37.10***	35.48*	38.79*	2.212	-8.526
	(0.015)	(0.014)	(0.003)	(0.002)	(0.015)	(0.014)	(0.004)	(0.004)	(0.046)	(0.002)	(0.066)	(0.056)	(0.917)	(0.771)
Second-hand price index									40.21***	40.74***	39.67***	42.22***	16.30	14.56
									(0.001)	(0.001)	(0.001)	(0.001)	(0.170)	(0.221)
Ships' size									-17.92	-33.07	-19.34	-21.40*	12.81	16.13
									(0.162)	(0.125)	(0.117)	(0.098)	(0.508)	(0.403)
Short maturity=1									47.08	36.28	49.39	40.91	67.66	67.88

	(1) sample2	(2) sample2	(3) sample2	(4) sample2	(5) sample3	(6) sample3	(7) sample3	(8) sample3	(9) sample1	(10) sample1	(11) sample1	(12) sample1	(13) sample1	(14) sample1
									(0.224)	(0.335)	(0.215)	(0.308)	(0.196)	(0.195)
Project finance=1									13.54	13.96	13.12	11.03	-1.973	-0.100
									(0.274)	(0.223)	(0.301)	(0.413)	(0.918)	(0.995)
SPV=1									85.15**	85.92**	58.35*	73.71**	27.01	27.76
									(0.015)	(0.023)	(0.060)	(0.034)	(0.689)	(0.676)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Repayment type	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Shipping segment	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Borrower FE	No	No	No	No	No	No	No	No	No	No	No	No	No	No
R-squared	0.804	0.812	0.688	0.688	0.818	0.830	0.699	0.701	0.912	0.919	0.915	0.916	0.869	0.871
Observations	4867	4867	9955	9955	4683	4683	9387	9387	463	463	463	463	511	511
BIC	53657.2	53465.0	110493.3	110496.9	51364.7	51057.3	104020.5	103984.1	4309.0	4274.7	4297.0	4286.9	5017.9	5016.9
AIC	53404.0	53205.4	110154.6	110151.0	51119.6	50805.7	103691.7	103648.2	4184.9	4150.6	4172.9	4162.8	4873.9	4868.7

p-values in parentheses
* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table D.2: Results of the regression analysis of loans margins, environmental performance and the Paris Agreement. Sensitivity: with industry fixed effects.

	(1) sample2	(2) sample2	(3) sample2	(4) sample2	(5) sample3	(6) sample3	(7) sample3	(8) sample3	(9) sample1	(10) sample1	(11) sample1	(12) sample1	(13) sample1	(14) sample1
CDP score	-5.294	-3.177			-6.692	-4.935								
	(0.387)	(0.552)			(0.285)	(0.370)								
Post 2015 dummy=1 × CDP score		-23.93				-32.11*								
		(0.152)				(0.094)								

	(1) sample2	(2) sample2	(3) sample2	(4) sample2	(5) sample3	(6) sample3	(7) sample3	(8) sample3	(9) sample1	(10) sample1	(11) sample1	(12) sample1	(13) sample1	(14) sample1
[1em] Refinitiv environmental score			-0.700**	-0.597			-0.669*	-0.582						
			(0.038)	(0.108)			(0.090)	(0.171)						
Post 2015 dummy=1 × Refinitiv environmental score				-0.757*				-1.248**						
				(0.089)				(0.013)						
[1em] Relative EIV									-35.23	-8.467				
									(0.135)	(0.792)				
Post 2015 dummy=1 × Relative EIV										-134.6				
										(0.314)				
[1em] AER											-34.18**	1.924		
											(0.043)	(0.957)		
Post 2015 dummy=1 × AER												-46.03		
												(0.271)		
Energy saving technologies													2.507	21.22
													(0.941)	(0.587)
Post 2015 dummy=1 × Energy saving technologies														-95.63
														(0.115)
Loan amount	19.71*	17.09**	6.359	6.322	21.06**	17.70**	6.373	6.907						

	(1) sample2	(2) sample2	(3) sample2	(4) sample2	(5) sample3	(6) sample3	(7) sample3	(8) sample3	(9) sample1	(10) sample1	(11) sample1	(12) sample1	(13) sample1	(14) sample1
	(0.059)	(0.047)	(0.277)	(0.277)	(0.045)	(0.026)	(0.324)	(0.277)						
Tranche amount	3.263	3.437	-1.666	-1.392	2.727	2.914	-1.692	-1.249	-0.0529	-1.272	-1.084	-1.433	7.385	6.304
	(0.708)	(0.690)	(0.592)	(0.666)	(0.764)	(0.747)	(0.629)	(0.739)	(0.961)	(0.443)	(0.373)	(0.233)	(0.201)	(0.232)
Number of lenders	-15.39	-13.46	-10.29	-9.686	-17.51	-14.48	-10.52	-10.40	3.157	11.21	8.145	10.45	-7.648	-4.638
	(0.148)	(0.227)	(0.215)	(0.242)	(0.123)	(0.230)	(0.237)	(0.239)	(0.562)	(0.283)	(0.162)	(0.132)	(0.368)	(0.586)
Maturity	25.15**	24.42**	15.83***	15.24**	21.15**	20.15*	14.87**	13.99**	-35.41*	-37.09*	-38.71*	-34.58	7.189	4.207
	(0.020)	(0.026)	(0.009)	(0.015)	(0.044)	(0.057)	(0.011)	(0.021)	(0.070)	(0.055)	(0.074)	(0.126)	(0.744)	(0.848)
Firm size	-20.49	-19.95	-16.03**	-16.02**	-17.65	-15.15	-16.37**	-16.18**	5.154	15.41	7.354	5.219	-18.82	-14.68
	(0.131)	(0.123)	(0.026)	(0.026)	(0.206)	(0.250)	(0.035)	(0.032)	(0.610)	(0.144)	(0.405)	(0.599)	(0.231)	(0.308)
Leverage	2.575	3.833	29.70**	28.11**	11.54	16.04	29.55**	27.25*	102.9***	97.59***	115.4***	96.68**	-3.537	17.00
	(0.911)	(0.866)	(0.037)	(0.048)	(0.633)	(0.509)	(0.049)	(0.070)	(0.006)	(0.009)	(0.003)	(0.017)	(0.954)	(0.784)
Profitability	-281.1*	-279.8**	-227.6**	-215.3*	-185.7	-161.8	-273.4**	-254.8**	138.6	191.3**	116.2	130.5*	89.97	82.75
	(0.052)	(0.042)	(0.039)	(0.055)	(0.268)	(0.287)	(0.029)	(0.043)	(0.111)	(0.026)	(0.147)	(0.055)	(0.534)	(0.568)
Collateral=1	123.2***	120.0***	85.38***	88.93***	127.0***	123.5***	87.89***	92.14***	55.48***	58.26***	59.53***	53.00***	48.11	34.29
	(0.006)	(0.006)	(0.001)	(0.001)	(0.006)	(0.006)	(0.002)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.110)	(0.354)
Second-hand price index									45.82***	41.65***	43.17***	40.57***	31.80***	26.78**
									(0.000)	(0.000)	(0.000)	(0.000)	(0.006)	(0.042)
Ships' size									9.288	6.100	-6.035	-5.524	55.36***	51.96***
									(0.622)	(0.746)	(0.770)	(0.800)	(0.001)	(0.004)
Short maturity=1									29.10	34.94	35.04	41.85	64.29	63.05
									(0.380)	(0.335)	(0.328)	(0.304)	(0.172)	(0.187)
Project finance=1									19.45***	23.48***	25.29***	29.80***	4.940	11.54
									(0.010)	(0.000)	(0.000)	(0.000)	(0.732)	(0.311)
SPV=1									35.18	-5.932	-14.89	-13.44	28.79	15.46
									(0.230)	(0.891)	(0.677)	(0.707)	(0.689)	(0.818)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

	(1) sample2	(2) sample2	(3) sample2	(4) sample2	(5) sample3	(6) sample3	(7) sample3	(8) sample3	(9) sample1	(10) sample1	(11) sample1	(12) sample1	(13) sample1	(14) sample1
Repayment type	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Shipping segment	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower FE	No	No	No	No	No	No	No	No	No	No	No	No	No	No
R-squared	0.863	0.866	0.733	0.736	0.872	0.876	0.744	0.750	0.956	0.958	0.959	0.960	0.912	0.915
Observations	4867	4867	9955	9955	4683	4683	9387	9387	461	461	461	461	509	509
BIC	51923.9	51827.0	109004.6	108906.8	49738.1	49583.0	102588.6	102370.9	3932.8	3911.7	3902.2	3888.0	4771.6	4754.3
AIC	51651.3	51548.0	108601.0	108496.1	49480.0	49318.5	102202.6	101977.8	3833.6	3812.5	3803.0	3788.8	4640.4	4623.1

p-values in parentheses
* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table D.3: Results of the regression analysis of loans margins, environmental performance and the Paris Agreement. Sensitivity: borrower fixed effect.

	(1) sample2	(2) sample2	(3) sample2	(4) sample2	(5) sample3	(6) sample3	(7) sample3	(8) sample3
CDP score	-0.135	3.648			4.805	7.096		
	(0.983)	(0.517)			(0.420)	(0.203)		
Post 2015 dummy=1 × CDP score		-34.67**				-31.98**		
		(0.026)				(0.038)		
Refinitiv environmental score			-0.00132	0.368			0.144	0.552
			(0.997)	(0.444)			(0.752)	(0.316)
Post 2015 dummy=1 × Refinitiv environmental score				-1.662***				-1.675***
				(0.000)				(0.000)
Loan amount	15.20**	14.67*	7.033	7.094	12.92	14.77	4.465	5.001

	(1) sample2	(2) sample2	(3) sample2	(4) sample2	(5) sample3	(6) sample3	(7) sample3	(8) sample3
	(0.050)	(0.064)	(0.180)	(0.210)	(0.141)	(0.121)	(0.458)	(0.443)
Tranche amount	-6.478	-5.980	-0.497	-0.626	-9.438*	-9.072*	-1.097	-0.905
	(0.249)	(0.297)	(0.897)	(0.880)	(0.080)	(0.098)	(0.791)	(0.841)
Number of lenders	4.941	9.094	-5.489	-5.506	11.72	14.27	-0.933	-1.913
	(0.599)	(0.360)	(0.508)	(0.516)	(0.255)	(0.180)	(0.921)	(0.845)
Maturity	24.69***	23.54***	16.78***	15.18**	25.29***	23.92***	18.92***	17.24***
	(0.005)	(0.007)	(0.008)	(0.021)	(0.005)	(0.007)	(0.002)	(0.008)
Firm size	-74.12	-74.39	-86.17**	-95.88***	-53.43	-59.48	-96.90***	-106.4***
	(0.269)	(0.214)	(0.011)	(0.003)	(0.435)	(0.349)	(0.004)	(0.001)
Leverage	116.8**	96.16**	54.97***	47.87**	103.2*	84.26	62.70***	56.81***
	(0.031)	(0.034)	(0.006)	(0.013)	(0.093)	(0.110)	(0.001)	(0.002)
Profitability	139.8	127.1	-73.63	-41.67	-46.15	-18.07	-123.3	-66.80
	(0.174)	(0.146)	(0.404)	(0.601)	(0.737)	(0.886)	(0.218)	(0.452)
Collateral=1	66.05*	62.23*	53.20**	61.32***	56.46*	56.55*	46.90**	55.59**
	(0.054)	(0.053)	(0.014)	(0.006)	(0.067)	(0.067)	(0.029)	(0.014)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Repayment type	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Shipping segment	No	No	No	No	No	No	No	No
Industry FE	No	No	No	No	No	No	No	No
Borrower FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.926	0.929	0.843	0.850	0.931	0.934	0.854	0.861
Observations	4867	4867	9955	9955	4683	4683	9387	9387
BIC	48861.0	48648.9	103516.3	103062.7	46733.3	46561.4	97133.8	96680.3
AIC	48672.8	48454.2	103264.1	102803.3	46552.7	46374.3	96890.8	96430.2

p-values in parentheses
* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table D.4: Results of the regression analysis of loans margins and environmental performance, period breakdown. Central model.

	(1) sample2 2010-2015	(2) sample2 2015-2021	(3) sample2 2010-2015	(4) sample2 2015-2021	(5) sample3 2010-2015	(6) sample3 2015-2021	(7) sample3 2010-2015	(8) sample3 2015-2021	(9) sample1 2010-2015	(10) sample1 2015-2021	(11) sample1 2010-2015	(12) sample1 2015-2021	(13) sample1 2010-2015	(14) sample1 2015-2021
CDP score	1.251	-46.36***			-1.312	-38.10**								
	(0.837)	(0.005)			(0.840)	(0.034)								
Refinitiv environmental score			-0.752**	0.556			-0.648	0.135						
			(0.033)	(0.200)			(0.102)	(0.809)						
Relative EIV									-146.7***	-3842.3***				
									(0.001)	(0.000)				
AER											-138.3***	-123.0***		
											(0.000)	(0.000)		
Energy saving technologies													-42.78	-1[illegible]4.4***
													(0.314)	(0.001)
Loan amount	-6.900	54.80***	-8.228	15.76	-9.049	80.26***	-7.918	12.79						
	(0.388)	(0.005)	(0.246)	(0.173)	(0.302)	(0.000)	(0.294)	(0.351)						
Tranche amount	-7.077	-11.91	-2.343	-5.439	-4.907	-34.96**	-1.987	0.323	6.136	0.0000297	2.618	7.77e-08	5.875	[illegible].476
	(0.205)	(0.516)	(0.576)	(0.498)	(0.448)	(0.020)	(0.671)	(0.964)	(0.152)	(0.309)	(0.358)	(0.316)	(0.440)	(0.484)
Number of lenders	0.299	53.13	-5.517	39.11**	0.868	45.30	-5.788	44.71**	1.349	-520.1***	0.469	-520.1***	-0.280	-437.4***
	(0.976)	(0.114)	(0.585)	(0.030)	(0.931)	(0.213)	(0.571)	(0.043)	(0.827)	(0.000)	(0.921)	(0.000)	(0.971)	(0.000)
Maturity	22.63**	16.76	12.35	6.132	20.26**	29.38	10.24	2.402	-20.75	-0.000349	-22.38	-0.0000136	25.64	-37.50***
	(0.019)	(0.452)	(0.115)	(0.506)	(0.030)	(0.244)	(0.192)	(0.829)	(0.107)	(0.432)	(0.139)	(0.432)	(0.338)	(0.000)
Firm size	-12.57	-36.94***	0.584	-54.17***	-9.339	-35.43***	-1.554	-55.35***	-33.56***	-58017.6***	-25.72**	2671.8***	-44.98***	-1382.7***
	(0.485)	(0.003)	(0.941)	(0.000)	(0.660)	(0.005)	(0.859)	(0.000)	(0.001)	(0.000)	(0.018)	(0.000)	(0.001)	(0.000)
Leverage	29.06	-11.80	39.64***	35.18	36.35	-14.53	39.06***	20.79	138.6***	149917.9***	164.3***	-7172.1***	61.38	3297.6***
	(0.273)	(0.727)	(0.007)	(0.224)	(0.227)	(0.691)	(0.009)	(0.530)	(0.001)	(0.000)	(0.001)	(0.000)	(0.287)	(0.000)
Profitability	291.3	-442.8***	-23.02	-620.9***	370.2	-433.6**	-41.12	-567.8***	-232.9***	4249008.2***	-219.5***	-202676.2***	-224.3**	707[illegible]0.9***

	(1) sample2 2010-2015	(2) sample2 2015-2021	(3) sample2 2010-2015	(4) sample2 2015-2021	(5) sample3 2010-2015	(6) sample3 2015-2021	(7) sample3 2010-2015	(8) sample3 2015-2021	(9) sample1 2010-2015	(10) sample1 2015-2021	(11) sample1 2010-2015	(12) sample1 2015-2021	(13) sample1 2010-2015	(14) sample1 2015-2021
	(0.192)	(0.009)	(0.832)	(0.003)	(0.102)	(0.014)	(0.765)	(0.008)	(0.007)	(0.000)	(0.010)	(0.000)	(0.010)	(0.000)
Collateral=1	12.39	213.2***	22.46	141.6***	7.182	205.4***	21.35	169.1***	3.040	-180757.8***	25.10	8949.9***	14.35	-3866.7***
	(0.478)	(0.000)	(0.178)	(0.001)	(0.645)	(0.000)	(0.205)	(0.001)	(0.841)	(0.000)	(0.132)	(0.000)	(0.535)	(0.000)
Second-hand price index									13.97	-249.5***	19.34	-102.7***	4.650	-90.96***
									(0.326)	(0.000)	(0.107)	(0.000)	(0.721)	(0.000)
Ships' size									-55.64***	-329.8***	-65.96***	-19.12***	-29.96	31.25***
									(0.001)	(0.000)	(0.001)	(0.000)	(0.105)	(0.004)
Short maturity=1									-29.99	-0.0000271	-40.22	-0.00000189	30.79	-5[illegible]80***
									(0.452)	(0.432)	(0.352)	(0.432)	(0.433)	(0.000)
Project finance=1									28.36***		33.75***		30.93***	
									(0.006)		(0.003)		(0.001)	
SPV=1									-38.79		-51.18		-47.00	
									(0.403)		(0.267)		(0.332)	
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes						
Repayment type	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Shipping segment	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Borrower FE	No	No	No	No	No	No	No	No	No	No	No	No	No	No
R-squared	0.872	0.928	0.754	0.814	0.883	0.933	0.766	0.828	0.964	1.000	0.964	1	0.934	0.994
Observations	4097	770	7606	2349	3945	738	7255	2132	384	79	384	79	408	103
BIC	42547.6	8356.6	81333.8	25986.0	40638.9	7987.3	77303.5	23523.4	3259.3	-1506.6	3248.7	.	3751.2	636.8
AIC	42345.4	8245.1	81070.2	25784.4	40444.2	7881.4	77048.5	23330.8	3168.4	-1516.1	3157.8	.	3638.9	628.9

p-values in parentheses
* p<0.10, ** p<0.05, *** p<0.01

Table D.5: Results of the regression analysis of loans margins and environmental performance, period breakdown. Sensitivity: industry fixed effect.

	(1) sample2 2010-2015	(2) sample2 2015-2021	(3) sample2 2010-2015	(4) sample2 2015-2021	(5) sample3 2010-2015	(6) sample3 2015-2021	(7) sample3 2010-2015	(8) sample3 2015-2021	(9) sample1 2010-2015	(10) sample1 2015-2021	(11) sample1 2010-2015	(12) sample1 2015-2021	(13) sample1 2010-2015	(14) sample1 2015-2021
CDP score	5.225	-13.21			3.676	-3.198								
	(0.232)	(0.617)			(0.427)	(0.910)								
Refinitiv environmental score			-1.057***	-0.336			-1.009***	-0.987						
			(0.003)	(0.520)			(0.007)	(0.200)						
Relative EIV									202.3**	-3842.3***				
									(0.011)	(0.000)				
AER											252.4***	-123.0***		
											(0.000)	(0.000)		
Energy saving technologies													-21.70	-154.4***
													(0.677)	(0.001)
Loan amount	-6.450	136.7***	6.576	17.49	-5.746	172.0***	5.757	14.99						
	(0.364)	(0.000)	(0.327)	(0.184)	(0.425)	(0.000)	(0.431)	(0.370)						
Tranche amount	-0.470	-28.86**	-0.827	-8.608	-1.693	-45.25***	-0.928	-6.091	-1.713	0.0000251	2.172*	6.65e-08	4.933	1.476
	(0.949)	(0.047)	(0.850)	(0.272)	(0.827)	(0.001)	(0.852)	(0.418)	(0.256)	(0.309)	(0.063)	(0.316)	(0.431)	(0.484)
Number of lenders	-6.511	61.41	-14.19	25.19	-4.946	75.20	-14.35	34.21	1.893	-520.1***	3.594	-520.1***	-2.043	-437.4***
	(0.536)	(0.158)	(0.121)	(0.172)	(0.661)	(0.127)	(0.134)	(0.123)	(0.733)	(0.000)	(0.279)	(0.000)	(0.769)	(0.000)
Maturity	22.74**	49.18*	12.32*	16.71*	21.60*	88.87**	11.02	12.26	-15.80	-0.000294	-7.956	-0.0000116	24.33	-37.50***
	(0.044)	(0.071)	(0.093)	(0.089)	(0.055)	(0.022)	(0.129)	(0.249)	(0.127)	(0.432)	(0.330)	(0.432)	(0.352)	(0.000)
Firm size	-15.38	-57.07**	-7.129	-54.85***	-10.46	-73.00***	-5.673	-59.57***	15.62**	-58017.7***	14.83***	2671.8***	-34.35*	-1382.7***
	(0.249)	(0.014)	(0.328)	(0.000)	(0.472)	(0.003)	(0.454)	(0.000)	(0.027)	(0.000)	(0.000)	(0.000)	(0.066)	(0.000)
Leverage	16.15	154.4	34.72**	10.81	14.92	111.6	34.47**	-2.607	17.01	149918.1***	-77.01***	-7172.1***	37.56	3297.6***
	(0.551)	(0.135)	(0.015)	(0.618)	(0.626)	(0.391)	(0.020)	(0.905)	(0.623)	(0.000)	(0.002)	(0.000)	(0.568)	(0.000)

	(1) sample2 2010-2015	(2) sample2 2015-2021	(3) sample2 2010-2015	(4) sample2 2015-2021	(5) sample3 2010-2015	(6) sample3 2015-2021	(7) sample3 2010-2015	(8) sample3 2015-2021	(9) sample1 2010-2015	(10) sample1 2015-2021	(11) sample1 2010-2015	(12) sample1 2015-2021	(13) sample1 2010-2015	(14) sample1 2015-2021
Profitability	-178.6	118.2	47.25	-561.5***	-244.1	336.9	57.35	-536.9***	416.8***	4249014.4***	564.8***	-202676.2***	-117.8	70730.9***
	(0.292)	(0.553)	(0.612)	(0.004)	(0.177)	(0.229)	(0.629)	(0.005)	(0.000)	(0.000)	(0.000)	(0.000)	(0.483)	(0.000)
Collateral=1	27.29*	56.76	31.60**	141.1***	26.40*	-11.66	29.25**	162.4***	115.1***	-180758.0***	90.01***	8949.9***	14.70	-3866.7***
	(0.067)	(0.164)	(0.017)	(0.001)	(0.070)	(0.807)	(0.016)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.635)	(0.000)
Second-hand price index									77.04***	-249.5***	72.90***	-102.7***	5.094	-90.96***
									(0.000)	(0.000)	(0.000)	(0.000)	(0.737)	(0.000)
Ships' size									20.45	-329.8***	64.48***	-19.12***	-5.050	31.[illegible]5***
									(0.166)	(0.000)	(0.000)	(0.000)	(0.882)	(0.004)
Short maturity=1									-4.455	-0.0000229	15.97	-0.00000161	24.71	-5.380***
									(0.875)	(0.432)	(0.360)	(0.432)	(0.487)	(0.000)
Project finance=1									29.42***		19.17***		28.07***	
									(0.000)		(0.000)		(0.000)	
SPV=1									60.67*		115.7***		-11.30	
									(0.057)		(0.000)		(0.856)	
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes						
Repayment type	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Shipping segment	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower FE	No	No	No	No	No	No	No	No	No	No	No	No	No	No
R-squared	0.920	0.959	0.800	0.863	0.928	0.966	0.816	0.887	0.988	1.000	0.992	1	0.940	0.994
Observations	4097	770	7606	2349	3945	738	7255	2132	382	79	382	79	406	103
BIC	40639.2	7917.7	79805.8	25296.9	38748.5	7458.9	75628.7	22658.5	2778.0	-1533.7	2610.6	.	3668.5	636.8
AIC	40430.7	7815.5	79493.6	25066.4	38553.8	7371.4	75332.5	22437.6	2710.9	-1543.2	2543.5	.	3572.3	628.9

p-values in parentheses
* p<0.10, ** p<0.05, *** p<0.01

Table D.6: Results of the regression analysis of loans margins and environmental performance, period breakdown. Sensitivity: borrower fixed effects.

	(1) sample2 2010-2015	(2) sample2 2015-2021	(3) sample2 2010-2015	(4) sample2 2015-2021	(5) sample3 2010-2015	(6) sample3 2015-2021	(7) sample3 2010-2015	(8) sample3 2015-2021
CDP score	-3.708	223.8			-1.796	188.8		
	(0.354)	(0.192)			(0.679)	(0.143)		
Refinitiv environmental score			0.0221	-0.695			0.697	-0.302
			(0.979)	(0.299)			(0.416)	(0.716)
Loan amount	-6.566	-725.7	8.087	4.207	-5.010	-613.0	4.857	-1.756
	(0.290)	(0.202)	(0.201)	(0.803)	(0.520)	(0.131)	(0.512)	(0.936)
Tranche amount	-8.863	-30.29	-0.297	-1.056	-10.55	-35.54*	-0.664	0.776
	(0.200)	(0.117)	(0.954)	(0.878)	(0.114)	(0.099)	(0.906)	(0.906)
Number of lenders	5.777	91.11	-12.16	22.10	9.099	93.67	-10.59	41.28
	(0.459)	(0.152)	(0.157)	(0.459)	(0.212)	(0.137)	(0.292)	(0.208)
Maturity	21.84**	44.99	17.39**	-6.851	22.67**	87.10	19.20**	-0.832
	(0.037)	(0.212)	(0.030)	(0.620)	(0.031)	(0.312)	(0.017)	(0.952)
Firm size	68.30*	2344.2*	-7.941	-19.02	103.6**	2105.5**	-20.00	-78.91**
	(0.081)	(0.079)	(0.826)	(0.586)	(0.016)	(0.034)	(0.565)	(0.046)
Leverage	11.22	3097.6	17.07	-63.32	25.14	2676.6*	22.99	-5.381
	(0.686)	(0.115)	(0.387)	(0.421)	(0.399)	(0.065)	(0.253)	(0.938)
Profitability	222.2	2006.8*	80.98	-62.62	71.82	1717.6**	55.15	142.3
	(0.211)	(0.072)	(0.258)	(0.797)	(0.561)	(0.045)	(0.597)	(0.593)
Collateral=1	13.33**	45.60	16.46*	58.69*	3.880	51.08	7.840	56.53**
	(0.025)	(0.464)	(0.095)	(0.064)	(0.553)	(0.410)	(0.383)	(0.012)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Repayment type	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Shipping segment	No	No	No	No	No	No	No	No
Industry FE	No	No	No	No	No	No	No	No

	(1) sample2 2010-2015	(2) sample2 2015-2021	(3) sample2 2010-2015	(4) sample2 2015-2021	(5) sample3 2010-2015	(6) sample3 2015-2021	(7) sample3 2010-2015	(8) sample3 2015-2021
Borrower FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.951	0.975	0.886	0.930	0.958	0.976	0.896	0.943
Observations	4097	770	7606	2349	3945	738	7255	2132
BIC	38552.8	7502.8	75357.1	23604.4	36563.9	7178.5	71315.1	21068.8
AIC	38407.5	7423.8	75169.8	23471.9	36425.7	7109.5	71135.9	20944.2

p-values in parentheses
* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table D.7: Results of the regression analysis of loans margins, environmental performance and the Poseidon Principles. Central model.

	(1) sample2	(2) sample2	(3) sample3	(4) sample3	(5) sample1	(6) sample1	(7) sample1
CDP score	-2.482 (0.659)		-2.409 (0.670)				
Poseidon Principles signatory=1 × CDP score	-56.16*** (0.001)		-54.27*** (0.001)				
Poseidon Principles signatory=1 × CDP score							
Refinitiv environmental score		-0.246 (0.450)		-0.106 (0.779)			
Poseidon Principles signatory=1 × Refinitiv environmental score		1.228 (0.121)		1.057 (0.384)			
Poseidon Principles signatory=1 × Refinitiv environmental score							
Relative EIV					-13.59 (0.718)		
Poseidon Principles signatory=1 × Relative EIV					55.29 (0.126)		
Poseidon Principles signatory=1 × Relative EIV							
AER						-23.55 (0.234)	
Poseidon Principles signatory=1 × AER						-4.512 (0.529)	
Poseidon Principles signatory=1 × AER							
Energy saving technologies							-7.304 (0.807)
Poseidon Principles signatory=1 × Energy saving technologies							4.814 (0.910)
Poseidon Principles signatory=1 × Energy saving technologies							
Loan amount	4.953 (0.615)	-7.638 (0.177)	6.545 (0.522)	-5.638 (0.357)			
Tranche amount	-5.770 (0.326)	-2.989 (0.289)	-4.327 (0.471)	-2.258 (0.474)	7.277 (0.235)	7.146 (0.236)	12.17 (0.185)

	(1) sample2	(2) sample2	(3) sample3	(4) sample3	(5) sample1	(6) sample1	(7) sample1
Number of lenders	3.981	1.664	2.953	0.745	0.116	3.040	-2.217
	(0.744)	(0.851)	(0.814)	(0.937)	(0.990)	(0.742)	(0.842)
Maturity	28.80***	15.80**	26.86***	14.44**	-30.14	-34.32	21.77
	(0.004)	(0.019)	(0.006)	(0.030)	(0.140)	(0.121)	(0.376)
Firm size	-18.57	-8.665	-20.67	-12.17	-42.03***	-41.08***	-47.90***
	(0.162)	(0.207)	(0.141)	(0.120)	(0.001)	(0.002)	(0.000)
Leverage	22.06	38.38***	25.06	37.10***	47.63	40.60	10.61
	(0.364)	(0.002)	(0.316)	(0.003)	(0.331)	(0.418)	(0.866)
Profitability	80.57	-269.4**	134.6	-354.3**	-127.7	-122.7	-147.9
	(0.690)	(0.040)	(0.488)	(0.017)	(0.193)	(0.195)	(0.170)
Collateral=1	115.2**	79.70***	114.8**	79.24***	33.87**	36.40*	2.437
	(0.016)	(0.003)	(0.016)	(0.005)	(0.031)	(0.052)	(0.911)
Second-hand price index					39.53***	38.72***	16.29
					(0.001)	(0.001)	(0.169)
Ships' size					-21.61	-23.05*	12.42
					(0.122)	(0.091)	(0.524)
Short maturity=1					45.47	49.75	67.51
					(0.237)	(0.216)	(0.200)
Project finance=1					14.00	14.23	-1.802
					(0.243)	(0.245)	(0.925)
SPV=1					80.20**	47.67	26.94
					(0.025)	(0.140)	(0.691)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Repayment type	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Shipping segment	No	No	No	No	Yes	Yes	Yes
Industry FE	No	No	No	No	No	No	No
Borrower FE	No	No	No	No	No	No	No
R-squared	0.808	0.689	0.822	0.701	0.914	0.916	0.869
Observations	4867	9955	4683	9387	463	463	511
BIC	53564.4	110463.1	51273.9	103995.2	4301.5	4292.0	5023.9
AIC	53298.3	110110.1	51015.8	103652.1	4177.4	4167.8	4875.6

p-values in parentheses
* p<0.10, ** p<0.05, *** p<0.01

Table D.8: Results of the regression analysis of loans margins, environmental performance and the Poseidon Principles. Sensitivity: industry fixed effect.

	(1) sample2	(2) sample2	(3) sample3	(4) sample3	(5) sample1	(6) sample1	(7) sample1
CDP score	-4.959		-6.438				
	(0.405)		(0.290)				
Poseidon Principles signatory=1 × CDP score	-39.35**		-38.38**				
	(0.017)		(0.013)				
Refinitiv environmental score		-0.714**		-0.689*			
		(0.031)		(0.077)			
Poseidon Principles signatory=1 × Refinitiv environmental score		0.827		0.269			
		(0.278)		(0.804)			

	(1) sample2	(2) sample2	(3) sample3	(4) sample3	(5) sample1	(6) sample1	(7) sample1
Relative EIV					-34.06		
					(0.147)		
Poseidon Principles signatory=1 × Relative EIV					-11.86		
					(0.434)		
AER						-33.67**	
						(0.047)	
Poseidon Principles signatory=1 × AER						-1.903	
						(0.392)	
Energy saving technologies							2.464
							(0.942)
Poseidon Principles signatory=1 × Energy saving technologies							-0.889
							(0.784)
Loan amount	18.34*	6.317	19.76**	6.307			
	(0.061)	(0.280)	(0.045)	(0.330)			
Tranche amount	2.824	-1.812	2.412	-1.749	-0.0865	-1.088	7.383
	(0.744)	(0.566)	(0.789)	(0.618)	(0.937)	(0.371)	(0.202)
Number of lenders	-14.44	-10.18	-16.65	-10.42	3.351	8.164	-7.667
	(0.173)	(0.218)	(0.140)	(0.240)	(0.541)	(0.163)	(0.368)
Maturity	25.36**	15.91***	21.45**	14.90**	-35.48*	-38.62*	7.219
	(0.020)	(0.009)	(0.042)	(0.011)	(0.069)	(0.075)	(0.743)
Firm size	-19.10	-15.83**	-16.22	-15.91**	5.508	7.268	-18.86
	(0.135)	(0.025)	(0.221)	(0.036)	(0.579)	(0.410)	(0.233)
Leverage	2.454	29.33**	11.55	29.22**	102.6***	115.1***	-3.560
	(0.916)	(0.040)	(0.635)	(0.049)	(0.006)	(0.003)	(0.954)
Profitability	-271.9*	-226.6**	-173.3	-273.3**	141.1	116.0	89.82
	(0.054)	(0.041)	(0.281)	(0.030)	(0.104)	(0.148)	(0.536)
Collateral=1	122.0***	84.76***	125.5***	87.11***	55.74***	59.39***	48.07
	(0.006)	(0.001)	(0.006)	(0.002)	(0.000)	(0.000)	(0.111)
Second-hand price index					45.84***	43.11***	31.79***
					(0.000)	(0.000)	(0.006)
Ships' size					9.440	-6.073	55.37***
					(0.618)	(0.769)	(0.001)
Short maturity=1					29.24	35.15	64.28
					(0.380)	(0.328)	(0.173)
Project finance=1					19.50***	25.37***	4.943
					(0.010)	(0.000)	(0.733)
SPV=1					34.43	-14.84	28.95
					(0.237)	(0.678)	(0.688)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Repayment type	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Shipping segment	No	No	No	No	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Borrower FE	No	No	No	No	No	No	No
R-squared	0.866	0.734	0.874	0.745	0.956	0.959	0.912
Observations	4867	9955	4683	9387	461	461	509
BIC	51866.4	108993.4	49681.4	102581.9	3938.4	3908.1	4771.6

	(1) sample2	(2) sample2	(3) sample3	(4) sample3	(5) sample1	(6) sample1	(7) sample1
AIC	51580.9	108575.5	49410.5	102181.7	3835.1	3804.7	4640.4

p-values in parentheses
* p<0.10, ** p<0.05, *** p<0.01

Table D.9: Results of the regression analysis of loans margins, environmental performance and the Poseidon Principles. Sensitivity: borrower fixed effect.

	(1) sample2	(2) sample2	(3) sample3	(4) sample3
CDP score	-0.0967		4.692	
	(0.987)		(0.430)	
Poseidon Principles signatory=1 × CDP score	-26.83***		-25.79***	
	(0.002)		(0.003)	
Poseidon Principles signatory=1 × CDP score				
Refinitiv environmental score		-0.0228		0.149
		(0.956)		(0.741)
Poseidon Principles signatory=1 × Refinitiv environmental score		0.690		-0.970
		(0.491)		(0.261)
Poseidon Principles signatory=1 × Refinitiv environmental score				
Loan amount	14.65*	6.914	12.58	4.461
	(0.060)	(0.187)	(0.154)	(0.458)
Tranche amount	-6.589	-0.590	-9.515*	-1.040
	(0.243)	(0.878)	(0.080)	(0.803)
Number of lenders	5.615	-5.176	12.21	-0.890
	(0.546)	(0.531)	(0.231)	(0.924)
Maturity	24.82***	16.78***	25.35***	18.91***
	(0.005)	(0.008)	(0.005)	(0.002)
Firm size	-64.95	-84.05**	-45.06	-94.22***
	(0.306)	(0.012)	(0.491)	(0.004)
Leverage	109.7**	54.75***	96.66*	61.71***
	(0.033)	(0.005)	(0.098)	(0.001)
Profitability	144.3	-69.70	-37.08	-122.8
	(0.153)	(0.418)	(0.786)	(0.218)
Collateral=1	64.98*	52.63**	55.64*	45.88**
	(0.054)	(0.013)	(0.067)	(0.030)
Year FE	Yes	Yes	Yes	Yes
Borrower Country FE	Yes	Yes	Yes	Yes
Repayment type	Yes	Yes	Yes	Yes
Shipping segment	No	No	No	No
Industry FE	No	No	No	No
Borrower FE	Yes	Yes	Yes	Yes
R-squared	0.926	0.844	0.932	0.855
Observations	4867	9955	4683	9387
BIC	48821.3	103503.0	46695.5	97097.5

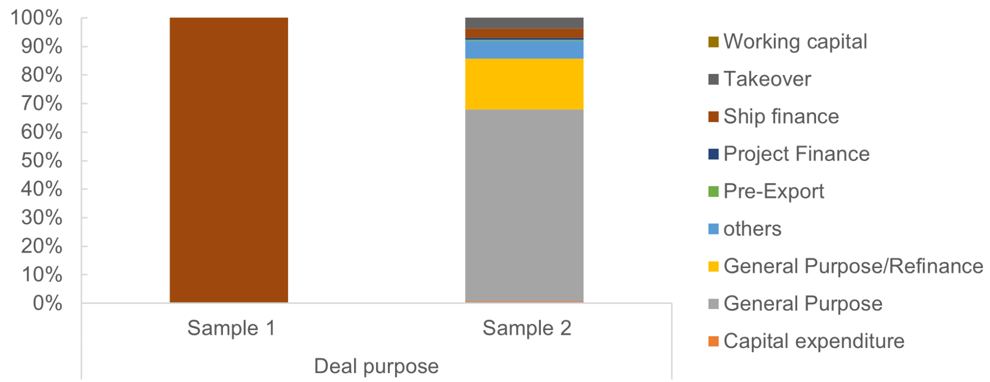
	(1) sample2	(2) sample2	(3) sample3	(4) sample3
AIC	48620.2	103236.4	46501.9	96840.2

p-values in parentheses
* p¡0.10, ** p¡0.05, *** p¡0.01

D.2 WALS results

D.3 Sample bias

Table D.11 shows the statistics of the continuous control variables used in our models in the various samples of estimation. On average, the loans provided are much larger in the corporate finance sample than when only financing ships. The average number of lenders is also lower in the ship samples than in the corporate finance samples. Not surprisingly, the large majority of the loans in the ships sample are secured by a collateral, which is likely to be the financed ship directly. On the other hand, only a minority of corporate loans are secured.



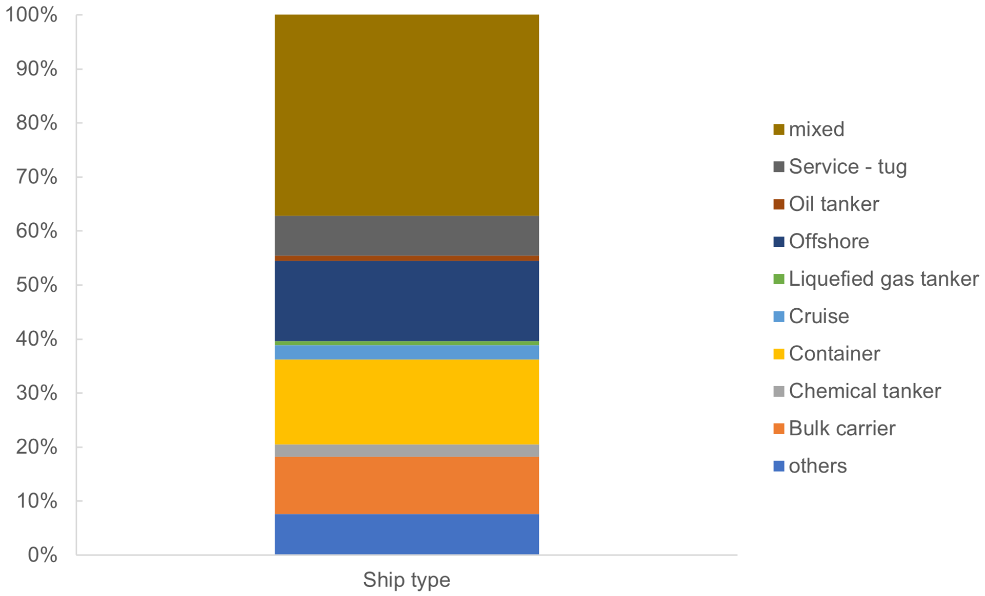


Figure D.1: Samples composition

(a) The labels correspond to the number of observations

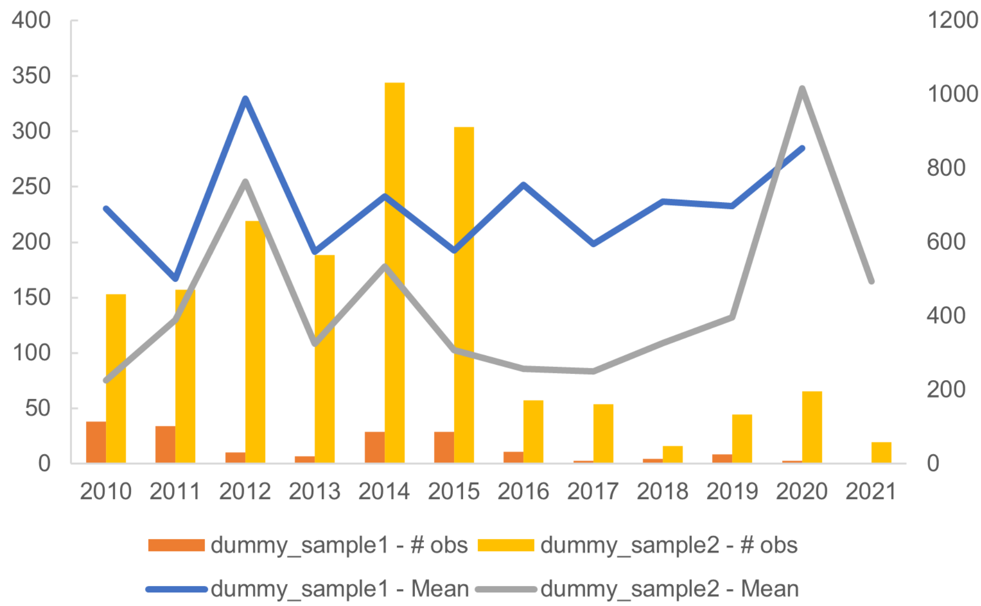


Figure D.2: Observations per year

Table D.10: Results of the WALS procedure on Sample 1

WALS estimates - Weibull	Number of observations	=	492
	k1	=	2
	k2	=	14
	q	=	0.8876
	alpha	=	0.1124
	c	=	0.6931
	sigma	=	52.1235

all_in_spread_drawn_bps	Coef.	Std. Err.	t	[1-Std. Err. Bands]	
_cons	494.3	122.1	4.1	372.2	616.4
Relative EIV	-43.3	8.9	-4.9	-52.1	-34.4
Deal Amount	2.3	5.1	0.5	-2.8	7.4
Tranche amount	9.6	3.4	2.8	6.2	13.1
Number of lenders	-33.6	5.6	-6.0	-39.2	-28.0
Maturity	-20.7	8.7	-2.4	-29.3	-12.0
Firm size	-22.9	3.6	-6.4	-26.5	-19.4
Leverage	55.6	12.5	4.5	43.1	68.1
Profitability	49.3	43.7	1.1	5.7	93.0
Second-hand price index	1.7	0.9	1.9	0.8	2.6
Age	-0.4	1.5	-0.3	-1.9	1.1
Ships' size	27.9	5.2	5.3	22.6	33.1
Collateral dummy	23.2	15.2	1.5	8.0	38.4
Short maturity	18.1	9.1	2.0	9.1	27.2
Project finance	21.9	14.6	1.5	7.3	36.4
SPV	494.3	122.1	4.1	372.2	616.4

To check whether those samples are biased, we compare the average leverage, profitability and company size to all companies classified under the NAIC "Deep sea, coastal and Great Lakes water transportation", and to all companies which provided a ticker in Clarksons over the period 2010 to 2021. The results can be found in Table D.11. It is first worth noting that even those two samples might be biased compared to the average shipowner, as most shipowners do not report publicly that information. Second, those two samples do not compare well with each other, with companies classified under the NAIC "Deep sea, coastal and Great Lakes water transportation" being significantly smaller than those who reported in Clarksons which have a ticker. It can be expected that only the largest shipowners would report publicly their information and/or be publicly listed.

Borrowers of our corporate finance sample (sample 2) are much larger than the average company classified under the NAIC "Deep sea, coastal and Great Lakes water transportation" and larger than the average Clarksons company reporting a ticker. Borrowers who borrowed money to finance ships (samples 1) are on average much smaller and are a bit more leveraged than those of the corporate finance sample and of shipowners who have displayed a ticker. They are however larger than the average firm of NAIC "Deep sea, coastal and Great Lakes water transportation" and have similar leverage. This suggests that both samples, but in particular the corporate sample, are biased towards large firms in terms of assets.

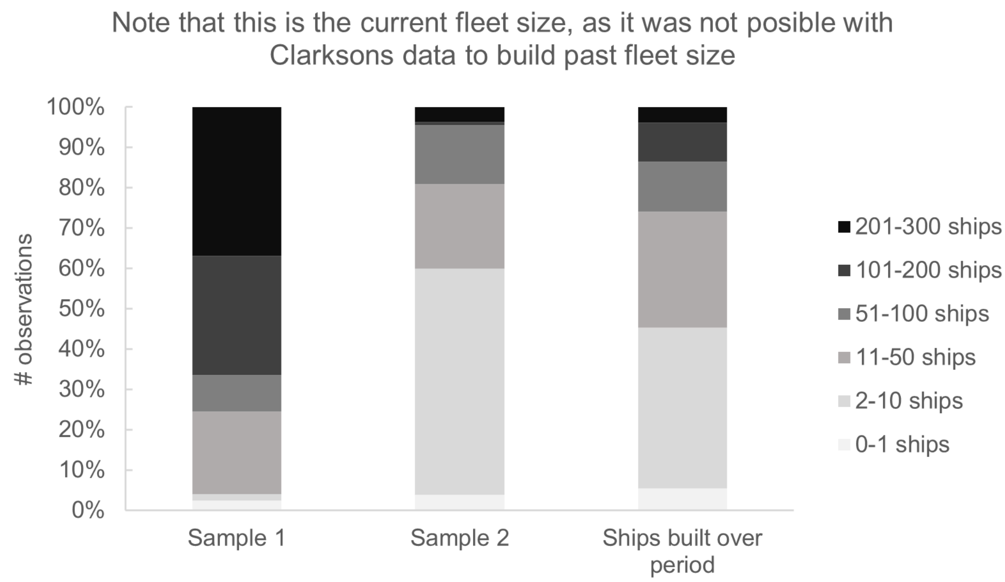


Figure D.3: Shipowner size by sample

(a) The first four columns represent the number of observations in the sample.

(b) The last column corresponds to the number of ships built between 2010 and 2021.

(c) The numbers plotted correspond to current fleet size of the shipowner rather than fleet size at the time of loan provision, as it was not possible from Clarksons data to build past fleet size by shipowner.

D.4 Correlation matrix

Table D.11: Average of continuous control variables in Sample 1 and 2

	Sample 1	Sample 2	Selected NAIC	Clarksons owners with ticker
AIDS (bps)	220	150		
Number of Lenders	9	31		
Loan Amount (million USD)	650	5,292		
Tranche Amount (million USD)	325	2,502		
Maturity (months)	88	41		
Firm Size (million USD)	9,436	68,770	2,299	54,355
Profitability	0.02	0.01	0.00	0.01
Leverage	0.48	0.35	0.43	0.34
CDP score (E=0, A=8)	2.3	4.8		
Relative EIV	- 0.32			

Table D.12: Correlation matrix between the control variables

	Deal amount	Tranche amount	Number of lenders	Collateral	Short maturity	Maturity	Firm size	Capitalisation	Leverage	Profitability	Second-hand price index	SPV	Age	Size quintile	Second-hand
Deal amount	1.00														
Tranche amount	0.071	1.00													
Number of lenders	0.59	0.36	1.00												
Collateral	0.11	-0.05	0.27	1.00											
Short maturity	-0.30	-0.20	-0.18	0.05	1.00										
Maturity	0.13	0.24	-0.26	-0.27	-0.59	1.00									
Firm size	0.56	0.30	0.48	-0.06	-0.07	-0.11	1.00								
Capitalisation	0.54	0.27	0.46	-0.05	-0.06	-0.12	1.00	1.00							
Leverage	-0.21	-0.21	-0.06	0.03	0.05	-0.29	-0.24	-0.23	1.00						
Profitability	0.05	0.12	0.02	0.05	0.00	-0.07	-0.16	-0.19	0.23	1.00					
Second-hand price index	0.02	-0.02	0.24	0.09	-0.20	0.03	-0.06	-0.07	-0.18	0.12	1.00				
SPV	-0.060	-0.47	-0.25	-0.15	0.10	-0.03	-0.16	-0.15	0.24	-0.01	0.02	1.00			
Age	-0.14	0.00	-0.10	0.10	0.23	-0.23	-0.30	-0.32	0.30	0.31	-0.25	-0.09	1.00		
Size quintile	0.48	0.37	0.50	-0.10	-0.14	-0.13	0.44	0.43	-0.02	0.07	0.00	-0.46	0.07	1.00	
Second-hand	-0.07	0.09	-0.12	0.16	0.21	-0.28	-0.26	-0.24	0.33	-0.05	-0.32	-0.14	0.53	-0.06	1.00

D.5 Robustness analysis

Table D.13: Results summary of the robustness analysis

Climate risk	Metrics	Period breakdown	Sample	Industry dummies	Firm dummies	Pricing of climate risk whole period	Pricing of climate risk before 2015	Pricing of climate risk after 2015	Poseidon Principles increase the pricing of climate risk
Asset	AER	N	1	N	N				
Asset	AER	Y	1	N	N				
Asset	AER	N	1	Y	N				
Asset	AER	Y	1	Y	N				
Asset	EST	N	1	N	N				
Asset	EST	Y	1	N	N				
Asset	EST	N	1	Y	N				
Asset	EST	Y	1	Y	N				
Asset	EIV	N	1	N	N				
Asset	EIV	Y	1	N	N				
Asset	EIV	N	1	Y	N				
Asset	EIV	Y	1	Y	N				
Corporate	CDP	N	2	N	N				
Corporate	CDP	Y	2	N	N				
Corporate	CDP	N	2	Y	N				
Corporate	CDP	Y	2	Y	N				
Corporate	CDP	N	2	N	Y				
Corporate	CDP	Y	2	N	Y				
Corporate	CDP	N	3	N	N				
Corporate	CDP	Y	3	N	N				
Corporate	CDP	N	3	Y	N				
Corporate	CDP	Y	3	Y	N				
Corporate	CDP	N	3	N	Y				
Corporate	CDP	Y	3	N	Y				
Corporate	Refinitiv	N	2	N	N				
Corporate	Refinitiv	Y	2	N	N				
Corporate	Refinitiv	N	2	Y	N				
Corporate	Refinitiv	Y	2	Y	N				
Corporate	Refinitiv	N	2	N	Y				
Corporate	Refinitiv	Y	2	N	Y				
Corporate	Refinitiv	N	3	N	N				
Corporate	Refinitiv	Y	3	N	N				
Corporate	Refinitiv	N	3	Y	N				
Corporate	Refinitiv	Y	3	Y	N				
Corporate	Refinitiv	N	3	N	Y				

Climate risk	Metrics	Period breakdown	Sample	Industry dummies	Firm dummies	Pricing of climate risk whole period	Pricing of climate risk before 2015	Pricing of climate risk after 2015	Poseidon Principles increase the pricing of climate risk
Corporate	Refinitiv	Y	3	N	Y				

(a) Positive corresponds to a positive pricing of climate performance, i.e. a negative coefficient on the CDP/Refinitiv scores (a higher score leads to a lower margin) and a positive coefficient on the AER (a higher carbon intensity leads to a higher margin). Inversely, negative corresponds to a negative pricing of climate performance.
(b) The colours correspond to the level of significance of the coefficient of interest.

not measured/sample too small
non-significant coefficient
Positive 10% significant
Positive 5% significant
Positive 1% significant
Negative 10% significant
Negative 5% significant
Negative 1% significant

Appendix E

Qualitative data collection and analysis (Chapter 6)

E.1 Interview guide

Investments decisions – descriptive

1. What types of financial products do you provide to shipowners?
2. How long is the tenor and the profile typically?
3. What type of ships and clients do you finance?
4. If you had to give 3 main factors you consider when deciding whether or not you will provide finance for a ship, which ones would they be?
5. If you had to give 3 main factors which influence the interest rate you give, what would they be?
6. Why signing the Poseidon Principles?

Evolution of the industry over the last decade

1. Could you tell me the story of the first ship investment that you made in your carrier?
2. Could you tell me the story of the last ship investment that you made?

3. Have you observed any evolution in the way your company views and mitigates for climate risks since you joined?

Expectations concerning future stranded assets

1. How do you feel the demand for cargo shipping such as oil, coal and natural gas will evolve in the coming [*insert tenor] years?

2. How likely do you feel it is that it will impact the value of the fleet you finance?

3. How do you feel the pressures to limit carbon emissions from shipping will evolve in the coming [*insert tenor] years?

4. How likely do you feel it is that the ships you finance lose their value because of efforts to limit carbon emissions from shipping?

5. How do you mitigate for those risks (if at all)?

6. Under which conditions would you finance alternative-fuelled ships?

E.2 Detailed description of the themes and codes

Table E.1: Description of themes and codes used in the thematic analysis

Theme/code	Description
1. Heuristics	Evidence of sticky or evolving heuristics. Heuristics include, as per the theoretical framework, believes and financial tools & instruments.
1.1. Beliefs	A per the theoretical framework, those cover financiers' beliefs of the drivers of the transitions, such as the availability and risk of the incumbent and new technology and the strength of landscape pressures (policy, customer demand for example) behind the transition.
1.1.1. Beliefs on landscape pressures	Financiers' perceptions of the existing and upcoming exogenous pressures to shipping.

Theme/code	Description
Cyclicality of shipping markets	Even without considering climate risks, the cyclicality of the shipping revenues means that financiers are exposed to the risks that shipowners go bankrupt of non-performing loans and devaluation of underlying ship assets.
Financiers' expectations of climate risks has increased	There has been a general increase in financiers' expectations of climate risks over the last few years.
Target to reduce shipping emissions	The financier has published a target for reducing emissions of its shipping portfolio. Note that the targets are not homogeneous and not all aligned with a 1.5-degree pathway.
Further regulation and public support necessary for the transition	The private sector cannot self-regulate climate risks and need some kind of regulatory or financial support from the public institutions
IMO failure to act fast enough	The IMO has been slow to regulate shipping emissions and more efforts are required
Role of public finance	Instances where public finance has been an Enabler of the transition.
Increasing regulatory pressure on emissions	The financier perceives increasing regulatory pressures on shipping emissions.
Society & customer demand for climate mitigation	Growing demand from society and stakeholders for climate mitigation of shipping emissions and/or land-based sectors decarbonization
Customer and charterer demand for low or zero-carbon shipping	Customer and charterers increased demand for low/zero-carbon shipping is a driven of profitability of low/zero-carbon ships
ESG as legitimacy demand from society to financiers	Financiers perceive that there is social demand towards financiers for ESG/responsible investment.
Shareholder demand for ESG	Equity investors have started to require ESG/climate consideration from financiers and shipowners.
Technology risk	Financiers are worried that ships might become obsolescent earlier than they have historically.

Theme/code	Description
My company is not at risk of stranded assets because we only finance modern ships	The interviewee's company only finances the most modern, fuel-efficiency or carbon-efficiency ships so they do not believe they will be at risk of being stranded.
Demand-side risk is not material	Because there is no expected large decrease of fossil fuel shipping demand, fossil fuel carriers are not at risk of being stranded.
Demand-side risk is material	The financier believes that fossil fuel carriers are at risk of being stranded.
Financiers' ambition to reduce the emissions of their land-based sectors portfolio	The financier has committed or expressed the ambition to align their land-based sectors portfolio (e.g. energy, manufacturing, etc) to a decarbonization trajectory.
Shipping opportunities from the decarbonization of land-based sectors	The financier ambitions to support shipping demand linked to renewables, e.g. offshore wind
1.1.2. Beliefs on shipowners	This theme regroups all statements characterising the behaviour of shipowners.
Niche entrant shipowners = first movers	Financiers perceive that emerging niche actors are taking up the opportunities arising from the transition to low/zero-carbon shipping and the decarbonization of land-based sectors.
Regime shipowners = Creative Self-Destruction	Financier perceive that shipowners anticipate a growth in shipping and no significant decarbonization, hence increasing investments into the existing technologies.
Regime shipowners = first movers	Financiers perceive that incumbent shipowners are taking up the opportunities arising from the transition to low/zero-carbon shipping and the decarbonization of land-based sectors.
Low or zero-carbon shipping will lead to a consolidation of the market	The shipowners believe that the transition to low/zero-carbon shipping will favour the largest historical shipowners, leading to difficulties from the smaller shipowners and a consolidation of the market.
Regime shipowners = Inert	Financiers perceive that some or all shipowners are not expecting the risks and opportunities arising from the transition to low/zero-carbon shipping and of the decarbonization of land-based sectors to materialise.

Theme/code	Description
Regime shipowners are Winding Down exposure	Financiers perceive that shipowners are reluctant to invest in new ships today because of the uncertainty of the transition.
1.2. Adaptation of financial tools instruments	As per the theoretical framework, those include the tools and rules of thumbs used by financiers to make decisions. Those include for example the credit risk methodology adapted by each financier; the rule of thumbs used to judge the quality of a transaction; and the financial tools and instruments available to financiers.
1.2.1. Sticky heuristics - backward-looking risk management	Backward-looking heuristics and tools which have been traditionally used by shipping financiers to assess the quality and the risk of a transaction continue being used in the transition.
Quantitative backward-looking risk assessment	Standardised quantitative credit risk assessment, based on historical backward-looking data.
Standardised financing instrument	The type of financial product is standardised within and across financiers
1.2.2. Type of business = corporate financing	This set of codes look at how financiers view shipping finance as corporate finance, i.e. finance to a shipowner, rather than asset finance. Concretely, when assessing whether or not the finance will finance a ship, they will look at the characteristics of the shipowners before looking at the characteristics of the ship asset.
Analysis of the asset is secondary	The financier either does not look at the asset, or looks at it after having looked at the corporate.
Large range of financial products to few shipowners	Financiers not only provide ship secured debts but a large range of products to a few clients.
Prevalence of corporate non climate-related metrics	Financiers primarily use financial (non-climate-related) corporate metrics which do not include climate risks on the shipowner to judge of the quality of a deal.
Shipowners' reputation is an important criterion of decision	Qualitative criteria related to the shipowners' reputation are used in financiers' assessment process.
Shipping finance is relationship-driven	The financier has long-term relationship with its clients; it will primarily lend to them, will trust their opinion and maintains a dialogue with them.

Theme/code	Description
Targeting the top-tier shipowners	Financiers are targeting a few incumbent and top-tier shipowners.
1.2.3. Financial innovations	Financiers have started to adjust their heuristics, beliefs and tools used to make decisions to adapt to the transition of shipping and its cargo.
Focus on corporate climate strategy and ESG metrics	Climate characteristics of the shipowners (climate strategy, whether it is credible or not; ESG metrics are developed, and data is collected) are measured and taken into account in the financiers' decisions.
Impact of the Poseidon Principles (PPs) on investment decisions	The signing of PPs has impacted the lending behaviour of the financier.
Knowledge build-up of demand-side risk	The financier has used resources to build an understanding of the risks and opportunities for shipping arising from the decarbonization of land-based sectors.
Other financial innovations	There have been attempts for financial innovations (e.g. carbon credits to finance ships; retrofit financing)
Risk-sharing by a larger range of actors	Traditionally, financiers would only need to share financial risk with shipowners. Financing low/zero-carbon ships requires this risk to be shared by a larger range of actors (charterers, public authorities e.g. export credit agencies, fuel providers). Financial instruments need to adapt to this new way of sharing risk.
Ship asset greenness becomes a criterion of decision	Ships' characteristics such as carbon/energy intensity, ability to retrofit and dedication to fossil-fuel shipping are taken into account in financiers' investment decisions.
Climate risks are incorporated into the financial risk analysis	
Uptake of green shipping finance	The financier has provided or is planning to provide green form of finance to shipping. This includes sustainability-linked loans, SBTi-aligned, climate-aligned loans/bonds; or inclusion of carbon intensity metrics on the ships' emissions in the covenants.
2. Typical behaviours	This category collects the text which supports the classification of the shipping financiers' behaviour in one of the ideal-typical behaviours proposed in the theoretical framework.
2.1. Creative Self-Destruction	Financiers push shipowners to invest in the incumbent technology which exacerbates the risks of stranded assets

Theme/code	Description
2.2. Inert	Financiers are not expecting climate risks and opportunities arising from the transitions and keep their activities as business as usual to materialise.
Full divestment is not an option	The financier rejects the option of divesting from the sector despite perceived risks.
Inertia towards LNG as a marine fuel	There is an Inertia to move away from LNG as a marine by putting faith in its drop-in fuels such as bio-methane or e-LNG
It is risky to be a first mover	There are barriers and uncertainties to low/zero-carbon ships which make them more risky than conventional. It is safer to be a follower than a first mover.
Mispricing of climate risks	Loans pricing is determined by the market competition between financiers, not by climate considerations.
Others are not expecting supply-side risks to materialise	Other financiers are not expecting supply-side risks to materialise, or not as much as the speaker does.
Will continue financing fossil carriers	The financier intends to continue financing fossil fuel carriers.
2.3. Loyal Enabler	Financiers is/willing to support in some way the transition to low/zero-carbon shipping.
Influence of financiers on shipowners	Financiers are necessary to shipowners and as a consequence, they have a large power of influence over the transition to low/zero-carbon shipping
Knowledge build-up of low/zero-carbon shipping	Knowledge build-up of low or zero-carbon shipping
Mitigating emissions is the right thing to do	The financier justifies its action by a moral driver of the financiers to support the transition to low/zero-carbon shipping.
Pushing the transition favours the interests of the financier	The financier feels that it will benefit from the transition to low/zero-carbon shipping; and is therefore trying to influence the process to accelerate it.
Support for LNG as a transition fuel	A financier has supported or is supporting LNG as a transition fuel

Theme/code	Description
The financier will help incumbents into doing the transition	Financiers will help existing incumbents/existing clients to invest in the ship assets necessary for the transition.
2.4. Redirecting Enabler	Financiers support niche actors to lead the transition to low/zero-carbon shipping.
Fit & conform	Evidence of attempts by industry players (both niche and incumbent) and financiers to adjust the fitness of the shipping industry and ship assets to the expectations and needs of potential new investors.
2.5. Winding Down	Financiers are adopting a cautious approach to the shipping sector altogether, either by retrieving or by requiring harder lending conditions.
Replacement of traditional financiers by other financiers	Uptake of alternative types of finance than commercial banks focusing on the incumbent shipowners to fill the financing gap for low/zero-carbon technologies.
Traditional banks are retrieving from shipping finance	European banks have retrieved from shipping finance after 2010.
Winding Down from demand-side risk	Financiers are reducing their exposure/financial flows to shipping segments carrying fossil fuels because of the decarbonization of land-based sectors.
Winding Down from supply-side risks	Financiers are reducing their exposure/financial flows to shipping as a whole because of uncertainties linked to the transition to low/zero-carbon shipping.

Appendix F

Detailed equations defining the land-shipping SFC model (Chapter 7)

F.0.1 Firms

Let us first look at how economic activity, i.e. goods production and shipping, is modelled in the land-shipping SFC model. Output is determined by demand, according to post-Keynesian assumptions, in equation F.1 (from Godley and Lavoie (2007)). It equals the sum of households (H) and government consumption, and investment from firms (I^F) and government (I^{gov}).

$$Y_t = C_t^H + I_t^F + I_t^{gov} + C_t^{gov} \tag{F.1}$$

The two sectors of the economy, shipping and land, are assumed to be carried out by individual firms who take decisions on investment and technology independently. Each year, part of the capital stock is depreciated and some capital is added through investments (F.2, from Godley and Lavoie (2007)). This is the case for both sources (sc) of capital, i.e. public (gov) and private (F). Each firm s decides to invest in new capital at time t to replace depreciated capital, with δ the depreciation rate of capital, and depending on the past year utilisation of capital (u) (equation F.3 as proposed in Dafermos and Nikolaidi (2021)). This corresponds to the post-

Keynesian view that 1/ firms wish to have reserve capacity to face unexpected (i.e. deeply uncertain) increase in demand and 2/ firms invest based on the heuristics of target utilisation and that present and recent past utilisation is a good indicator of future utilisation (Lavoie, 2022). Firms choose the proportion of investment in green and dual-fuel assets, while brown is the residual (equations F.4 and F.5).

$$K_t^{sc,s,c} = K_{t-1}^{sc,s,c}(1-\delta^s) + I_t^{sc,s,c} \tag{F.2}$$

$$I_t^{F,s} = K_{t-1}^{F,s}(\delta^s + \frac{\alpha^{s0}}{1+exp^{\alpha_1-\alpha_2 u_{t-1}^s}}) \tag{F.3}$$

$$I_t^{s,c} = \beta_t^s I_t^s, \text{ if } s \in \{G, DF\} \tag{F.4}$$

$$I_t^{s,B} = I_t^s - I_t^{s,G} - I_t^{s,DF} \tag{F.5}$$

The production costs are differentiated by sector and technology. The total unit cost *tuc* includes the levelised cost of energy and the carbon price (equation F.7) or subsidy (equation F.6). Note that this cost is expressed per nominal output, not per real output, so it excludes the effects of inflation. CT is the carbon tax expressed in USD\kg CO2 (or USD trillion\giga-tonne CO2), *em* is the carbon intensity of brown technology, *ei* is the energy intensity of shipping, and *sub* is the subsidy expressed per amount of energy. The levelised cost is calculated using the discounted sum over the technology profile of operating expenses (fuel cost SFC), the total capital expenditure (KB), and the discounted sum of the nominal output Yn produced (equation F.8). Note that as long as dual-fuel ships are more profitable running on brown, dual-fuel ships fuel cost corresponds to brown fuel cost; once green becomes cheaper, fuel cost corresponds to green fuel cost. The capital cost *cc* corresponds to the price of capital and allows one to convert real capital K into nominal capital. The capital cost of brown increases at a decreasing rate with time (equation F.9 equation F.9), as per Dafermos and Nikolaidi (2021). The capital cost of green and dual-fuel decreases every year, assuming as per Dafermos and Nikolaidi (2021) that the rate of decline is more rapid as the share of non-fossil energy increases (equation F.11 equation F.12). This reduction is, however, capped by a maximum reduction, called *mincc*. This captures the technical progress of green technology.

$$tuc_t^{s,G} = lc_t^{s,G}(1 - sub_t^{s,G} \times ei_t^s) \tag{F.6}$$

$$tuc_t^{s,B} = lc_t^{s,B}(1 + ct_t^s \times em_t^s \times ei_t^s) \tag{F.7}$$

$$lc_t^{s,c} = \frac{K_{t-1}^{s,c} + \sum_{y=0}^{profile^s} SFC_{t-1}^{s,c}(1 + wacc_{t-1}^{s,c})^{-y}}{\sum_{y=0}^{profile^s} Yn_{t-1}^{s,c}(1 + wacc_{t-1}^{s,c})^{-y}} \tag{F.8}$$

$$cc_t^{s,B} = cc_t^{s,B}(1 + g_t^{cc,s,B}) \tag{F.9}$$

$$g_t^{cc,s,B} = g_{t-1}^{cc,s,B}(1 - \zeta^{cc,B}) \tag{F.10}$$

$$cc_t^{s,c} = max(cc_t^{s,c}(1 - g_t^{cc,s,G})\frac{1 - \Theta_t^{s,G} - \Theta_t^{s,DF}}{1 - \Theta_{t-1}^{s,G} - \Theta_{t-1}^{s,G}}, mincc^s \times cc_t^{s,c}) \text{ if } c \in G, DF \tag{F.11}$$

$$g_t^{cc,s,G} = g_{t-1}^{cc,s,G}(1 - \zeta^{cc,G}) \tag{F.12}$$

Firms finance those investments using loans (L) and retained earnings (RE). An exogenous share *leverage* of investments is financed by new loans NL (equation F.13), which is consistent with interviews conducted in chapter 6 that highlighted that lenders request a maximum loan-to-value when lending to shipowners; and consistent with the post-Keynesian finance frontier reported in Lavoie (2022), by which outside finance is limited to a share of new investments, the remaining portion being financed by retained earnings. The remaining is financed through savings (equation F.15).

$$NL_t^{s,c} = leverage_t^{s,c} \times I_t^{F,s,c} \tag{F.13}$$

$$L_t^{s,c} = L_{t-1}^{s,c}(1 - \rho) + NL_t^{s,c} \tag{F.14}$$

$$V_t^s = V_{t-1}^s + RE_t^s - I_t^{F,s} + NL_t^s + \delta^s K_t^{F,s} - \rho L_{t-1}^s \tag{F.15}$$

The share of output by colour is equal to the share of the colour nominal capital (corrected for the difference in capital cost) into the total sector's nominal capital (equation F.16, F.17). The underlying assumption is that all nominal capital is equally utilised. Production of the output Yn requires energy E (equation F.18), which depends on the energy intensity ei of the sector. Energy intensities are modelled in a similar way to the green capital cost (equations F.19 and F.20). It decreases every year, with a more rapid rate of decline as the share of non-fossil energy goes up. This reduction is, however, capped by a maximum reduction, called ei^s. In the shipping sector, this corresponds to the adoption of carbon-efficiency operations (e.g. reducing speed, utilisation optimisation), the installation of energy efficiency devices (e.g. trim optimisation, kites, shore power) and the use of alternative source of energy apart from the fuel (sails, shore power when in port). Green energy is assumed to have 0 emissions, and brown energy is assumed to emit em CO2 per unit of energy (equation F.21). As long as it is more profitable for dual-fuel ships to run on the brown technology, they emit as much as the brown ships. The carbon intensity of brown energy decreases at a decreasing rate, as per Dafermos and Nikolaidi (2021) (equations F.22 and F.23).

$$\Theta_t^{s,c} = \frac{K_t^{s,c}/cc_{t-1}^{s,c}}{\sum_{k \in colours} K_t^{k,c}/cc_{t-1}^{k,c}} \tag{F.16}$$

$$Y_{s,c,t} = \Theta_{s,c,t} Y_{S,t} \tag{F.17}$$

$$E_t^{s,c} = ei_t^s \times Yn_{s,c,t} \tag{F.18}$$

$$ei_t^s = max(ei_{t-1}^s(1-g_t^{ei})\frac{1-\Theta_{t-1}^{s,G}-\Theta_{t-1}^{s,DF}}{1-\Theta_{t-2}^{s,G}-\Theta_{t-2}^{s,G}}, ei^{min,s}) \tag{F.19}$$

$$g_t^{ei} = g_{t-1}^{ei}(1-\zeta^{ei}) \tag{F.20}$$

$$Em_t^s = em_t^s((1-\mu_t^s)E_t^{s,DF} + E_t^{s,B}) \tag{F.21}$$

$$em_t^s = em_{t-1}^s(1+g_t^{em,s}) \tag{F.22}$$

$$g_t^{em,s} = g_{t-1}^{em_s}(1-zeta^{em,s}) \tag{F.23}$$

Several costs occur to the firms. Fuel costs occur to shipping firms and depend on fuel prices, which increases as land price increases (equation F.24). Shipping firms also pay for other supplier expenses, marked as $SOth$ (equation F.25), while shipping is a supplier expense to the land sector and is shared equally between green and brown land activity (equation F.25). Together with fuel costs, they create intermediate demand for the land sector (equations F.26 and 7.4). Those costs are not included in Dafermos and Nikolaidi (2021) and were added to more realistically represent shipping costs. Both shipping and land firms pay carbon taxes depending on their emissions Em (equation F.27).

A share $ShareTaxRecycling$ is used to subsidise green technologies. If a carbon tax is implemented before much green capital has been built, like it might happen in the shipping sector, this results in subsidies being well over total green firms cost during the first few years, before falling again once green shipping takes up. This unrealistic peak was corrected by limiting the subsidies to a share of the operating costs of the shipping firms. The subsidy per unit of energy is calculated in equation F.28. The maximum potential subsidy is $ShareTaxRecycling \sum_{c \in colours} CT_t^{s,c}$ and must be shared between green ships and dual-fuel ships if those run on green, that is, $E_t^{s,G} + \mu_t^s E_t^{s,DF}$. This amount is capped by the fact that subsidies cover only a part of the green shipping cost, that is, $MaxSubsidyShareCost \frac{SFC_t^{s,G} + delta^s K_t^{F,s,G}}{E_t^{s,G}}$. Subsidies are then calculated according to equation F.29. In the first years of carbon tax implementation, if green technology does not make a large share of activity, some subsidies may therefore remain unused and are kept by the government (US, Equation F.30).

The wages are paid for labour, and there is no assumption of labour scarcity (equation F.31, according to Godley and Lavoie (2007), BMW model). Capital costs KB include interest costs and capital depreciation (equation F.32, Godley and Lavoie (2007), BMW model); however, non-performing loans NPL are assumed to be repaid in later years, i.e. only interest payments are lost to banks (as per Dunz et al. (2021)).

$$SFC_t^{s,c} = \begin{cases} 0, \text{if } s = L \\ \lambda^{S,c} \times P_t^{L,B} \times E_t^{s,c}, \text{ if } c = B \text{ or } (c = DF \text{ \& } \mu_t^S = 0) \\ \lambda^{S,c} \times P_t^{L,G} \times E_t^{s,c}, \text{ otherwise} \end{cases} \tag{F.24}$$

$$SOth_t^{s,c} = \begin{cases} Y_t^S \times \Theta_t^{L,c}, \text{ if } s = L \\ \lambda^{S,Oth} Yn_t^{S,c}, \text{otherwise} \end{cases} \tag{F.25}$$

$$S_t^{s,c} = SOth_t^{s,c} + SFC_t^{s,c} \tag{F.26}$$

$$CT_t^{,s,c} = ct_t^s Em_t^{s,c} \tag{F.27}$$

$$sub_t^s = min \left(\begin{array}{c} \frac{ShareTaxRecycling \sum_{c \in colours} CT_t^{s,c}}{E_t^{s,G} + \mu_t^s E_t^{s,DF}} \\ MaxSubsidyShareCost \frac{SFC_t^{s,G} + delta^s K_t^{F,s,G}}{E_t^{s,G}} \end{array} \right) \tag{F.28}$$

$$Sub_t^{s,c} = \begin{cases} sub_t^{s,c} E_t^{s,c}, \text{ if } c = G \text{ or } (c = DF \text{ and } \mu_t^s = 1) \\ 0, \text{ otherwise} \end{cases} \tag{F.29}$$

$$US_t = \sum_{c \in colours, s \in sectors} (CT_t^{s,c} - Sub_t^{s,c}) \tag{F.30}$$

$$WB_t^{s,c} = \omega^s \times Yn_t^S \tag{F.31}$$

$$KB_t^{s,c} = r_{t-1}^{s,c}(L_t^{s,c} - NPL_t^{s,c}) + \delta^s K_t^{F,s,c} \tag{F.32}$$

As in Godley and Lavoie (2007) and in line with post-Keynesian assumptions (Lavoie, 2022), there is no market-clearing mechanism via price, but firms set a price which allows them to pass some of their costs to their clients (mark-up pricing). As Lavoie (2022) suggests, in the absence of strongly differentiated products, prices are uniform and determined by the price leader on the market. Lavoie (2022) suggests that the long-term price leader is the most cost-effective firm, which is the approach taken here. However, it might be that in the short term, especially while the most cost-effective technology represents a small share of the market (e.g. green after the implementation of a carbon tax), the price leader is the brown technology and sets a price above the production cost of green. This would imply that the profitability of the incumbent would remain high, and they would not suffer immediate asset stranding. However, the bill of stranded assets would effectively be passed onto the customers, so for clarity purposes, but keeping in mind that this represents a worst-case scenario, it is assumed here that the price leader is the most profitable technology. The price is set as a mark-up above direct unit costs that the firm passes onto its customer, that is, the labour bill, the suppliers bill, the capital costs and the carbon costs (equation F.33).

$$P_t^{s,c} = (1 + markup^s)(S_t^{s,c} + WB_t^{s,c} + KB_t^{s,c} + CT_{t+1}^{s,c} - Sub_{t+1}^{s,c})/Yn_t^{s,c} \tag{F.33}$$

Profits are calculated as the sum of revenues minus costs (equation F.34). A share of those profits is distributed as dividends (Equation F.36, Godley and Lavoie (2007), GROWTH model), while the residual is kept as retained earnings (Equation F.35).

$$\Pi_t^{s,c} = Y_t^{s,c} - WB_t^{s,c} - KB_t^{s,c} + \Theta_t^{s,c} r^v V_t^s - CT_t^{,s,c} + Sub_t^{s,c} - T_t^{s,c} \tag{F.34}$$

$$RE_t^{s,c} = max((1 - \pi^s) \sum_{c \in colours} \Pi_t^{s,c}, 0) \tag{F.35}$$

$$Div_t^{s,c} = \Pi_t^{s,c} - RE_t^{s,c} \tag{F.36}$$

The amount of non-performing loans depends on the non-performing loan ratio npl (equation F.37) which is itself a function of firm illiquidity, as per Dafermos and Nikolaidi (2021) (equation F.38). However, while Dafermos and Nikolaidi (2021) only looks at illiquidity at the aggregate level across all sectors and colours, here illiquidity is calculated at the sector and colour level, so that differentiated non-performing loans and interest rates can be calculated. Equation F.38 implies that when cash outflows exceed cash inflows, firms experience a reduced capacity to repay their debts. The measure of firms' lack of liquidity is represented by an illiquidity ratio $illiq$ (equation F.39). Capacity utilisation is calculated as the nominal output divided by the nominal capital, i.e. the amount invested divided by the price of capital, and multiplied by the productivity of capital ε_s. Dafermos and Nikolaidi (2021) does not correct for the price of capital, but it was added because the costs of green and brown ships can differ significantly.

$$NP_t^{s,c} = npl_t^{s,c} L_t^{s,c} \tag{F.37}$$

$$npl_t^{s,c} = \frac{def_{max}}{1 + def_0 e^{(def_1 - def_2 illiq_{t-1}^{s,c})}} \tag{F.38}$$

$$illiq_t^{s,c} = \frac{KB_t^{s,c} + WB_t^{s,c} + S_t^{s,c} + T_t^{s,c} + CT_t^{s,c} - Sub_t^{s,c}}{Y_t^{s,c}} \tag{F.39}$$

$$u_t^s = \frac{Yn_t^s}{\varepsilon^s \sum_{c \in colours} K_t^{s,c} / cc_t^{s,c}} \tag{F.40}$$

F.0.2 Banks

Let us now look at how the financial sector is modelled in the land-shipping SFC model. How banks are modelled is more closely aligned with the work of Dunz et al. (2021) because it explicitly models the variation in interest rates depending on the perceived risks of the loans.

Banks make profits by collecting interest rates on loans L and government bonds GB^{Bk}, and have to pay interest on savings V and advance from the Central Bank A (equation F.41, from Godley and Lavoie (2007), GROWTH model). While the yield on government bonds r^{gov} and the interest rate on central bank advances r^A are exogenous and constant, the other rates are decided by the bank to make profits and respect regulation. Similarly to firms, banks redistribute a fixed share of their profits as dividends (equation F.43) and the residual retained earnings (equation F.44) are added to the banks' equity (equation F.45).

$$\Pi_t^{Bk} = \sum_{c \in colours, s \in sectors} r_{t-1}^{s,c} (L_t^{s,c} - NPL_t^{s,c}) + r^{gov} GB_{t-1}^{Bk} - r_{t-1}^V V_{t-1} - r^A A_{t-1} \tag{F.41}$$

$$V_t = \sum_{s \in sectors} V_t^s + V_t^H \tag{F.42}$$

$$Div_t^{Bk} = \pi^{Bk} \Pi_t^{Bk} \tag{F.43}$$

$$RE_t^{Bk} = (1 - \pi^{Bk}) \Pi_t^{Bk} \tag{F.44}$$

$$E_t^{Bk} = E_{t-1}^{Bk} + RE_t^{Bk} \tag{F.45}$$

In light of the 2007 Financial Crisis, the Basel III framework was introduced to enhance stability in the banking sector. It requires banks to meet specific criteria, including capital requirements and loan loss provisioning, based on the quality of their assets. Additionally, banks are required to maintain a minimum Capital Adequacy Ratio (*CAR*). The Capital Adequacy Ratio is a measure of the bank's equity compared to the risk-weighted loans it holds and reflects the liquidity of the banking sector in relation to loans that are considered safe (equation F.46). χ represent the sector- and colour-specific risk weights. As in Dunz et al. (2021) and Godley and Lavoie (2007), GROWTH model, the banks achieve their target CAR^T by adjusting interest rates. The deposit rate is estimated as in Dunz et al. (2021) as the moving average determined by the percentage difference between CAR_t and the target CAR^T (equation F.47). Mirroring the former, the base lending rate r_t^L decreases when the CAR_t increases (equation F.48).

$$CAR_t^{Bk} = \frac{E_t^{Bk}}{\chi^B L_t^B + \chi^G (L_t^G + L_t^{DF})} \tag{F.46}$$

$$r_t^V = r_{t-1}^V + \kappa_0 (CAR_t - CAR^T)/CAR^T \tag{F.47}$$

$$r_t^L = r_{t-1}^L - \kappa_0 (CAR_t - CAR^T)/CAR^T \tag{F.48}$$

Following Dunz et al. (2021) and Godley and Lavoie (2007) but contrary to Dafermos and Nikolaidi (2021), firms obtain all the loans they request from banks, but the latter adjust the cost of debt depending on the perceived risk of the transaction. This implicitly assumes that there is no credit rationing. This is consistent with the evidence in the literature that the WACC can be differentiated by technology (Kempa et al., 2021), although this is not yet the case for shipping (see the results in

Chapter 6). Furthermore, it is consistent with the findings of the literature (Akgül and Çetin, 2019) and interviews (see Chapter 6) with shipping lenders that the cost of debt directly impacts the profitability and investment decisions of shipowners, although short-term market variations are the main driver of investment decisions Akgül and Çetin (2019) and Alizadeh and Nomikos (2009). It is not assumed that an individual bank would always provide finance to a shipowner: interviews have shown that lenders, in fact, quite often refuse to provide loans to a shipowner. A higher cost of debt also represents a situation where a riskier borrower would need to go to alternative sources of lending with a higher WACC if the mainstream and cheap lenders refused to lend them all or part of the requested amount.

The remaining equations can be found in Section F.0.2.

F.0.3 Households

Let us now look at how households are modelled. Households consume goods depending on disposable income YD and savings V^H (equation F.49 , Godley and Lavoie (2007), GROWTH model). Their disposable income is equal to the income received as wages WB, the dividends from firms and banks (equation F.51), the interest from savings and from holding government bonds, and minus the household tax (equation F.50).

$$C_t^H = \sigma_1 YD_{t-1} + \sigma_2 V_{t-1}^H \tag{F.49}$$

$$YD_t = WB_t + Div_t + r_{t-1}^v V_{t-1}^H + r^{gov} GB_{t-1}^H - T_t^H \tag{F.50}$$

$$Div_t = Div_t^{Bk} + \sum_{s \in sectors} Div_t^s \tag{F.51}$$

$$V_t^H = V_{t-1}^H + YD_t^H - C_t^H - \Delta GB_t^H \tag{F.52}$$

F.0.4 Government

Let us now look at the role of the government in the land-shipping SFC model.

The government consumes C^{gov} (equation F.53) and invests I^{gov} (equation F.54) as a constant share of the tax received. However, the current model ignores the role of government expenditure in shipping, so public investments in shipping are assumed to be 0. This is because shipping capital only represents ships (not fuel production or bunkering, which are covered by the land sector), an area where public ownership has been limited. Public investments can be brown or green, in the same proportions as firms' investments (equation F.55). The total investments for each sector and colour are the sum of private and public investments (equation F.56). Each year, the government collects taxes from firms, banks, and households (equation F.57). Taxes on banks and firms are a share of profits before tax (equation F.60, equation F.59), and tax on households is a share of income (equation F.58). To finance its spending, when tax is not sufficient, government can also emit bonds (equation F.61, Godley and Lavoie (2007), GROWTH model) which are bought by banks and households in a fixed proportion (equation F.62, equation F.63).

$$C_t^{gov} = gov^C \times T_t \tag{F.53}$$

$$I_t^{gov,s} = \begin{cases} gov^I \times T_t, \text{ if } s = L, \\ 0, \text{ if } s = S \end{cases} \tag{F.54}$$

$$\begin{cases} I_t^{gov,L,G} = \beta_t^{s,L,G} I_t^{gov,L} \\ I_t^{gov,L,B} = (1 - \beta_t^{s,L,B}) I_t^{gov,L} \end{cases} \tag{F.55}$$

$$I_t^{s,c} = I_t^{gov,s,c} + I_t^{F,s,c} \tag{F.56}$$

$$T_{t+1} = T_t^H + T_t^{Bk} + \sum_{c \in colours, s \in sectors} T_t^{s,c} \tag{F.57}$$

$$T_{t+1}^H = \tau_H (WB_t + Div_t + r_{t-1}^v V_{t-1}^H + r^{gov} GB_{t-1}^H) \tag{F.58}$$

$$T_{t+1}^{s,c} = \tau_F (Y_t^{s,c} - WB_t^{s,c} - KB_t^{s,c}, -S_t^{s,c} - CT_t^{s,c} + subsidy_t^{s,c} + \Theta_t^{s,c} \times r_{t-1}^v V_{t-1}^F) \tag{F.59}$$

$$T_{t+1}^{Bk} = \tau^{Bk} \Big(\sum_{c \in colours, s \in sectors} r_{t-1}^{s,c} (L_t^{s,c} - NPL_t^{s,c}) + r^{gov} GB_{t-1}^{Bk} - r^A A_{t-1} - r_{t-1}^V (V_{t-1}^H + \sum_{s \in sectors} V_{t-1}^s) \Big) \tag{F.60}$$

$$GB_t = GB_{t-1} + C_t^{gov} + I_t^{gov} + r^{gov} GB_{t-1} - T_t - US_t - r^A A_{t-1} \tag{F.61}$$

$$GB_t^{Bk} = h_2 \times GB_t \tag{F.62}$$

$$GB_t^H = GB_t - GB_t^{Bk} \tag{F.63}$$

F.0.5 Central Bank

Finally, let us now look at the role of the Central Bank. The Central Bank provides liquidity to banks, but its role as quantitative easing is not modelled here. To meet reserve requirements, banks save a share h_1 of savings as high-powered money kept by the central bank (equation F.64, Godley and Lavoie (2007), GROWTH model). Advances are calculated as the residual amount after considering the budget constraint of banks (equation F.65,Godley and Lavoie, 2007, INSOUT model).

$$HPM_t = h_1 V_t \tag{F.64}$$

$$A_t = -V_t + GB_t^{Bk} + L_t + HPM_t - E_t^{Bk} \tag{F.65}$$

The stock flows and transaction flows of the model, described in the above equations, are detailed in the flow matrices in Table F.1. By construction, the sum of flows in the economy equals 0 (i.e. no money is ”lost” but is simply moved each year between the actors), and the wealth of the economy is equal to the amount of existing capital.

	Household	Firm		Government	Bank		Central Bank		
		Current	Capital		Current	Capital	Current	Capital	
Consumption	$-C_t^H$	$-C_{H,t}^H + C_t^{Gov}$		$-C_t^{Gov}$					0
Investment		$+I_t^F + I_t^{Gov}$	$-I_t^F$	$-I_t^{Gov}$					0
Wages	$+WB_t$	$-WB_t^F$							0
Profits	$+Div_t$	$-\Pi_t^F$	$+RE_t^F$		$-\Pi_t^{Bk}$	RE_t^{Bk}			0
Suppliers		$+S_t - S_t$							
Taxes	$-T_t^H$	$-T_t^F - US_t$		$T_t + US_t$	$-T_t^{Bk}$				0
Depreciation		$-\delta K_{t-1}^F$	$+\delta K_{t-1}^F$	$\delta K_t^{Gov} - \delta K_t^{Gov}$					
i loans		$\sum_{\substack{s\ in\ sectors \\ c,olours}} -r_{t-1}^{s,c} \times (L_{t-1}^{s,c} - NPL_{t-1}^{s,c})$			$\sum_{\substack{s\ in\ sectors \\ c,olours}} -r_{t-1}^{s,c} \times (L_{t-1}^{s,c} - NPL_{t-1}^{s,c})$				0
i deposits	$+r_{t-1}^V V_{t-1}^H$	$+r_{t-1}^V V_{t-1}^F$			$-r_{t-1}^V V_{t-1}$				0
i gov. bonds	$+r^{Gov} GBond_{t-1}^F$			$-r^{Gov} GBond_{t-1}$	$+r^{Gov} GBond_{t-1}^{Bk}$				0
i advances				$r_A A_{t-1}$	$-r_A A_{t-1}$				0
ΔLoans			$+\Delta L_t^F$			$-\Delta L_t^F$			0
ΔDeposits	$-\Delta V_t^H$		$-\Delta V_t^F$			$+\Delta V_t$			0
ΔGov bonds	$-\Delta GBond_t^F$			$+\Delta GBond_t$		$-\Delta GBond_t^F$			0
ΔHPM						$-\Delta \mathrm{HPM}$		$+\Delta \mathrm{HPM}$	0
Δadvances						$+\Delta \mathrm{A}$		$-\Delta \mathrm{A}$	0
Σ	0	0	0	0	0	0	0	0	0

Table F.1: Transaction and capital flows matrices

	Households	Firm	Government	Bank	Central Bank	$\sum$
Capital stock		$+K_t^F$	$+K_t^{Gov}$			K_t
Deposits	$+V_t^H$	$+V_t^F$		$-V_t$		0
Gov. bonds	$+GBond_t^H$		$-GBond_t$	$+GBond_t^{Bk}$		0
Loans		$-L_t^F$		$+L_t^F$		0
Advance				$-A_t$	A_t	0
HPM				$+HPM_t$	$-HPM_t$	0
$\sum$	NW_t^H	NW_t^F	NW_t^{Gov}	E_t^{Bk}	NW_t^{CB}	$NW_t^H + NW_t^F + NW_t^{Gov} + NW_t^{CB} + E_t^{Bk}$

Appendix G

GloTraM Bugs fixing

Previously, the time-charter rate for a year was determined by adding the maximum annual cost from the previous time step for any cohort with active vessels. For most years after 2018, this included the cost of the engine and tank. However, when no new vessel was built for a year, this meant that previous generations were used, whose annual cost only included operational cost and possibly retrofit costs. Their capital cost, estimated in GloTraM, is much lower, leading to wild swings in time-charter rates, leading to unstable speeds. The condition of having at least one active vessel is dropped, so that the capital cost of the new vessels is now always used. In addition, capital costs are included in the 2018 estimates.

HFO was manually added to the list of allowed fuels in 2018, otherwise the fleet was set to run on MDO.

The lock of Oil Tanker size 3 on 2-stroke was removed, as historical generations had a mix of 2- and 4-strokes.

Newbuilds are now checked for CII (before, only EEDI).

The fuel used in ECA for single-fuel ships is now the auxiliary fuel, to be consistent with dual-fuel ships.

The calculation of storage cost was corrected, as the previous version was picking up the wrong fuel energy densities.

Appendix H

Chapter 7's calibration

H.1 Calibration of the land-shipping SFC model

This section explains how the inputs used to calibrate and initialise the land-shipping SFC model were derived. The shipping sector is calibrated using various sources, which are detailed here. The variables calibrated include:

- The ratio of asset over shipping revenue
- The ratio of liabilities over assets
- Shipping output (revenue)
- The depreciation rate of capital
- Share of revenue spent into fuel cost, suppliers other than fuel cost providers and wages
- Average profit rate
- Share of capital dedicated to the transport of fossils
- The innovation and immitation factors underlying the choice of technology in new investments

Because information was mostly available for the three main shipping segments, namely bulk carriers, oil tankers, and containerships, the model was eventually calibrated onto those. Together, they represent roughly 60% of the fleet value, 81% of the total deadweight of the fleet in 2021 (Clarksons Research, 2021) and 61% of emissions (GloTraM output).

The financial data of shipowners was collected during the period 2000-2019 from Eikon-Refinitiv, which collects financial data reported by companies in their annual reports. The initial sample of shipowners is made up of 431 companies that have a stock exchange ticker in Clarksons WFR. However, many of those are large conglomerates where shipping activity might only constitute a small share of their activity. For these companies, the financial data and ratios may not reflect the actual shipping sector. To filter out those, only shipping companies classified under the NAIC "Deep Sea, Coastal, and Great Lakes Water Transportation" and "Scenic and Sightseeing Transportation, Water" were selected, i.e. 128 companies. The remaining sample covers 11% of the fleet capacity (in deadweight) but 1% of the number of shipowners. This is because it is biased toward large shipowners, with a third of the sample of shipowners owning at least 11 ships, versus 6% for all shipowners. This bias remains, although it is less important when looking at the fleet capacity, rather than the number of shipowners: 87% of the fleet capacity is owned by shipowners who own at least 21 ships in the sample, against 57% for shipowners altogether (see the graph on the left in Figure H.1). This means that our sample might be biased towards shipowners with larger borrowing capacity and, therefore, leverage. The breakdown by segment, however, is fairly consistent between the entire population of shipowners and the sample, with shipowners whose main ship type are bulk carriers, tankers, and containers according to Clarksons World Fleet Register (WFR) making the bulk of the sample (see the right graph in Figure H.1).

On certain shipping segments (e.g. bulk carriers, oil tankers), ships are typically operated on time-charter markets, where ships are leased out to charterers who bear most of the operating cost, in particular fuel costs. In others (e.g. containerships and ferries), ships are typically operating on the voyage-charter market, where ships are directly operated by the shipowner, who therefore pay for fuel and other voyage cost. Using revenue from shipowners operating mostly on time-charter markets might bias the results, as their revenue likely corresponds to shipping revenue

- voyage cost. To calibrate operating costs, the sample was further divided between shipowners operating mainly in time-charter markets and those operating mainly on voyage-charter markets. The former sub-sample contains shipowners whose primary ship type is oil and chemical tankers, bulk carriers, and general cargo. The latter contains shipowners whose primary ship type is containers, Cruise, Ro-Ro, ferries, or vehicle containers. The breakdown of reported revenue is plotted on the top graph of Figure H.2.

Data after 2020 were not collected because those years were not considered representative of long-term conditions due to the Covid epidemic, especially in the container sector. Each company has an observation for each year it reported financial data. The final sample contains 1577 observations from 2001 to 2019 covering a cumulative revenue of $62 billion. The increase in revenue observed on the lower graph is less due to the growth of the shipping output than to the increase in transparency of companies over the period since more shipowners would publicly report their financial data (see Figure H.2, bottom graph). The amount of observations has increased over time from 38 in 2001 to 117 companies reporting revenue in 2019.

More data on shipping price, activity, and fuel cost was collected from Clarksons SIN. Quarterly shipping spot rates were collected from Clarksons SIN on 134 routes that cover containers, bulk carriers, oil tanks, and chemical tankers. The former are expressed in $/tonne or $/TEU and were transformed into $/tonne-mile and $/TEU by dividing with the route distance collected from sea-distances.org, or where available, route distance provided by Clarksons methodology note[1]. The total annual shipping output was then obtained by multiplying the average shipping price ($/tonne) by the shipping activity provided by Clarksons SIN (expressed in billion tonne-miles or billion TEU-miles) on those segments from 2009 to 2023. It increased from $209 million in 2009 to to $277 million in 2019, with an average growth of 4% per year, but with a great variation every year (Figure H.3).

The Low-Sulphur Heavy Fuel Oil (LSHFO), Marine Diesel Oil (MDO) and LNG bunker prices were collected from Clarksons SIN and the average price was

[1]Where the port was not clear from the route name, the largest port in the region/country specified was taken.

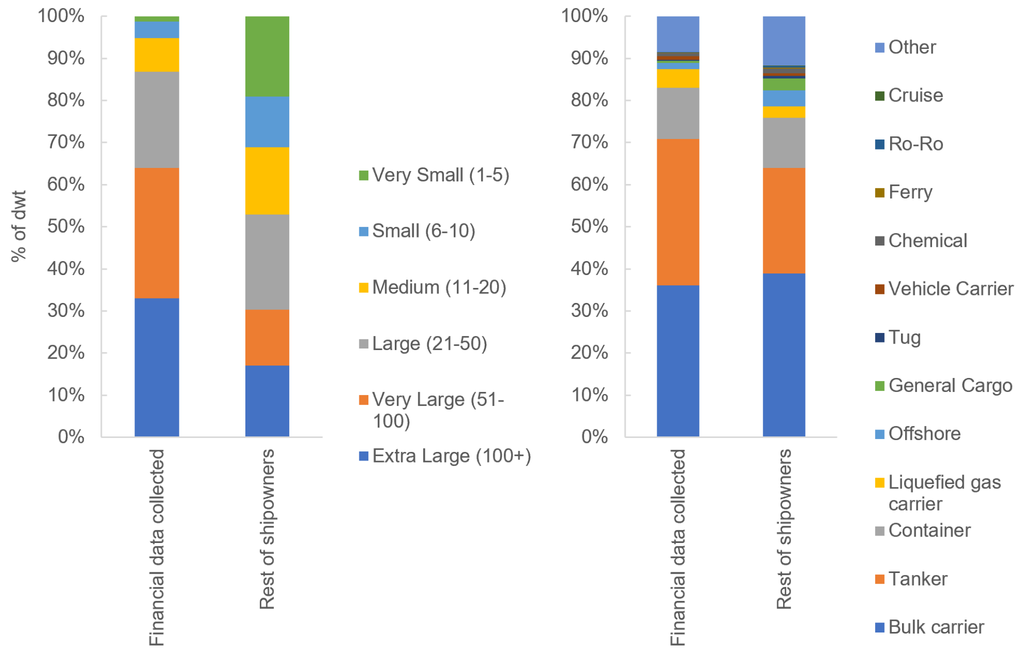


Figure H.1: Sample of companies whose financial data is used for calibration

(a) Numbers plotted correspond to the amount of deadweight owned by shipowners in the sample.

(b) Source: Clarksons WFR, collected on 2023-06-14

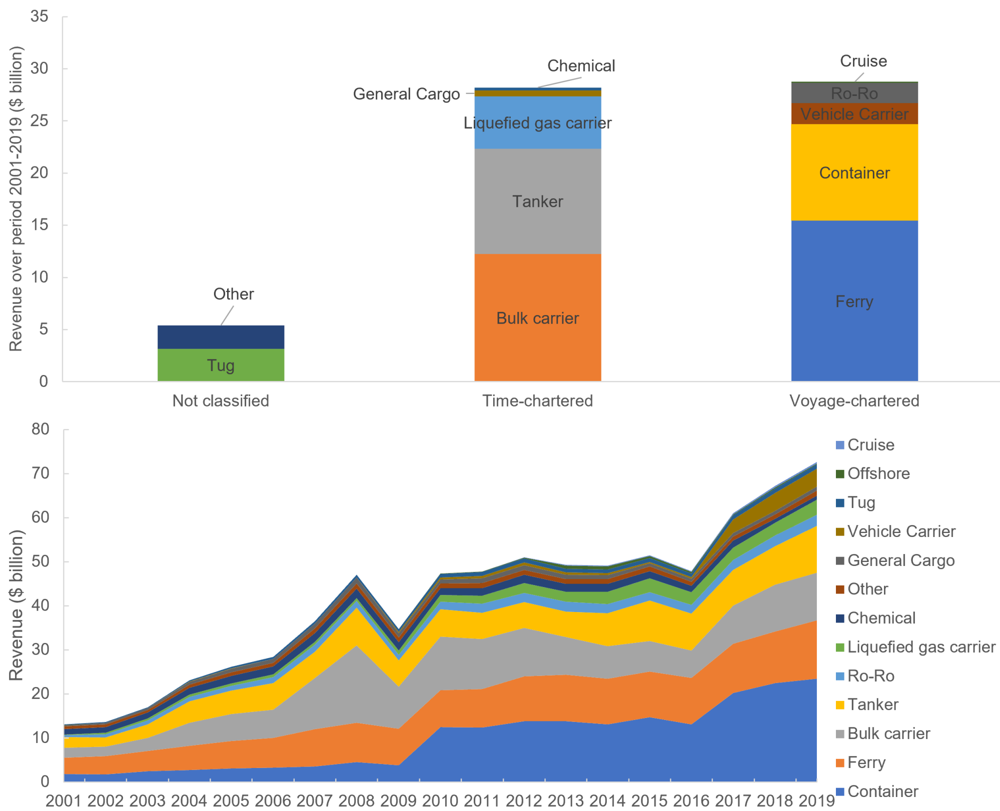


Figure H.2: Sample of financial reports used for calibration

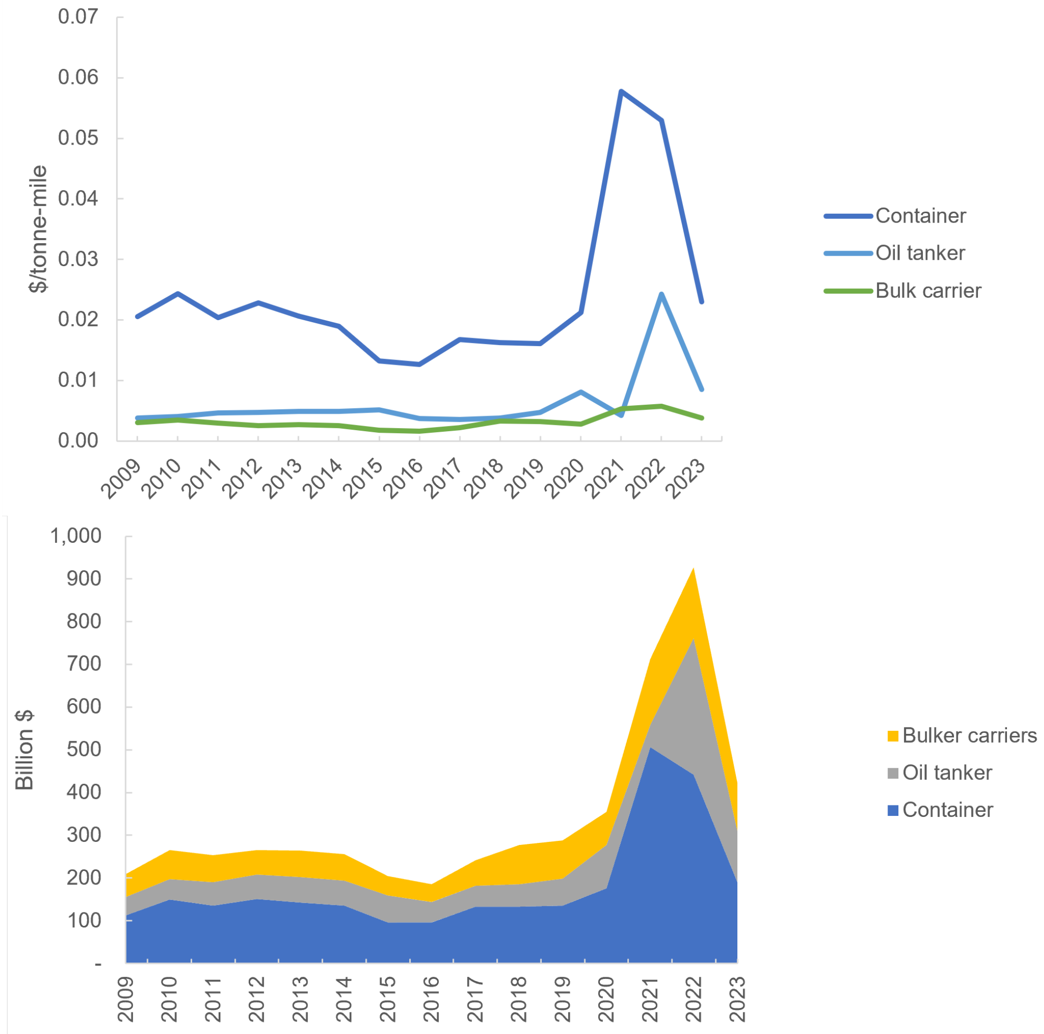


Figure H.3: Shipping price and output on for the shipping segments containers, oil tankers and bulk carriers

calculated in the 15 reported bunker ports. The annual fuel cost was obtained by multiplying the fuel prices by the total fuel consumption by segment from Faber et al. (2020) (top-down approach). On 69 bulk carrier routes, fuel consumption per route was also available from Clarkson methodology and allowed for a bottom-up estimate of fuel cost for each route (bottom-up approach). On these routes, the fuel price was used at the closest origin and destination bunker ports.

Those inputs allow one to calibrate the ratio of fuel cost over revenue. Three methods to estimate this ratio were used and compared:

1. Annual fuel cost estimated using the top-down approach was divided by the

total output per segment per year (top-down approach). The results for bulk carriers, containers, and oil tankers are plotted in Figure H.4. During the 2016-2019 period (excluding later years due to the impact of the Covid epidemic), the fuel cost amounted to 28% of the estimated revenue of the three sectors, with variation by segment and year.

2. For the bulk carriers routes where the bottom-up approach was possible, the share of cost was estimated more granularly by dividing the voyage fuel cost by the voyage revenue estimated from the spot rate on the route (bottom-up approach). From 2000 to 2019, the fuel cost represented an average of 35% of the revenue on these routes (35% during the period 2016-2019). Results are plotted in Figure H.5.

3. The ratio of fuel cost to revenue can be calculated from financials by differentiating between the two sub-samples, time-chartered dominated and voyage-chartered dominated. Simplifying the picture, revenue from time-chartered firms excludes fuel cost, while revenue from voyage-chartered firms includes it. Let us assume that the ratio of capital to revenue, including fuel cost, is the same. The ratio between fuel cost and revenue can then be calculated from the respective ratios of non-current assets (proxy for capital) and revenue in the two sub-samples (see equation H.1). During the period 2000-2019, the found ratio is 26%.

$$SFC/Y = 1-(Y-SFC)/Y \quad = 1-\frac{\frac{K}{Y}}{\frac{K}{SFC-Y}} = 1-\frac{\frac{NonCurrentAssets^{voy-chartered}}{Revenue^{voy-chartered}}}{\frac{NonCurrentAssets^{time-chartered}}{Revenue^{time-chartered}}} \tag{H.1}$$

Those three numbers validate fairly well with each other. It should be noted that with the top-down method, the ratio for bulk carriers is 33%, close to the estimate with the bottom-up method. The ratio used for calibration is 27%, because both the top-down and financial methods account for several shipping segments, while the bottom-up method only accounts for bulk carriers.

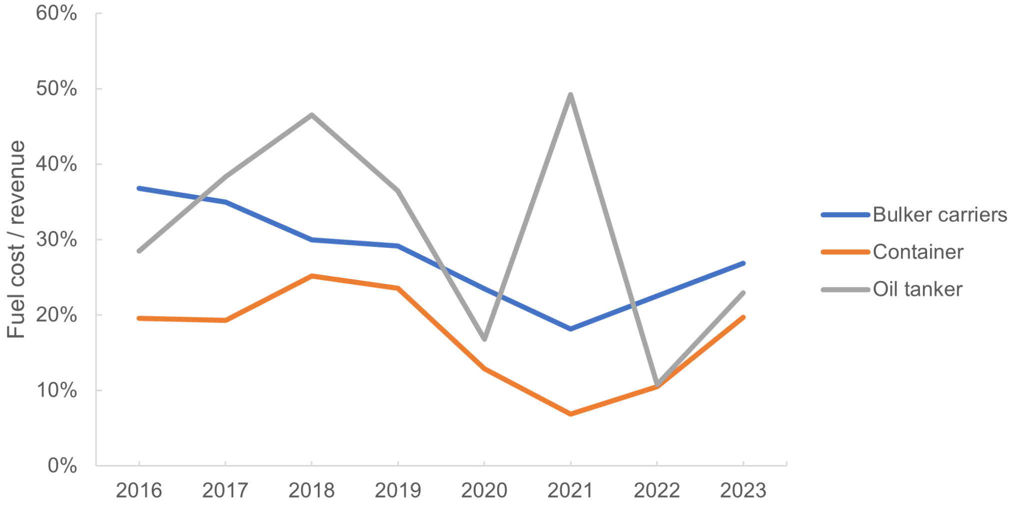


Figure H.4: Calibration of the ratio between fuel cost and revenue. Top down approach

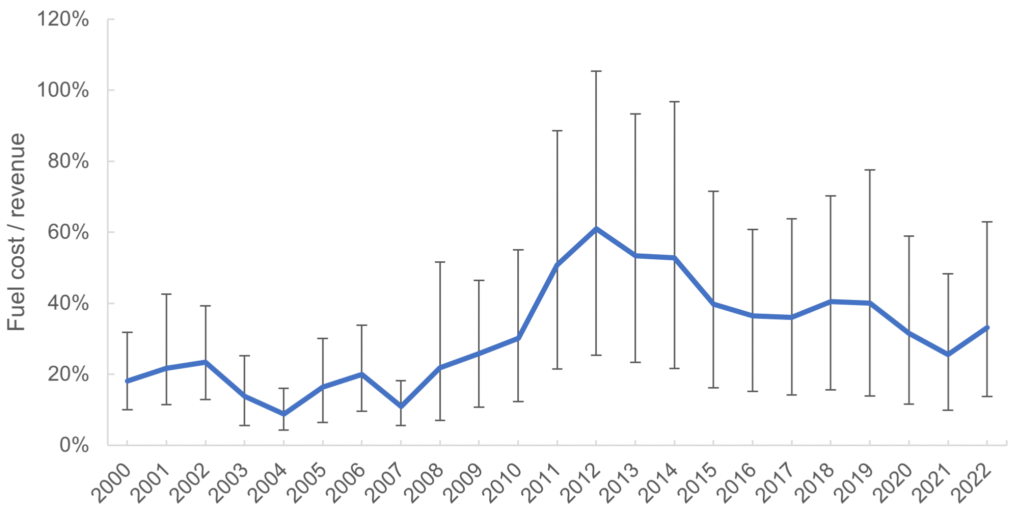


Figure H.5: Calibration of the ratio between fuel cost and revenue. Bottom-up approach

(a) Error bars correspond to the 10% and 90% percentiles of observations each year (route × date). They suggest a large variability of the ratio between fuel cost and revenue by route, potentially ship size and time.

The ratio of capital over output is calculated using three different approaches:

1. The ratio of non-current output and revenue over the period 2000-2019 from the shipowners' financial data. The ratios were calculated for each main ship type of the shipowners. This estimate is likely biased towards high value for the time-chartered segments, because fuel cost would be excluded from their revenue. Only the estimate for voyage-chartered dominated segments can be used directly for calibration.

2. The above ratio, corrected for fuel cost. For segments which are mostly time-chartered and for which the share of revenue spent as fuel could be calculated, the revenue is corrected using the average ratio of fuel over output $(SFC/Y)^s$ in this segment calculated above with the top-town method.

$$Y_t^{s,corrected} = Y_t^{s,reported} \frac{1}{1 - SFC/Y^s} \tag{H.2}$$

3. Dividing the depreciated fleet value in 2018, as estimated in GloTraM, by the shipping activity in 2018 (in tonne-miles) multiplied with the long-term average price of shipping per segment (average price over the 2000-2019 period) (equation H.3). In equation H.3, K^s denotes the value of the depreciated fleet on the shipping segment s, avP^s the average price of shipping on the segment s ($/tonne or $/TEU) and A^s the activity on the segment s (in tonne-miles or TEU-miles). The ratio could only be calculated for the segments for which the total output was estimated, i.e., bulk carriers, oil tankers, and containers.

$$K/Y^s = \frac{K^s_{2018}}{avP^s_{2000-2019} \times A^s_{2018}} \tag{H.3}$$

The results are plotted in Figure H.6. The results of approaches 1 and 2 validate fairly well. Once corrected for fuel cost, the time-chartered-dominated segments and the voyage-chartered-dominated segments do not appear to differ significantly. A ratio of 1.9 is obtained by only looking at voyage-chartered segments, and 1.7 by looking at all segments and correcting for fuel cost. Method 3 estimates are well above the financial ones for both bulk carriers and oil tankers. This could be because the valuation methodology overestimates the value of the fleet at least in 2018 (see 4.1.1.1). An employee of a shipowner also suggested that the book value of the ships is lower than their market value, which would result in a lower capital-to-output ratio. The ratio found using methods 2 is used (1.73), as it is more conservative in terms of fleet value and, therefore, potential for stranded assets than the ratio found in method 3. It concerns the sectors modelled in the SFC and sits between the various averages. Furthermore, it is consistent with the other inputs used for the models taken from valuation data, i.e. average profits, fuel and other costs, and average depreciation.

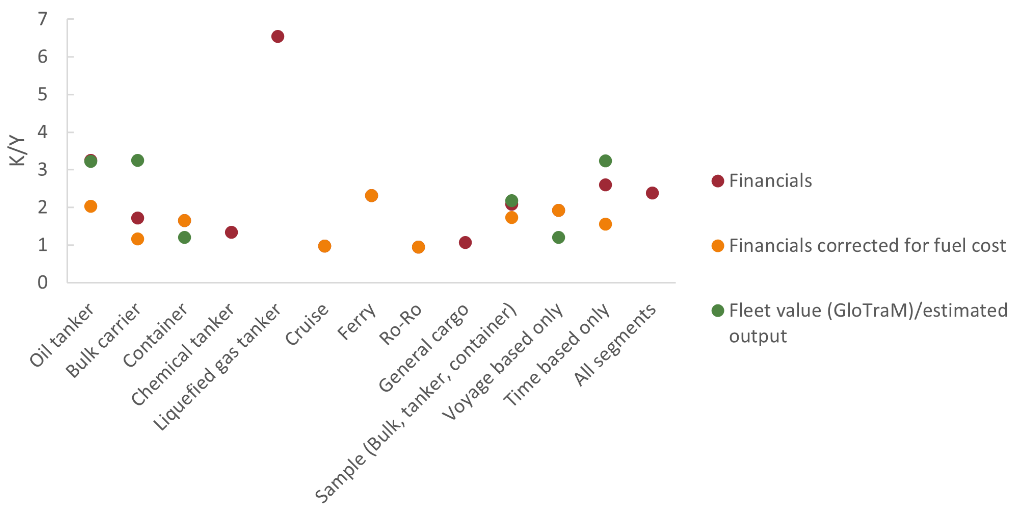


Figure H.6: Calibration of the ratio between capital and revenue

(a) Chemical tankers, liquefied gas tankers and general cargo ships are mostly time-chartered, but no estimate of average fuel cost on those segments is available so the financial ratio could not be corrected.

(b) No estimate of total output is available for cruise, ferries, Ro-Ro, General cargo and liquefied gas tankers, so the ratio of fleet value / estimated output was not computed.

$$P_t^r = Spot_t^r / distance \tag{H.4}$$

Finally, the innovation and imitation coefficients β^0 and β^1 were calibrated on the historical uptake of LNG-capable ships. It is assumed that newbuild investments represent on average 8% of the capital stock (*renewal*), which is the average annual new orders over the deadweight of the fleet since 2005 from Clarkson's SIN. The curve 'Predicted Beta' is calibrated to the observed monthly share of LNG-capable ships in the newly ordered deadweight (see Figure H.7). The resulting parameters are as follows: $\beta^0 = 0.02$, and $\beta^1 = 10$. Both of those values are uncertain as different technologies might adopt different values. For example, this calibration does not fit well with the recent ordering of methanol dual-fuel ships (see Figure H.8), which is faster than predicted. Therefore, the sensitivity of the results to the choice of β^0 and β^1 is tested in a sensitivity analysis.

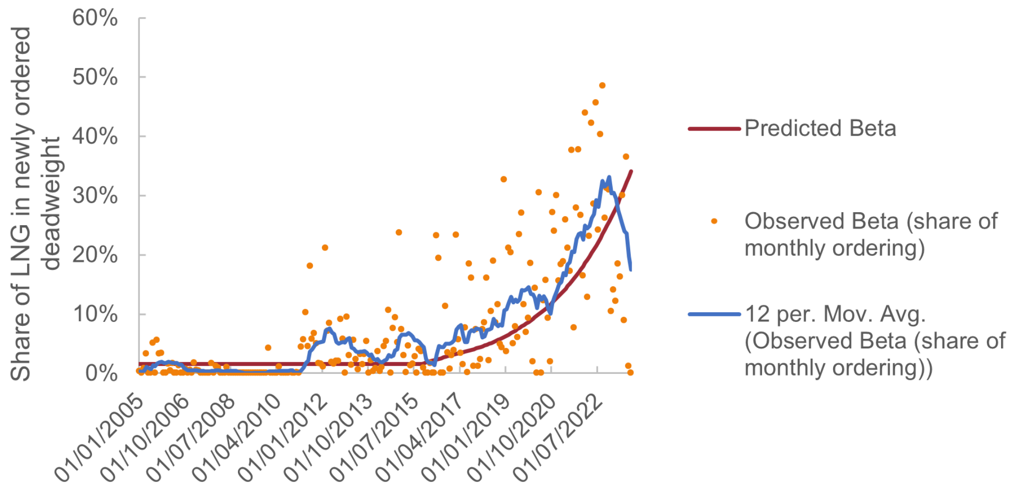


Figure H.7: Calibration of β^0 and β^1 onto orders of LNG-capable ships (data collected from Clarksons SIN
)

The inputs used to initialise the variables are listed in Table H.1. In practice, as in Dunz et al. (2021), the model is run for 10 time steps to let the different variables stabilise and create a history of past non-performing loans and profits that banks can use to decide for interest rates. Therefore, the variables are initialised at time -10 with the input value of Table H.1 and the results are re-scaled to the initial output ($85.9 trillion) at time 0 or 2018. The constant parameters used to calibrate the model are listed in Table H.2.

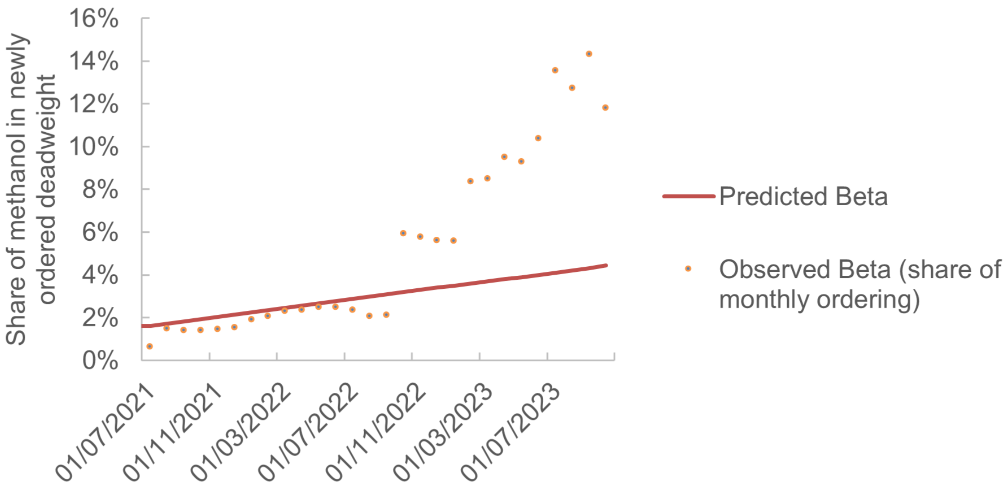


Figure H.8: Validation of β^0 and β^1 onto orders of methanol dual-fuel ships (data collected from Clarksons SIN

)

Table H.1: Initialisation of variables of the SFC model

Symbol	Value	Unit	Description	Method
μ_0^S	0.000		Use of green fuel by dual-fuel ships	
C_0^{gov}	14.603	Trillion $	Government expenditure	$= 0.17 \times Y_0$. 17% is the ratio of government expenditure to GDP as per Dafermos et al (2021)
C_0^H	47.043	Trillion $	Household consumption	$= Y_0 - C_0^{gov} - I_0$
CAR_0	0.080		Capital adequacy ratio	$= CAR^T$
E_0^{Bk}	5.566	Trillion $	Bank equity	$= CAR_0 \times L_0$
$E_0^{L,B}$	535.953	EJ	Land brown energy	$= E_0^L - E_0^{LG}$
$E_0^{L,G}$	46.605	EJ	Land green energy	$= \Theta_0^{L,G} \times E_0^L$
$E_0^{S,B}$	7.442	EJ	Shipping brown energy	$= E_0^L - E_0^{LG}$
$E_0^{S,G}$	0.000	EJ	Shipping green energy	In 2018, nearly all shipping is fossil-fuelled
E_0^L	582.558	EJ	Land energy	$= E_0 - E_0^S$
E_0^S	7.442	EJ	Shipping energy	GloTraM output
E_0	590.000	EJ	Total energy	As per Dafermos et al (2021)
ei_0^L	6.782	EJ/trillion $	Land energy intensity	$= E_0^L / Y_0^L$
ei_0^S	26.868	EJ/trillion $	Shipping energy intensity	$= E_0^S / Y_0^S$
em_0^L	0.067	Gigatonne CO_2/EJ	Emission intensity of land	$= Em_0^L / E_0^L$
Em_0^L	35.926	Gigatonne CO_2	Annual emissions of land	$= Em_0 - Em_0^S/(E_0^L - E_0^S)$
em_0^S	0.077	Gigatonne CO_2/EJ	Carbon intensity of shipping	$= Em_0^S / E_0^S$
Em_0^S	0.574	Gigatonne CO_2	Annual emissions of shipping	GloTraM output
Em_0	36.500	Gigatonne CO_2	Total emissions	As per Dafermos et al (2021)
g_0^{em}	0.000		Growth rate in carbon intensity of brown energy	
$g_0^{cc,B}$	0.005		Initial growth in technology cost of brown	As per Dafermos et al (2021)
$g_0^{cc,G}$	0.010		Initial annual reduction factor of the cost of green	As per Dafermos et al (2021)
g_0^{ei}	0.034		Initial annual reduction factor of the energy intensity	Compound annual growth rate of EEOI from 2008 to 2018 (Faber et al, 2020)
GB_0^{Bk}	13.302	Trillion $	Government bonds held by banks	$= GB_0 - GB_0^{Bk}$
GB_0^H	56.707	Trillion $	Government bonds held by households	As per Dafermos et al (2021)
GB_0	70.009	Trillion $	Government bonds	As per Dafermos et al (2021)
$I_0^{F,L,B}$	16.037	Trillion $	Private investment in brown land capital	$= K_0^{G,L,B} \times (\delta^L + 4\%)(1 - 28\%)$. 4% is the growth rate of output assumed, 28% is the proportion of public investment total investment

Symbol	Value	Unit	Description	Method
$I_0^{F,L,G}$	1.394	Trillion $	Private investment in green land capital	$= K_0^{G,L,G} \times (\delta^L + 4\%)(1 - 28\%)$. 4% is the growth rate of output assumed, 28% is the proportion of public investment total investment
$I_0^{F,S,B}$	0.032	Trillion $	Private investment in brown shipping capital	$= K_0^{G,S,B} \times (\delta^S + 4\%)\%)$. 4% is the growth rate of output assumed
$I_0^{F,S,DF}$	0.000	Trillion $	Private investment in dual-fuel shipping capital	$= K_0^{G,S,G} \times (\delta^S + 4\%)$. 4% is the growth rate of output assumed
$I_0^{F,L,DF}$	0.000	Trillion $	Private investment in green shipping capital	$= K_0^{G,S,DF} \times (\delta^S + 4\%)$. 4% is the growth rate of output assumed
$K_0^{gov,L}$	77.033	Trillion $	Land capital stock held by the government	$= 28\% \times K_0^L$. 28% is the proportion of public investment in total investment
$K_0^{gov,S}$	0.000	Trillion $	Shipping capital stock held by the government	In the absence of information on the share of ships financed by public investment, this is assumed to be 0.
$K_0^{L,B}$	253.106	Trillion $	Brown land capital stock	Calibrated to obtain a $\Theta^{L,G}$ of 11% (EIA, 2023, values in 2018)
$K_0^{L,G}$	22.009	Trillion $	Green land capital stock	$= K_0^L - K_0^{L,B}$
$K_0^{S,B}$	0.485	Trillion $	Brown shipping capital stock	$= K_0^S$
$K_0^{L,DF}$	0.000	Trillion $	DF shipping capital cost	
$K_0^{S,G}$	0.000	Trillion $	Green shipping capital stock	In 2018, nearly all the fleet is fossil-fuelled, but a small portion of green (0.0000001%) is kept to compute the cost of green
K_0^L	275.115	Trillion $	Land capital stock	$= K_0 - K_0^S$
K_0^S	0.485	Trillion $	Shipping capital stock	$= Y_0^S \times 1.75$. 1.75 is the ratio of non-current asset / revenue found by collecting financial data (see detailed calculations)
K_0	275.600	Trillion $	Capital stock	As per Dafermos et al (2021)
L_0^{LB}	63.783	Trillion $	Brown land loans	$= 0.35 \times K_0^{LB}$. 0.35 is the debt to GDP ratio of the non-financial sector from Dunz et al (2021)
L_0^{LG}	5.546	Trillion $	Green land loans	$= 0.35 \times K_0^{LG}$. 0.35 is the debt to GDP ratio of the non-financial sector from Dunz et al (2021)
L_0^{SB}	0.247	Trillion $	Brown shipping loans	$= 0.51 \times K_0^{SB}$. 0.51 corresponds to the non-current liabilities / non-current assets from financial data
L_0^{SG}	0.000	Trillion $	Green shipping loans	$= 0.51 \times K_0^{SG}$. 0.51 corresponds to the non-current liabilities / non-current assets from financial data
NPL_0^{LB}	2.360	Trillion $	Non-performing land loans	$= 0.037 \times L_0^{L,B}$. 3.7% is the default rate based on World Bank used in Dafermos et al (2021)
NPL_0^{LG}	0.205	Trillion $	Non-performing land loans	$= 0.037 \times L_0^{L,G}$. 3.7% is the default rate based on World Bank used in Dafermos et al (2021)
NPL_0^{SB}	0.009	Trillion $	Non-performing shipping loans	$= 0.0347 \times L_0^{S,B}$. 3.47% is the average default rate based on Kavussanos et al (2016)
NPL_0^{SG}	0.000	Trillion $	Non-performing shipping loans	$= 0.0347 \times L_0^{S,G}$. 3.47% is the average default rate based on Kavussanos et al (2016)
r_0^L	0.080	% per year	Lending rate	
r_0^V	0.025	% per year	Interest rate on deposits	
$cc_0^{L,B}$	0.301	Trillion $/EJ/yr	Capital cost of brown land technology	$= (1 - \Theta_0^G) \times u_0^L \times 0.47$; 0.47 is the ratio of energy over output from Dafermos et al (2021)
$cc_0^{L,G}$	0.213	Trillion $/EJ/yr	Capital cost of green land technology	$= 0.71 \times cc_0^{L,B}$; 0.71 is the ratio of the average cost of renewables to conventional electricity generation from IRENA (2018)
cc_0^{SB}	0.046	Trillion $/(EJ/yr)	Capital cost of brown shipping	$= K_0^S \times u_0^S / E_0^S$

Symbol	Value	Unit	Description	Method
cc_0^{SG}	0.059	Trillion $/(EJ/yr)	Capital cost of green shipping	$= cc_0^{SB} \times 1.3$. 1.3 is the ratio between the cost of ammonia fuelled ships and LSHFO-fuelled ships, and is an output of GloTraM (note that a factor 1.11 is used for methanol)
cc_0^{SDF}	0.059	Trillion $/(EJ/yr)	Capital cost of dual-fuel shipping	$= cc_0^{SG}$
u_0^L	0.700	%	Land utilisation	
u_0^S	0.700	%	Shipping utilisation	
V_0^{FL}	6.977	Trillion $	Land firms deposits	$= V_0^F - V_0^{FS}$
V_0^{FS}	0.023	Trillion $	Shipping firms deposits	$= V_0^F \times Y_0^S / Y_0$
V_0^F	7.000	Trillion $	Firms deposits	$= V_0 - V_0^H$
V_0^H	63.000	Trillion $	Household deposits	As per Dafermos et al (2021)
V_0	70.000	Trillion $	Deposits	As per Dafermos et al (2021)
Y_0^L	85.900	Trillion $	Land output	$= L_0$
Y_0^S	0.277	Trillion $	Shipping output	Long term price of shipping × ($/tonne-mile) shipping activity in 2018 for oil tankers, bulk carriers and containers. See detailed calculations.
Y_0	85.900	Trillion $	Output	As per Dafermos et al (2021)

Table H.2: Input of constant parameters of the SFC model

Symbol	Value	Unit	Description	Method
α_0	0.19		Parameters in the investment function	As per Dafermos et al (2021)
α_1	2.3		Parameters in the investment function	Calibrated to obtain 70% utilisation
α_2	1.030		Parameters in the investment function	As per Dafermos et al (2021)
χ^{gov}	0.000		Risk weight of the government bonds	As per Dunz et al (2021)
δ^L	0.048		Land depreciation rate	Kept as in Dafermos et al (2021)
δ^S	0.051		Shipping depreciation rate	Calculated using firms' financial data of shipping firms: Depreciation Depletion & Amortization/Non-current assets
ϵ^L	0.013	$/EJ	Productivity of land capital	Calibrated to the initial conditions. $= \frac{Y_0^L}{u_0^L(\frac{K_0^{LB}}{tc_0^{LB}}+\frac{K_0^{LG}}{tc_0^{LG}})}$
ϵ^S	0.037	$/(EJ/yr)	Productivity of shipping capital	Calibrated to the initial conditions. $= \frac{Y_0^S}{u_0^L(\frac{K_0^{SB}}{tc_0^{SB}}+\frac{K_0^{SG}}{tc_0^{SG}})}$
κ_0	0.100		Impact of the capital adequacy ratio on the basis rates of savings and lending	As per Dunz et al (2021)
κ_1	0.100		Impact of credit worthiness on the interest rate	As per Dunz et al (2021). Subject to sensitivity analysis.
κ_2	0.050		Impact of the differentiated capital weight on interest rates	As per Dunz et al (2021). Subject to sensitivity analysis.
$\lambda^{S,B}$	0.013		Parameter linking the cost of land brown energy to the share of revenue spent as brown fuel cost in the shipping sector	Calibrated to the initial conditions. $= \frac{0.27}{cc_0^{L,B}\times ei_0^S\times P_0^S}$. 0.27 is the initial share of revenue shared as fuel cost and is calculated using fuel cost, shipping activity and shipping spot rates over 2009 - 2019. See detailed calculations
$\lambda^{S,G}$	0.045		Parameter linking the cost of land green energy to the share of revenue spent as green fuel cost in the shipping sector	Calibrated to the initial conditions. $= \frac{0.27\times 3.56}{cc_0^{L,G}\times ei_0^S\times P_0^S}$. 0.27 is the initial share of revenue shared as fuel cost and is calculated using fuel cost, shipping activity and shipping spot rates over 2009 - 2019. See detailed calculations. 3.56 is the ratio of ammnoia fuel cost over LSHFO/MDO mix fuel cost in 2018 in GloTraM (a factor 5.44 used for methanol)
$\lambda^{L,B}$	0		Parameter linking the cost of land brown energy to the share of revenue spent as brown fuel cost in the land sector	0 because fuel cost for land sector is not separately calculated (the sector includes fuel production)
$\lambda^{L,G}$	0		Parameter linking the cost of land green energy to the share of revenue spent as green fuel cost in the land sector	0 because fuel cost for land sector is not separately calculated (the sector includes fuel production)
$\lambda^{S,Oth}$	0.460		Share of revenue spent to suppliers other than fuel cost	Calculated using firms' financial data of shipping firms. See detailed calculations
ω^L	0.520	% revenue	Share of land firms' revenue spent as wages	Labour costs/Value added in 2018 in OECD countries. OECD STAN database.
ω^S	0.110	% revenue	Share of shipping firms' revenue spent as wages	Calculated using firms' financial data of shipping firms: Labor & Related Expenses / Total revenue in voyage-based shipping segments
π^{Bk}	0.400	% profits	Share of profits distributed as dividends (Banking sector)	Roughly average payout ratio from S&P Market intellingence (2021, 2022)
π^L	0.500	% profits	Share of profits distributed as dividends (land sector)	Roughly average payout ratio from Financial Times (2018)
π^S	0.500	% profits	Share of profits distributed as dividends (shipping sector)	Roughly average payout ratio from Financial Times (2018)
ρ^L	0.100	% per year	Land loan repayment rate	As per Dafermos et al (2021)
ρ^S	0.080	% per year	Shipping loan repayment rate	Calibrated onto the interviews and to obtain a debt to capital ratio around 50% (financials data for shipping firms)
σ_1	0.900		Households propensity to consume out of income	Calibrated to obtain 3% GDP growth / year

Symbol	Value	Unit	Description	Method
σ_2	0.050		Households propensity to consume out of savings	As per Dafermos et al (2021), which is based on an econometric estimations over the period 1995-2018
τ^{Bk}	0.150	% profits	Tax rate on banks profits	As per Dafermos et al (2021)
τ^{F}	0.150	% profits	Tax rate on firms profits	As per Dafermos et al (2021)
τ^{H}	0.230	% profits	Tax rate on households	As per Dafermos et al (2021)
ζ^{em}	0		Rate of decrease in growth rate of emission intensity	
$\zeta^{cc,B}$	0.050		Rate of decrease in growth rate of the brown technology cost	As per Dafermos et al (2021)
$\zeta^{cc,G}$	0.100		Rate of decrease in growth rate of the green technology cost	As per Dafermos et al (2021)
a	7	years	Number of past years observed by banks to decide on the interest rate	Selected among a range of value. Subject to sensitivity analysis
b	7	years	Number of future years projected by banks to decide on the interest rate	Average shipping loan maturity. Subsject to sensitivity analysis
CAR^T	0.080		Target Capital Adequacy Ratio	Based on Basel III regulatory framework
CE	0.150	% per year	Cost of equity	Selected among a reasonable range of values
def^0	4.410		Parameter in the non-performing loan ratio	As per Dafermos et al (2021)
def_1	7.830		Parameter in the non-performing loan ratio	As per Dafermos et al (2021)
def_2	8.290		Parameter in the non-performing loan ratio	Calculated so that the initial non-performing loan ratio is 3.47% (Kavussanos, 2016)
def^{max}	0.200		Maximum non-performing loan ratio	As per Dafermos et al (2021)
$ei^{min,L}$	2.000	EJ / trillion USD	Minimum energy intensity of the land sector	As per Dafermos et al (2021)
$ei^{min,S}$	8.203	EJ / trillion USD	Minimum energy intensity of the shipping sector	$= (1 - 69.47\%) \times ei^{initial}$. 69.47% is the gain in energy efficiency found in Schwarz et al (2020); $ei^{initial}$ was calculated as E_0^S / Y_0^S
fleet_dedicated_to_fossil	0.390	% of capital	Share of shipping capital dedicated to transporting fossil fuels	Calculated using the estimated value of the containers, bulk carriers and oil tankers fleet in GloTraM and assuming that 19% of bulk carrier fleet is dedicated to coal transportation (from IMO MEPC, 2020)
gov^C	0.850		Share of taxes spent as public spending	Calibrated so that the share of public spending in total consumption remains constant
gov^I	0.300		Share of taxes spent as public investment	Calibrated so that the share of public capital in total capital remains constant
h_1	0.180		Banks reserves (high-powered money) to deposit ratio	As per Dafermos et al (2021), itself based on World Bank
h_2	0.190		Share of government bonds held by banks	$= GB_0^{Bk} / GB_0$
l_0	0.650		Share of investment financed by loans	Aligned with Mitroussi et al (2016), Kavussanos et al (2016) and Schinas et al (2018)
l_1	0.150		Additional leverage when a loan is secured by a public body	To obtain a leverage of 80%, as in Schinas et al (2018)
$markup^S$	0.1		Mark-up above operating costs	As per Dunz et al (2021)
$markup^L$	0.3		Mark-up above operating costs	Broadly in line with Dunz et al (2021), after internalizing the tax rate and with Deutsche Bank (2017)
MaxSubsidyShareCost	0.2		Maximum share of green production cost covered by subsidies	Calibrated so that green shipping profits are around 7% of revenue after the implementation of a carbon tax
$mincc^L$	0.689		Minimum technology cost of land, as share of initial cost	1-31%; 31% is the maximum reduction in the cost of ammonia possible in GloTraM (46% with methanol)

Symbol	Value	Unit	Description	Method
$mincc^S$	0.870		Minimum technology cost of shipping, as share of initial cost	1-13%. 13% is the reduction in the capital cost of ammonia newbuild found in GloTraM (0% reduction for methanol)
$profile^L$	20.000	years	Discount period used for the calculation of land levelised cost	$= \frac{1}{\delta^L}$
$profile^S$	20.000	years	Discount period used for the calculation of levelised cost	$= \frac{1}{\delta^S}$
ψ^{SG}	0.537	% revenue	Expected increase in green profits after the implementation of a carbon tax	Calibrated onto the results in the inert scenario (0.92 with methanol)
ψ^{SB}	-0.335	% revenue	Expected increase in brown profits after the implementation of a carbon tax	Calibrated onto the results in the inert scenario (-0.07 with methanol)
ψ^{SDF}	0.035	% revenue	Expected increase in green profits after the implementation of a carbon tax	Calibrated onto the results in the inert scenario (0.016 with methanol)
r^A	0.030	% per year	Interest rate on advances	As per Dafermos et al (2021)
r^{gov}	0.025	% per year	Interest rate on government bonds	As per Dafermos et al (2021)
sh_1	0.0020		Parameter linking land output to shipping output	Calibrated to generation the initial scenario. $= (1 - fleet\_dedicated\_fossils) \times Y_0^S / Y_0$
sh_2	0.0014		Parameter linking brown output to shipping output	Calibrated to generation the initial scenario. $fleet\_dedicated\_fossils \times Y_0^S / Y_0 / (1 - Y_0^G / Y_0)$

H.2 Calibration of GloTraM

This section provides some information on the calibration of GloTraM. Most of the GloTraM inputs were used as such and were not reviewed. However, assumptions on the capital expenditure of the engine and storage were reviewed against the literature, as they are critical to the estimation of stranded assets.

The cost of a newbuild engine is divided between the energy conversion cost (including the main engine, the auxiliary engine and the pipes), which varies by fuel, and the power distribution cost, which varies depending on the type of engine (internal combustion engine versus hybrid), but not depending on the fuel. The former was already included in GloTraM under the same ”engine cost” and is therefore simply reviewed. The latter was not previously included in GloTraM and was added according to the MARIN database input (European Sustainable Shipping Forum, n.d.: \$343/kW for ICE, \$1028/kW for hybrid). Energy conversion costs are compared with existing literature (European Sustainable Shipping Forum, n.d.; Kim et al., 2020; Lagemann et al., 2023; Laursen et al., 2022) in Figure H.9. LNG, HFO and methanol large engine cost validate fairly well with the literature, so they were kept as initial. Data for the cost of methanol small engines are only available with the MARIN database and are surprisingly high, so the initial value was also kept. However, the hydrogen and ammonia energy conversion costs of GloTraM were lower than the average from the literature, so the cost was updated to the average from the literature.

Tank costs were also reviewed against the literature. In the initial version of GloTraM, the cost of the HFO tank is not included, and other costs of the fuel tank correspond to the additional cost compared to LSHFO. When adding to all fuel tank costs the fuel tank cost of LSHFO from the MARIN database (European Sustainable Shipping Forum, n.d.), the tank cost of GloTraM validates well with the reviewed literature (Figure H.10), so it was kept as such. Dual-fuel ships have an LSHFO tank and an alternative fuel tank, apart from methanol dual-fuel ships, which only have one methanol tank that can contain both LSHFO and methanol, as per Maersk Mc-Kinney Møller Center for Zero Carbon Shipping (2022a).

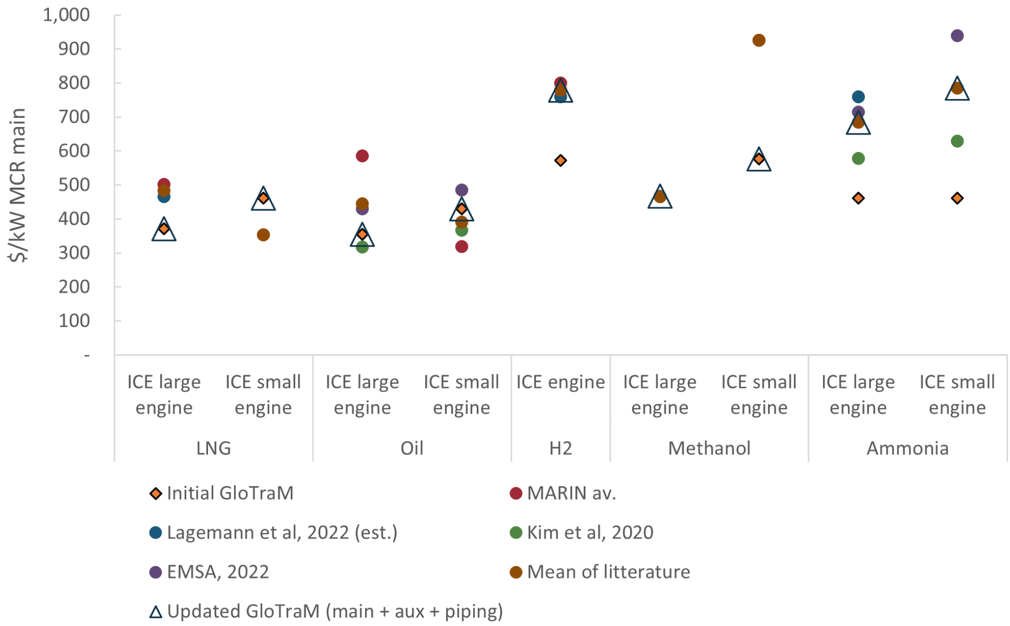


Figure H.9: Calibration of the newbuild energy conversion cost (main and auxiliary engines, piping)

(a) The values are expressed in \$/kW of main engine and include main engine cost, engine cost and piping (but no after-treatment device). The denominator is main engine MCR because some studies did not provide their assumptions for the sizing of the auxiliary engines. Those values were later converted to \$/kW of one engine only by assuming that the power of the auxiliary engines equals 5% of the power of the main engine. The piping cost from Lagemann et al. (2023) was added onto the Laursen et al. (2022) cost for comparability

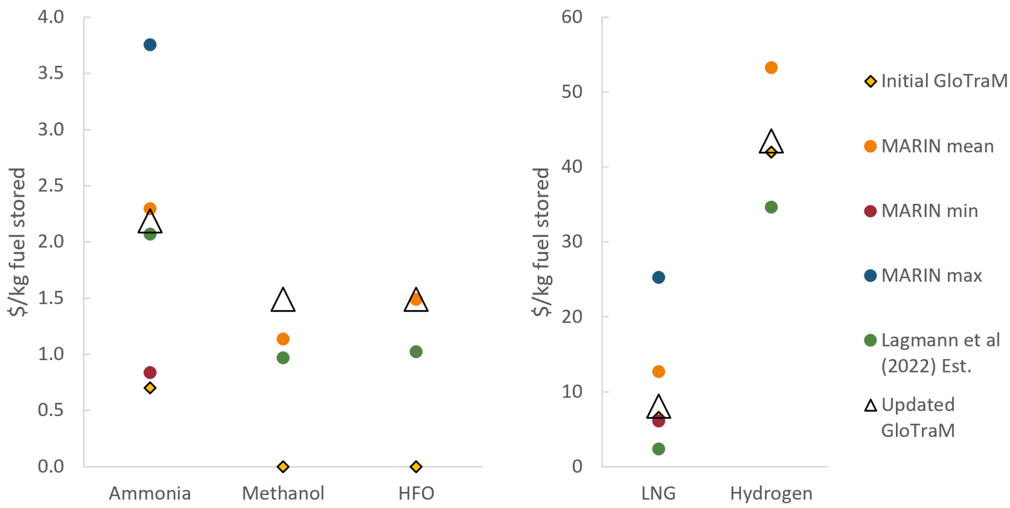


Figure H.10: Calibration of the tank cost

(a) LNG and hydrogen are plotted on a different scale for readability

The cost of retrofitting to an alternative fuel is equal to the newbuild cost of the engine, the shipyard, and the lost income of Lagemann et al. (2022) and the cost of adding a tank for the alternative fuel. The size of the engine is kept as the initial, and the size of the new tank is scaled for the difference in the energy density of the fuels. This assumes that all engines and ships can retrofit to an alternative fuel and that the cost of doing so is the same across initial engine and ship type. As a sensitivity, stranded capital was also calculated if retrofit costs are the same as in Lagemann et al. (2023).

Most of the other inputs to GloTraM were kept as per the previous version. However, the interest input for capital expenditure and the change input are summarised in Table H.3.

Table H.3: GloTraM input

Cost type	Unit	Engine/fuel type	Value
Newbuild engine investment cost (before learning effects) (C_e)	$/kW	2 stroke ICE LSHFO	677.6
	$/kW	4 stroke ICE LSHFO	752.6
	$/kW	DF LNG	692.6
	$/kW	4 stroke DF LNG	782.6
	$/kW	DF Methanol	782.6
	$/kW	4-stroke DF Methanol	892.6
	$/kW	DF Ammonia	988.0
	$/kW	4 stroke DF Ammonia	1087.8
	$/kW	4 stroke Hydrogen	1083.3
Engine retrofit cost (before learning effects) (C_e)	$/kW	DF LNG	678.7
	$/kW	4 stroke DF LNG	768.7
	$/kW	DF Methanol	768.7
	$/kW	4-stroke DF Methanol	878.7
	$/kW	DF Ammonia	974.1
	$/kW	4 stroke DF Ammonia	1073.9
	$/kW	4 stroke Hydrogen	1069.5
Fuel tank investment cost (C_s)	$/tonne fuel	LSHFO/MDO	1.5
	$/tonne fuel	Methanol	1.5
	$/tonne fuel	Ammonia	2.2
	$/tonne fuel	LNG	8.1
	$/tonne fuel	Hydrogen	43.5
Fuel tank retrofit cost (C_s)	$/tonne fuel	Methanol	0.9
	$/tonne fuel	Ammonia	2.2
	$/tonne fuel	LNG	8.1
	$/tonne fuel	Hydrogen	43.5
Hull investment cost (C_h)	Bulk carrier	$/dwt (a)	136.8
	Bulk carrier	intercept (b)	7108454.4
	Container	$/dwt (a)	113.3
	Container	intercept (b)	10411027.5
	Oil tanker	$/dwt (a)	102.0
	Oil tanker	intercept (b)	25612440.4
Cost of equity (d_e)	% per year		15%
Standard cost of debt (d_d)	% per year		8%
Tax rate (τ)	% profits before tax		15%
Debt weight in the absence of policy support ($leverage$)			0.65
Debt weight with guarantees			0.8
Profit assessment period	years		4.0
Discount rate of future profits	% per year		10%
Pay-off period for hull machinery and tank	years		15.0
Pay-off period for energy efficiency devices	years		3.0
Ship scrapping age	years		30.0

Appendix I

Chapter 7’s additional figures

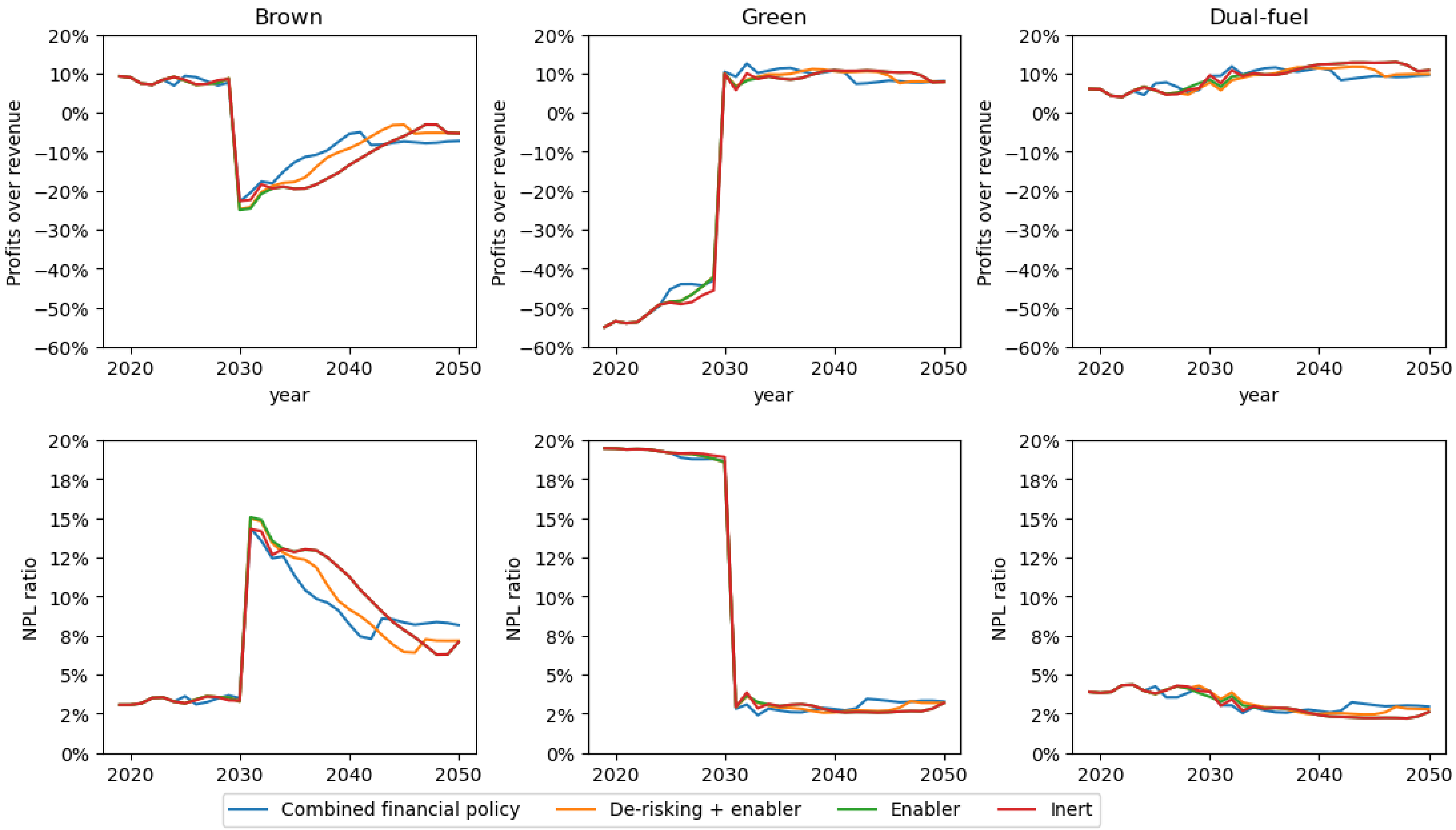


Figure I.1: Shipowners profits and non-performing loan ratio, as modelled by the land-shipping SFC model

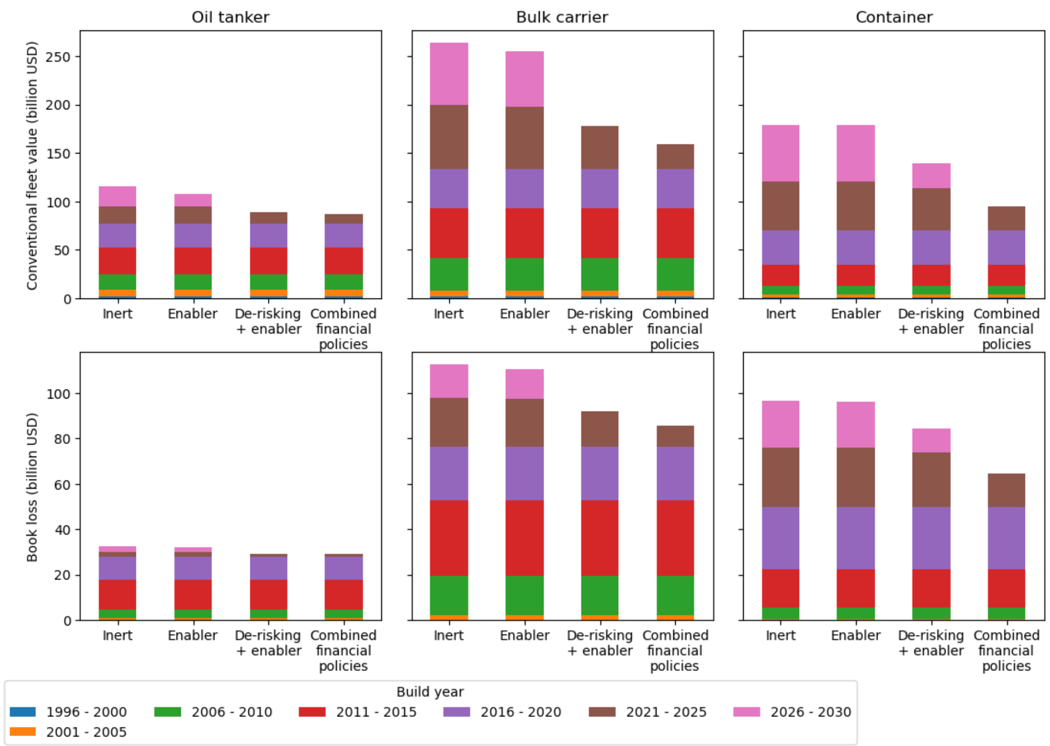


Figure I.2: Conventional fleet value and book loss by generation, as modelled by GloTraM

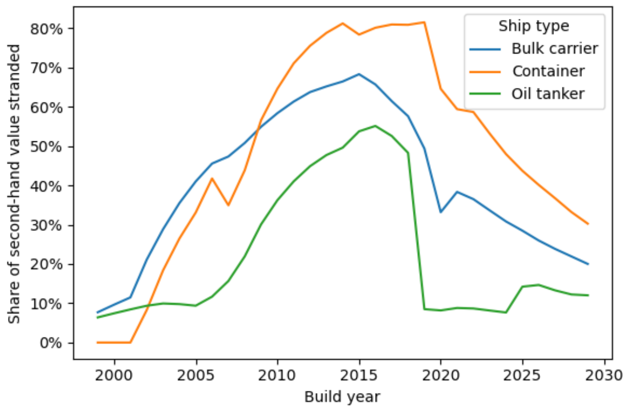


Figure I.3: Share of second-hand value stranded by generation, as modelled by GloTraM

(a) The surprising drop in the share of value stranded of oil tankers between 2019 and 2024 is due to a change in size composition in the generations built between those years. Large oil tankers (sizes 4 to 8) have a shorter lifespan ($\leq$ 25 years) than small tankers (sizes 1 to 3, $>$30 years). Large tankers built between 2019 and 2024 are near the peak of stranded share in 2030, while those built between 2019 and 2024 have not depreciated much; so that the retrofit cost represents a smaller share of their second-hand value. Between 2019 and 2024, there are fewer large ships built by GloTraM so that the share of stranded assets in second-hand value drops.

Appendix J

Chapter 7’s additional scenarios

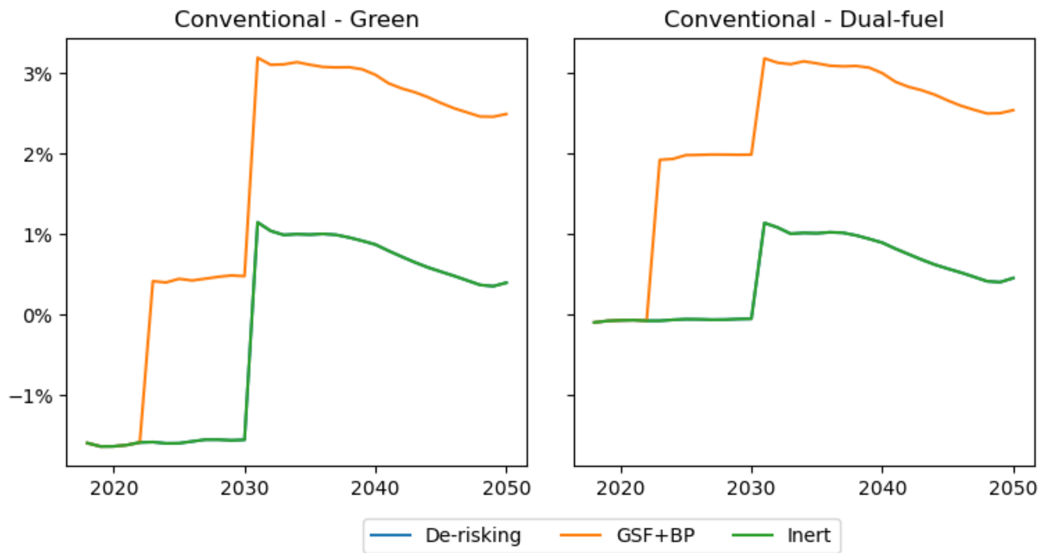


Figure J.1: Difference in interest rates between shipping loans

(a) The Y-axis represents the difference between the interest rates of conventional ships and green ships (using green fuel only, left graph), and conventional ships and dual-fuel ships (using whichever fuel is cheaper, right graph). Read: in 2020, conventional ships can access loans with interest rates 1 percentage point *lower* than green ships.

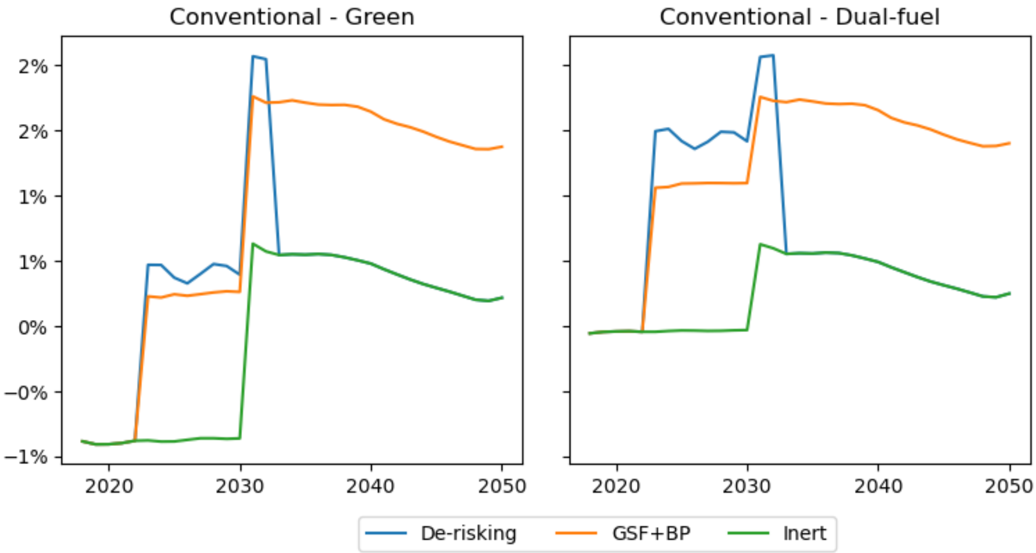


Figure J.2: Difference in WACC between green and conventional ships

(a) The Y-axis represents the difference between the WACC of conventional ships and green ships (using green fuel only, left graph), and conventional ships and dual-fuel ships (using whichever fuel is cheaper, right graph).

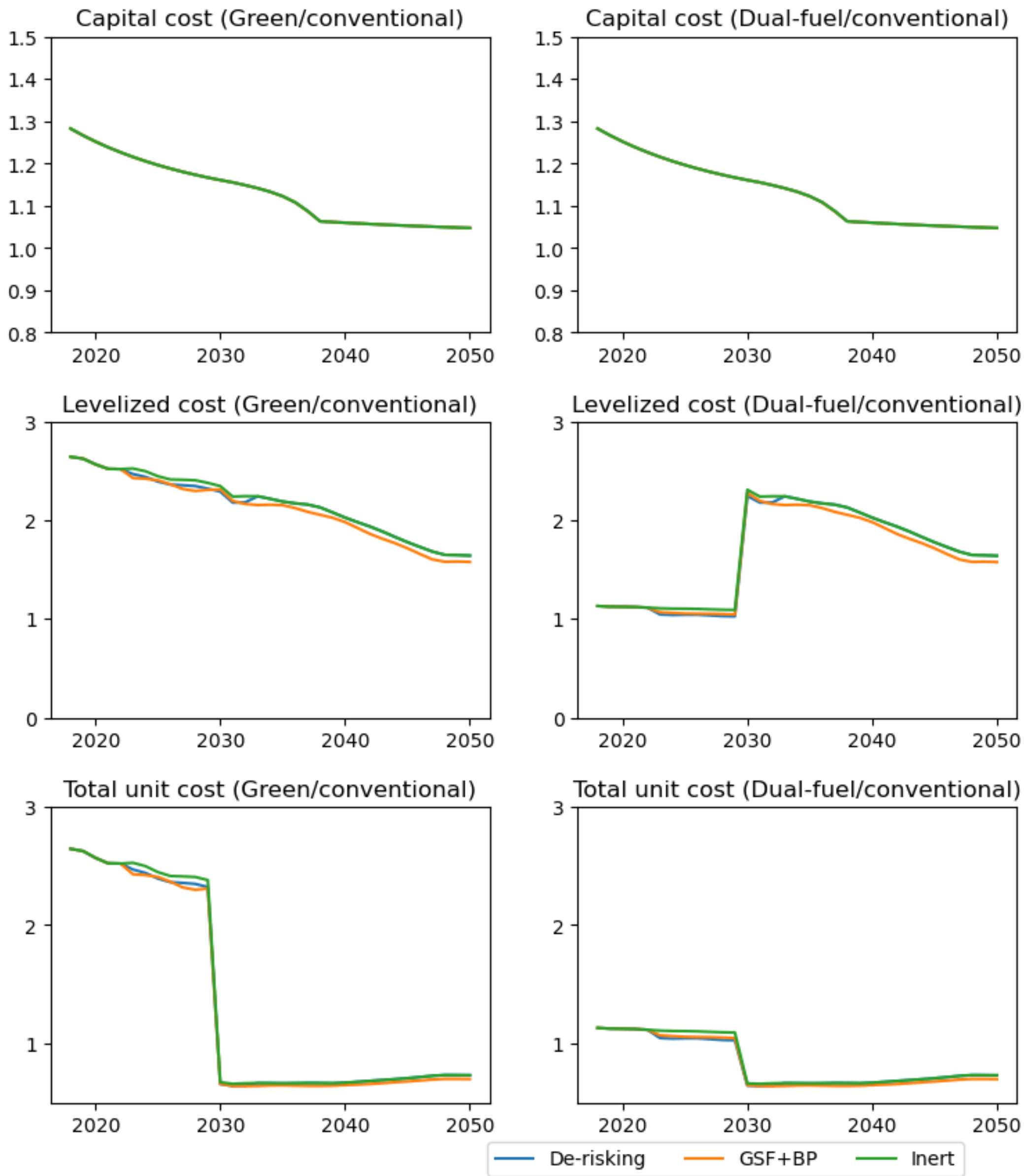


Figure J.3: Relative cost of shipping technologies

(a) The Y-axis of the left graph corresponds to the ratio of green shipping cost over conventional shipping cost. The right graphs corresponds to the ratio of dual-fuel shipping cost over conventional shipping cost. For example, the capital cost of green is originally 1.3 times larger than the one of conventional (top left graph). Capital cost only includes the capital cost of the initial engine. Levelized cost includes both capital and operational cost but excludes carbon price. Total unit cost further includes the carbon price (see calculation details in Appendix F.0.1)

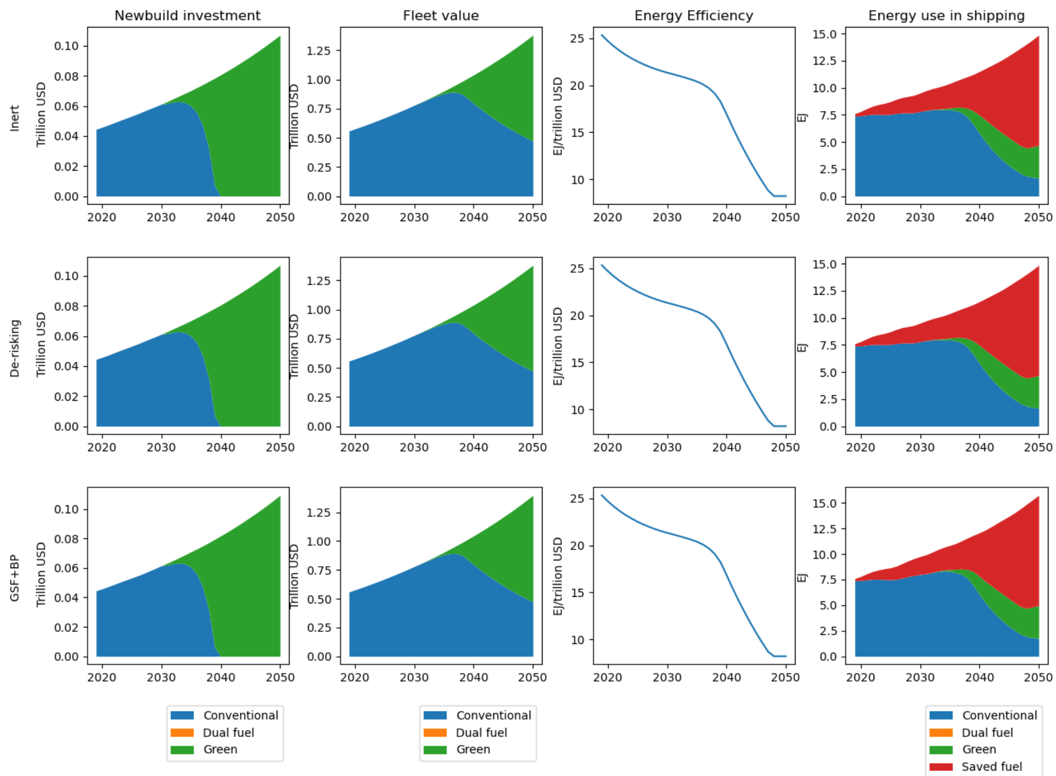


Figure J.4: Investment in newbuilds, fleet composition, energy efficiency and fuel consumption, as modelled by the land-shipping SFC model

(a) The fuel saved represents the fuel which was not consumed because of the improvement of the energy efficiency of the fleet after 2050, by using energy efficiency technologies and reduced speed. It allows to compare the respective importance of energy efficiency and alternative fuels in the transition to low-carbon shipping. It was calculated post-processing by multiplying the energy intensity in 2018 with the transport work per year, and retrieved the energy use of that year.

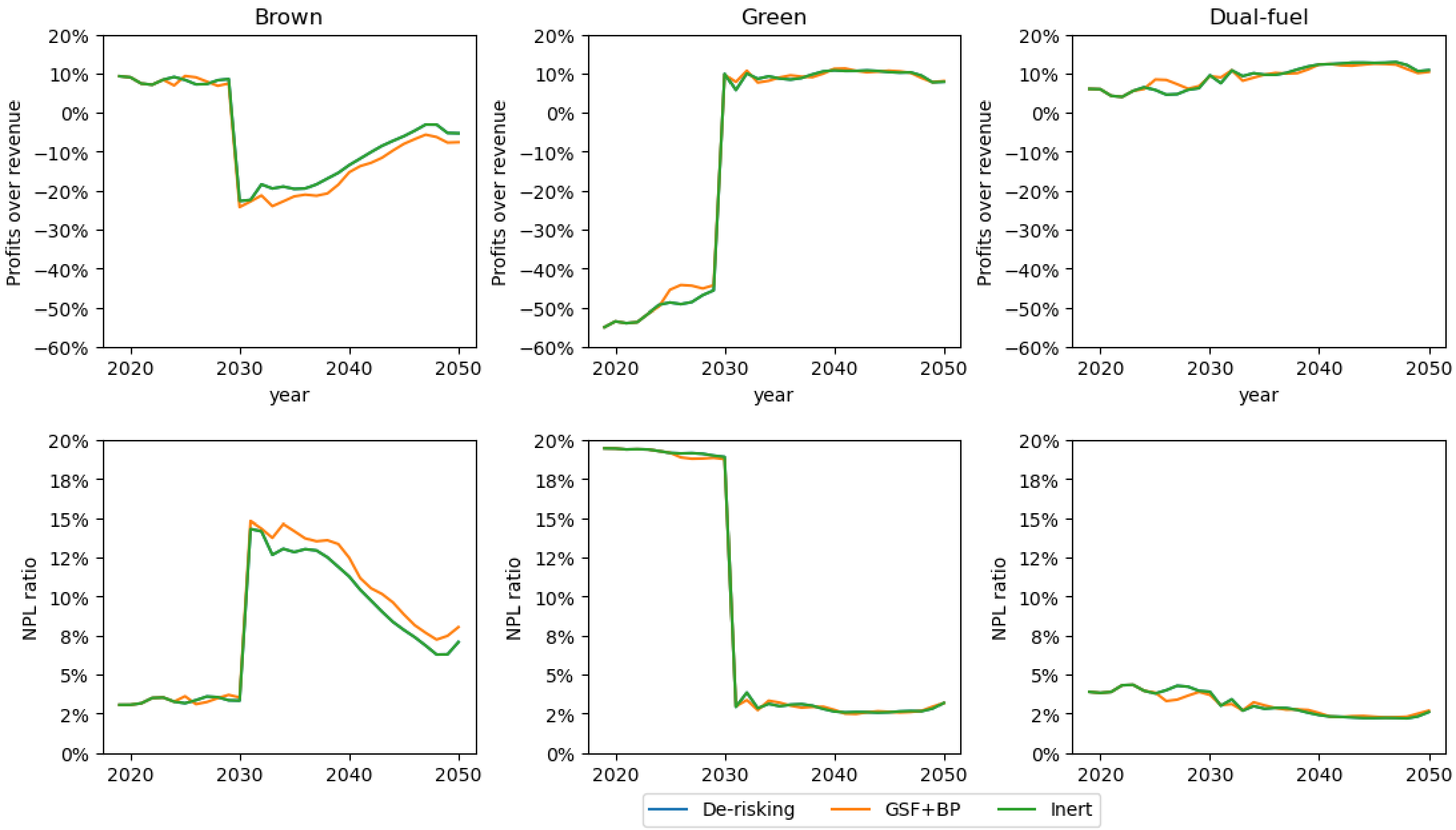


Figure J.5: Shipowners profits and non-performing loan ratio, as modelled by the land-shipping SFC model

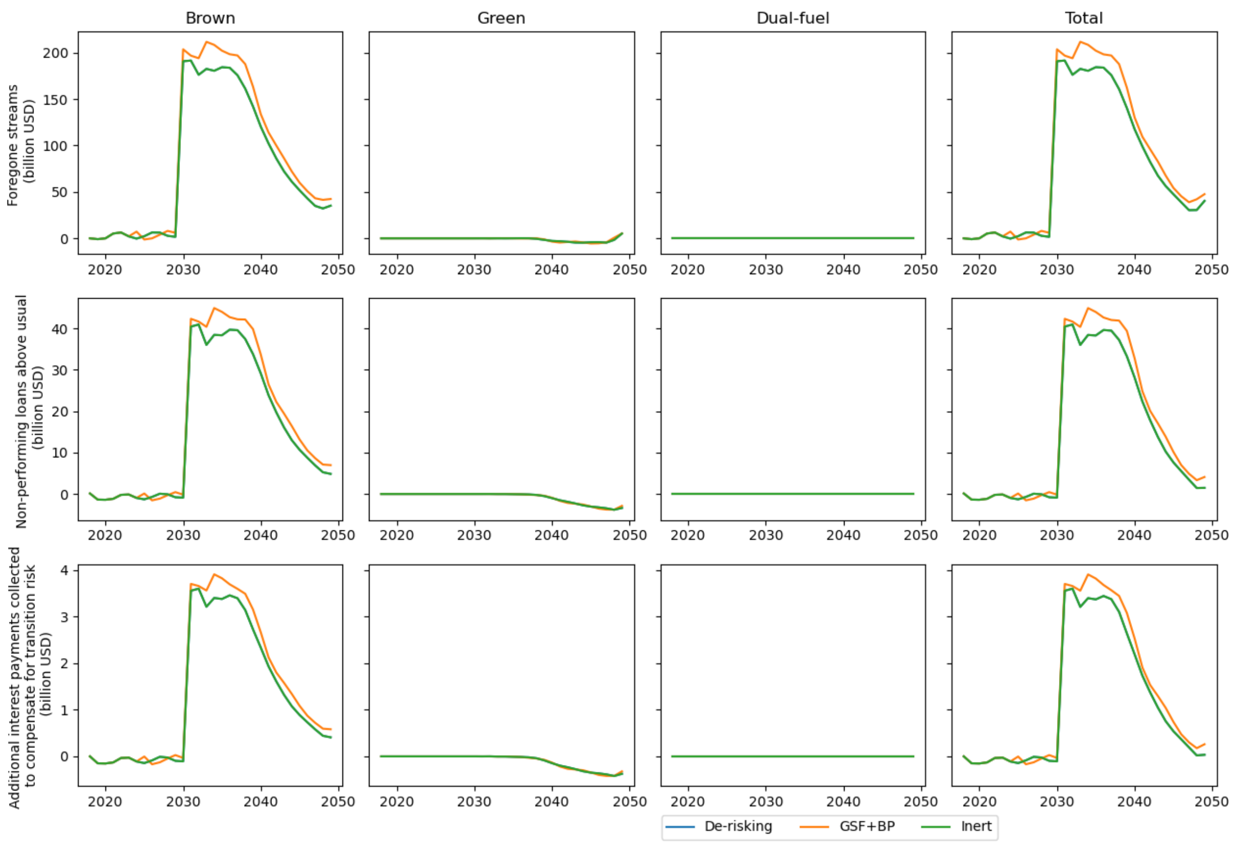


Figure J.6: Stranded assets in the form of foregone earning streams, interest payments defaulted to banks and non-performing loans to banks, as modelled by the land-shipping SFC model

(a) Normal average profits are assumed to be 8.96% of output and normal non-performing loan is assumed to be 3.87% per year, which are their values at $t = 0$ in the model. The usual margin above the lending rate and the pricing of the risk weight is 0.36%, which is the initial value in the model. The plotted value corresponds to the realised profits - normal average profits; non-performing loans above normal non-performing loans; and additional interest payments above normal interest payments.

(b) Additional interest payments do not include the effect of increased (resp. decreased) interest rates as a result of the differentiated CAR requirements, as those are compensated for by a decrease (resp. decrease) capacity to provide loans, hence a decreased (resp. increased) profitability.

Appendix K

Chapter 7's sensitivity analysis

Several inputs to modellisation are subject to uncertainty, so several sensitivity tests were carried out. The results are detailed in the following sections for the land-shipping SFC model and GloTraM.

K.1 Sensitivity analysis in the land-shipping SFC model

Let us first examine the sensitivity of the results from the land-shipping SFC model to initial assumptions. The sensitivity of the results of the model to the variables whose values could not be calibrated onto real-life data and/or to which the results might be greatly sensitive is tested. Those include:

- The sensitivity of the interest rates to the perceived credit risk (κ_1) and to change in the loan weighting (κ_2)
- How far in the past do lenders look for guidance on future profits (a) and how far in the future their look to anticipate future mitigation policy (b)
- The innovation and imitation coefficients which determine the uptake curve of new technologies (β_0 and β_1)
- The initial growth/reduction rate of the capital cost of brown and green technologies ($g_0^{cc,S,B}$ and $g_0^{cc,S,G}$)

For these variables, the model is run using a value 50% above and 50% below the central value used for the results described above. In addition, A scenario variant where green shipping technology is calibrated onto methanol rather than ammonia is run, for several reasons. First, although ammonia is found in GloTraM to be the most cost-effective option in 2030, this finding largely depends on the large-scale availability of cheaper bio-methanol or bio-methane (Lagemann et al., 2022, 2023) and safety issues raise doubts about its uptake (Balcombe et al., 2019; Serra and Fancello, 2020). Furthermore, as it is not available yet for ships, given the path-dependency and imitation effects previously demonstrated, there is a risk that in 2030 it has not created a sufficient basis of knowledge to become the dominant fuel. Furthermore, the results from GloTraM have shown that methanol, because its capital cost is lower than the other zero-/low-carbon ships, is more likely to benefit from the enabling behaviour of financiers as long as the cost of carbon is not internalised into fuel costs. Finally, a scenario variant where the carbon price is half of the central scenario is run to test the sensitivity of the results to the strength of the shipping mitigation policy.The values used in the sensitivity analysis are presented in Table K.1.

Table K.1: Summary of the sensitivity analysis run on the land-shipping SFC model

Variable	Range	Value used in the central scenario
κ_1	0.05-0.15	0.10
κ_2	0.025-0.075	0.05
a	4-10	7.00
b	4-10	7.00
β_0	0.01-0.03	0.02
β_1	5.0-15.0	10.00
$g^{ccG}{}_0$	0.005-0.015	0.01
$g^{ccB}{}_0$	0.003-0.007	0.01
dominant fuel	Ammonia, Methanol	Ammonia
Shipping carbon price	Late 1.5C-consistent, Half of 1.5C-consistent	Late 1.5C-consistent

The sensitivity of capital stock, of cumulative shipping emissions, of brown lost profits and of non-performing brown loans onto those variables in the combined financial policies, de-risking + enabler and inert scenarios are presented in figures K.1, K.2, K.3 and K.4. Several points are worth highlighting.

First, the effects of a change in κ_1, κ_2, a and b on the results is fairly limited (Figures K.1, K.4 and K.3), giving some confidence in the robustness of the results.

On the other hand, the adoption of green shipping and consequential lost profits and non-performing loans in the medium term are highly dependent on the coefficients governing the uptake of alternative technologies β_0 and β_1. On the other hand, they are only slightly sensitivity and on the speed of decrease in green capital costs $g_0^{cc,G}$ and increase in the brown capital costs $g_0^{cc,B}$ (Figures K.1, K.4 and K.3). This suggests that the speed of the transition, and consequently the amount of stranded assets, are subject to large empirical uncertainty. However, the impact of financiers onto stranded assets is not not sensitive to those changes of parameters: the scenarios combining several levers still lead to a faster uptake of green shipping, lower foregone streams and lower stranded paper. This gives confidence in the validity of the results in answering RQ4.

Furthermore, what fuel is available in the 2020s and becomes the price leader in 2030 has a large impact on the results in the de-risking + enabling scenario. Consistent with the results of GloTraM, when combining several levers, the difference in WACC is able to bridge the capital cost gap between conventional and methanol dual-fuel ships (financial policies and de-risking + enabler scenarios). This initiates a transition to methanol, which is still timid in 2030, but means that methanol represents the majority of the fleet by 2040 (Figure K.1). The share of green investments in 2040 greatly increase in the de-risking + enabler scenario when methanol is the dominant fuel, as opposed to ammonia. Both foregone streams and stranded paper are greatly reduced if methanol becomes the dominant fuel in 2030 and later compared to ammonia (Figures K.4 and K.3). This is because methanol is more expensive than ammonia on an operational basis, and therefore the price of shipping increases much more than in the case of a transition with ammonia, so that conventional ships are much more profitable, although they still do not make any profits. In this scenario, the cost of the transition is actually passed from the shipowners onto

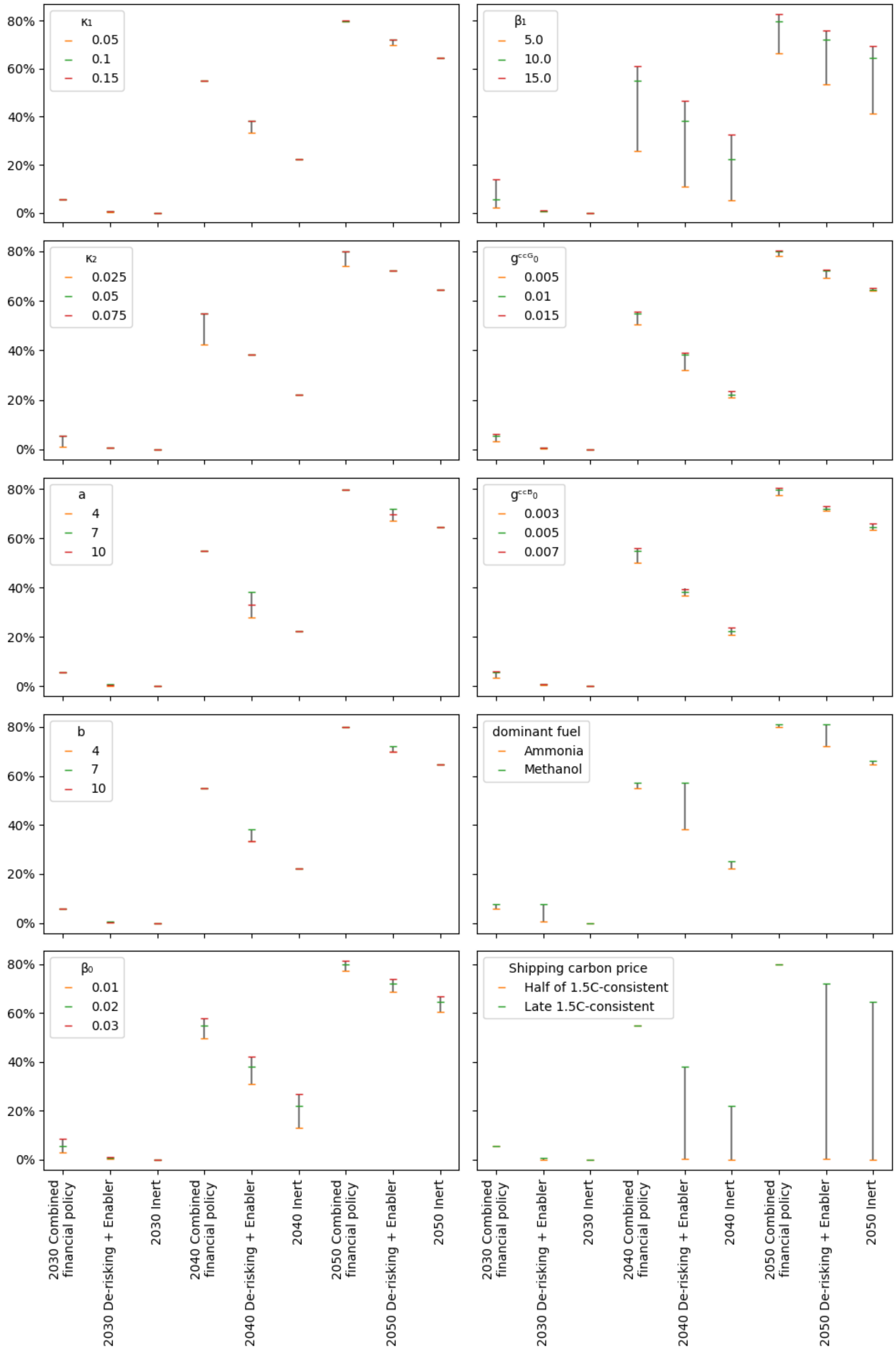


Figure K.1: Sensitivity of technology uptake ($\Theta^D F + \Theta^G$), as modelled by the land-shipping SFC model

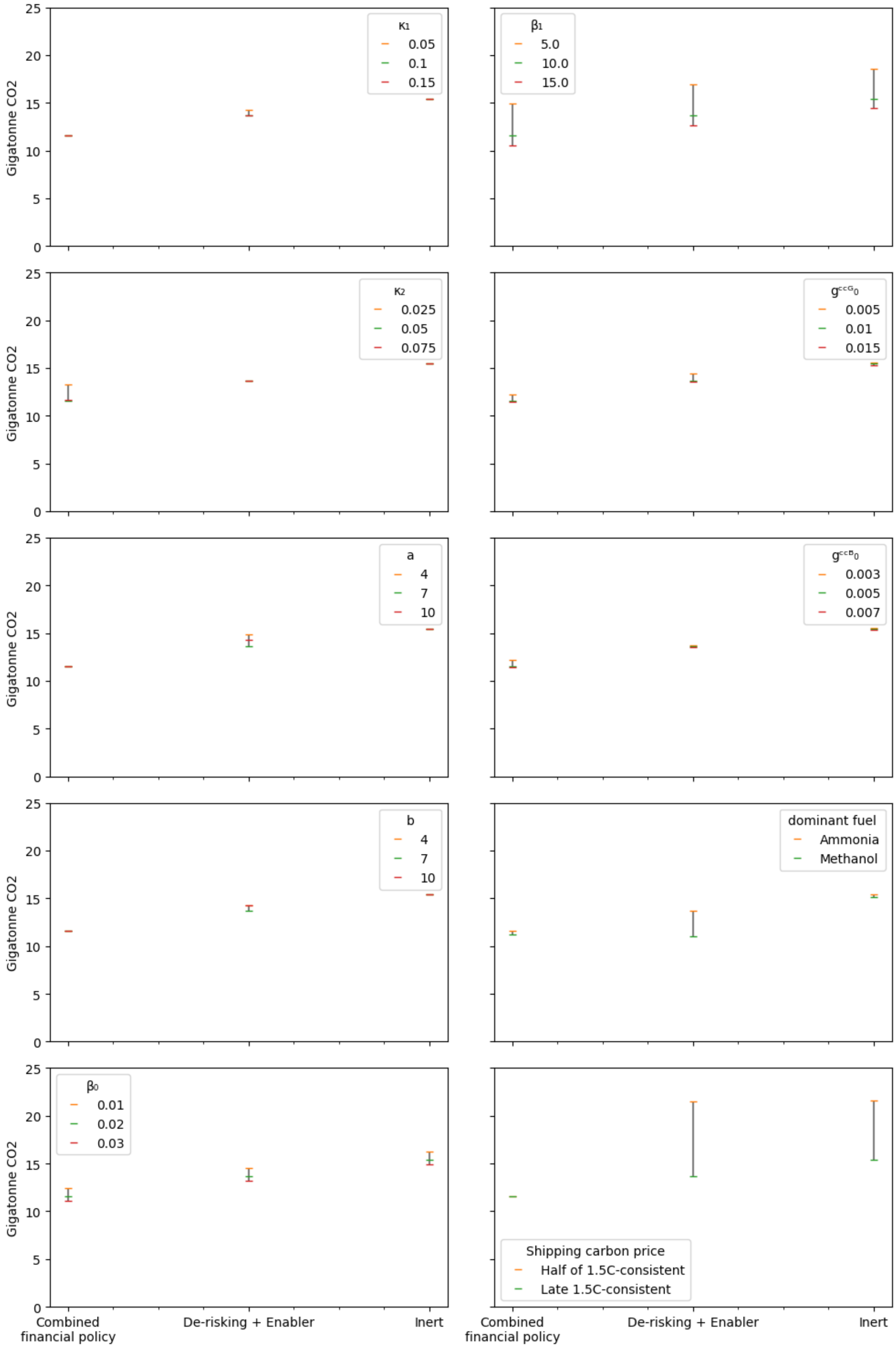


Figure K.2: Sensitivity of cumulative 2018-2050 shipping emissions, as modelled by the land-shipping SFC model

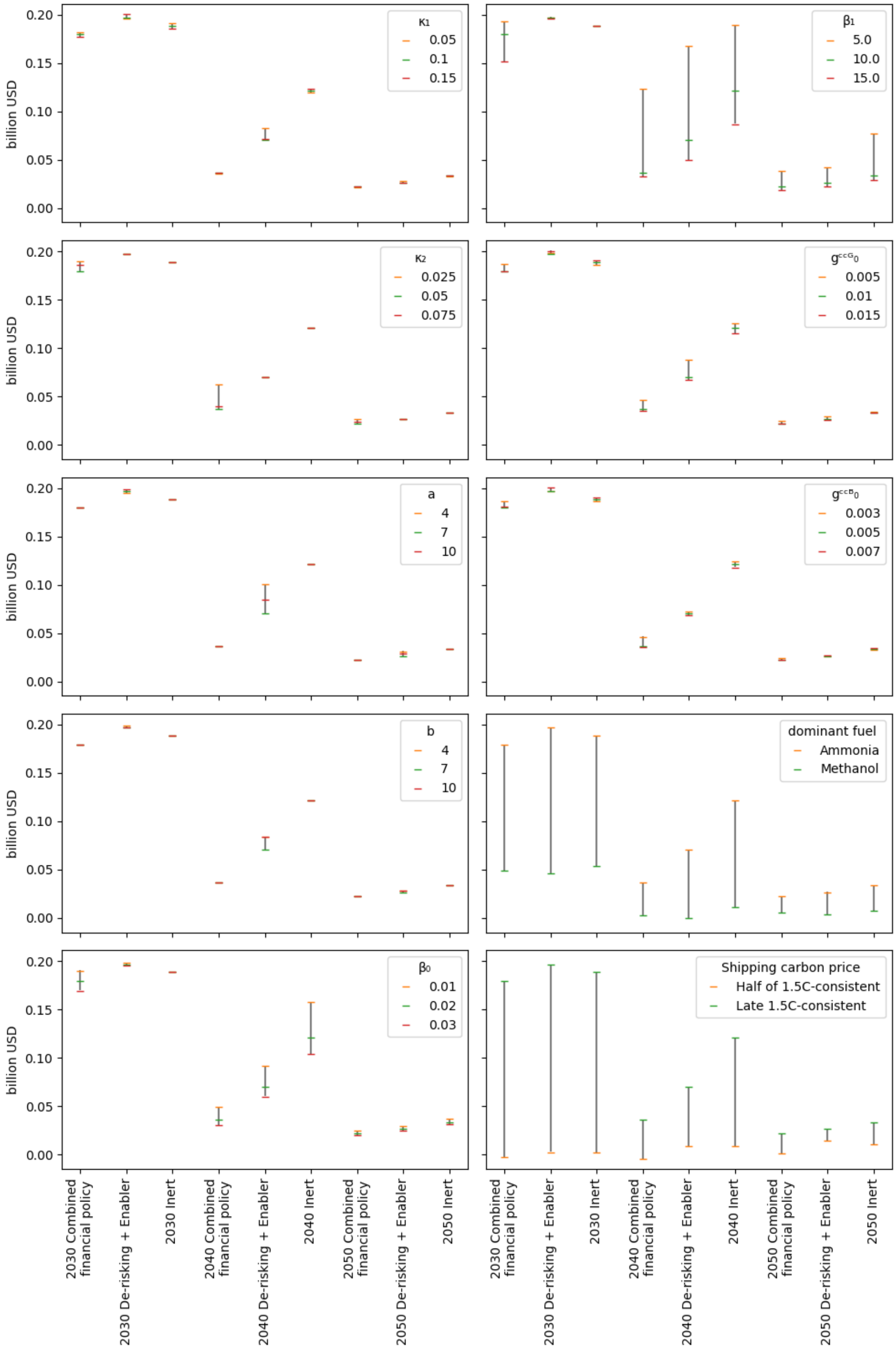


Figure K.3: Sensitivity of the lost profits of brown ships, as modelled by the land-shipping SFC model

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(a) Normal average profits are assumed to be 8.96% of output which is the value at $t = 0$ in the model. The plotted value corresponds to the profits realised - normal average profits.

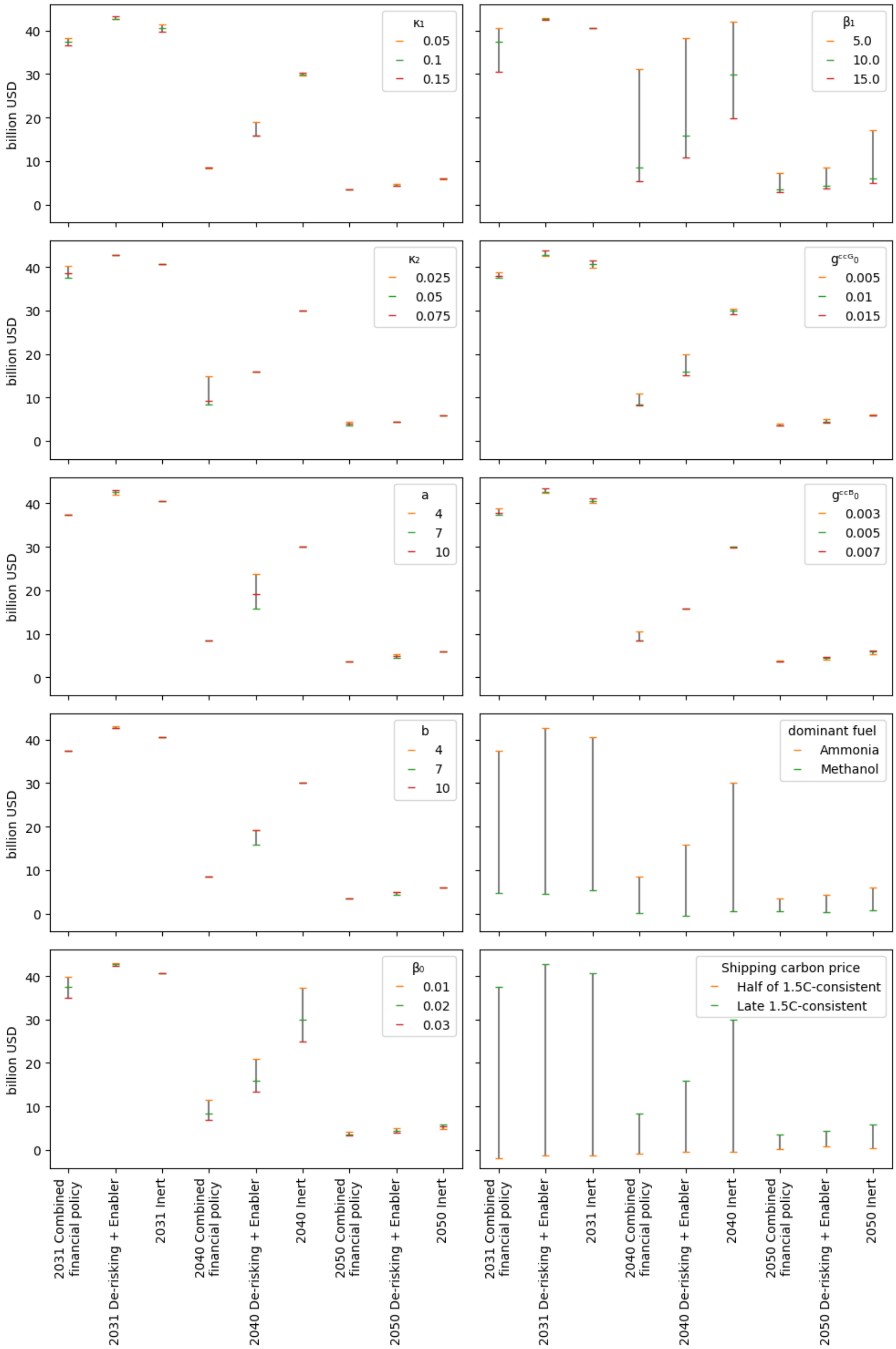

Figure K.4: Sensitivity of the non-performing loans to brown ships compared to expected, as modelled by the land-shipping SFC model

(a) Normal non-performing loan is assumed to be 3.87% per year, which is the values at $t = 0$ in the model. The plotted value corresponds to the non-performing loans above normal non-performing loans the customers. This suggests that the unfolding of the transition and the consequential amount of stranded assets are subject to large uncertainty. However, a strongly differentiated WACC further reduces the amount of foregone streams and stranded paper, which supports the robustness of the results in answering RQ4.

As the land-shipping SFC model does not take into account the interactions between alternative fuels, it is not possible to conclude from those results what the impact in terms of stranded assets from two successive transitions would be, one to methanol and one to ammonia. But intuitively, if methanol is not competitive with ammonia and ammonia becomes the price leader while a large share of the fleet concerns methanol dual-fuel ships, one could expect the same dynamics as modelled for the disappearing conventional fleet to take place, that is lost profits and non-performing loans.

The sensitivity of the results to the choice of carbon tax is informative in assessing the role of the financial system in compensating for a more timid shipping policy. Implementing a 330 $ / tonne CO2 carbon tax in 2030 is not large enough to drive the uptake of green fuel in the inert scenario. This means that brown shipping remains the price leader and there is no foregone profits nor stranded paper, as the carbon price is simply passed onto the shipping customers; but the sector does not decarbonise and emissions greatly increase. In the two other scenarios, the difference in WACC, however, compensates for the lower carbon tax, so that dual-fuel and then green shipping are still cheaper than brown shipping in 2030, and the transition occurs. In 2030, in he de-risking + enabler and combined financial policies scenarios, even though green shipping is the price leader, the fact that brown ships pay a much lower amount of carbon tax means and that prices increase to green price means that brown ships also do not operate at a loss, so that they are no stranded assets. In the de-risking + enabler scenario, banks stop favouring green shipping in 2030, as the uncertainty on the future profits has resolved; and the de-risking policy stops in 2033. As a result, green shipping becomes again more expensive than brown shipping and the transition stops. This suggests that strong financial policies can compensate a more timid shipping direct mitigation, but that a strong signal either from customers or from the shipping regulator is still needed for the transition to unfold.

Finally, it should be noted that in none of the modelled scenarios does the shipping industry respect its allocated 1.5°C carbon budget of 7.5 Gigatonne CO2 (Figure K.2). This confirms the finding that neither lenders' ambitious behaviour nor strong investments by shipowners into zero-/low-carbon ships alone are able to drive emissions sufficiently low, so that energy efficiency gains before 2030 and/or a decrease in shipping demand are needed. However, the sensitivity of emissions to lenders' behaviour in the case of an uptake of methanol suggests that lenders still have a significant impact on shipping emissions (Figure K.2). On the other hand, the large sensitivity of the result to a lower than expected imitation effects of shipowners on emissions (β_1) suggests that unless shipowners are themselves reactive to alternative technologies, lenders are unable to drive the market alone.

K.2 Sensitivity analysis in GloTraM

This section reports the results of the sensitivity analysis carried out on the GloTraM.

Similar to the land-shipping SFC model, which zero-/low-carbon fuel becomes dominant in 2030 has a large impact on the results. As already discussed, if drop-in fuels are available at scale and cost competitive in 2030, there is no stranded capital. Furthermore, as previously discussed, if a source of energy that is not retrofittable takes up (e.g. hydrogen, mostly wind), then practically all capital would be stranded (Figure 7.24). A further case is considered, where ammonia is not available in 2030 and methanol becomes the dominant fuel. Two sub-case cases are further looked at: one where all zero-/low-carbon fuels are available in 2030 along with the dominant fuel, i.e. hydrogen, ammonia, electricity, and methanol (but in practice no hydrogen, ammonia, and electricity have been built before 2030). The assumption of cohabitation between several alternative fuels, in particular between methanol and ammonia, is in line with Lloyd's Register (2023), but it is highly uncertain at this stage, as the fuel mix and competition between the different fuels will clarify only when fuel uptake starts. To control for this uncertainty, in the other case, only the dominant fuel is available, and the other zero-/low-carbon fuels become stranded (in practice, only methanol). The resulting book loss if retrofits are available (central scenario) are plotted in Figure K.5.

When only conventional ships need to be retrofitted, that is, when several zero/low-carbon fuels cohabit in 2030, which fuel becomes dominant does not significantly impact the amount of capital stranded. This is because, although retrofitting conventional ships to methanol is less expensive than retrofitting them to ammonia (step 2 in Figure 7.11), methanol-newbuilds are also less expensive than ammonia-newbuilds (step 1 on Figure 7.11). The resulting amount of stranded asset is therefore similar (step 3 in Figure 7.11).

However, if ammonia becomes the dominant fuel in 2030 and methanol is not competitive in 2030 so that methanol dual-fuel ships need to retrofit, the supportive behaviour of financiers toward methanol leads to a slight increase in the amount of book loss (scenarios de-risking + enabler and combined financial policies, Figure K.5). This is because methanol dual-fuel ships are more expensive than conventional ships. The increase is fairly limited when considering the whole fleet, but as those ships are newer, they might represent a large share of the loans portfolio and might therefore translate into a larger increase in stranded paper.

The sensitivity of the results to the calibration of machinery and tank costs was tested by adjusting the newbuild and retrofitting costs to those provided by Lagemann et al. (2023). These costs differ depending on the previous engine: for example, they estimate that it is cheaper to retrofit LNG to ammonia than to retrofit LSHFO to ammonia. On the other hand, GloTraM assumes a constant retrofit cost per kW and per kg, independent of the fuel of origin. The results plotted in Figure K.6 show that the results in the variant of a transition to ammonia in 2030 are not very sensitive to the change in retrofit costs, which supports the robustness of the results. On the other hand, the estimates of book loss in the case of a transition to methanol are significantly reduced when using the input from Lagemann et al. (2023). This is because Lagemann et al. (2023) assumes similar newbuild costs for methanol dual-fuel ships but significantly lower retrofit costs from LSHFO to methanol.

Finally, the total amount of book loss is not very sensitive to assumptions on the average age of ships at scrap time (Figure K.7), which confirms the robustness of the results despite the uncertainty of the fleet valuation method.

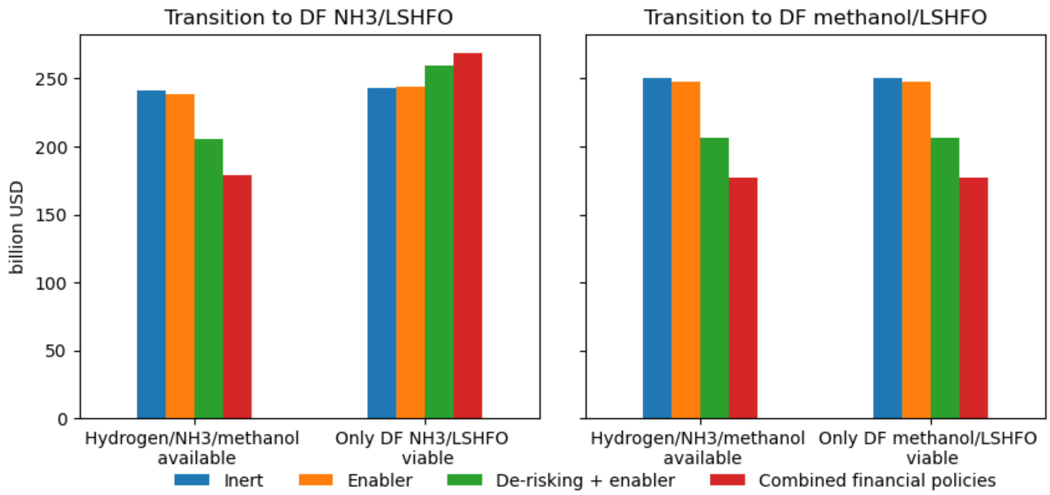

Figure K.5: Sensitivity of book loss by dominant fuel and fuel availability, as modelled by GloTraM

To validate the evolution of the cost of debt and cost of capital predicted by the land-shipping SFC model, the results are compared below to their observed evolution in other sectors (energy production and power generation) and test for the sensitivity of the GloTraM results to those.

The cost of debt for renewables has largely fallen over the last two decades, a fall particularly well documented in Europe (Egli et al. (2018), Geels and Gregory (2023), and Zhou et al. (2021) find a fall in loan spreads ranging from 0.3 to 4 percentage points for offshore wind, onshore wind, and solar). In parallel, the loan spreads for fossil power generation have increased since 2000 (Xiaoyan et al. (2023) and Zhou et al. (2021) find an increase of around 1 percentage points). Table K.2, based on Xiaoyan et al. (2023) and Zhou et al. (2021)'s reported loan spreads, shows that renewables were priced on average 0.1 percentage points more than fossil power generation before 2010, but 1.1 fewer in 2020-2021. This hides important regional and technological differences, with some countries well advanced in the

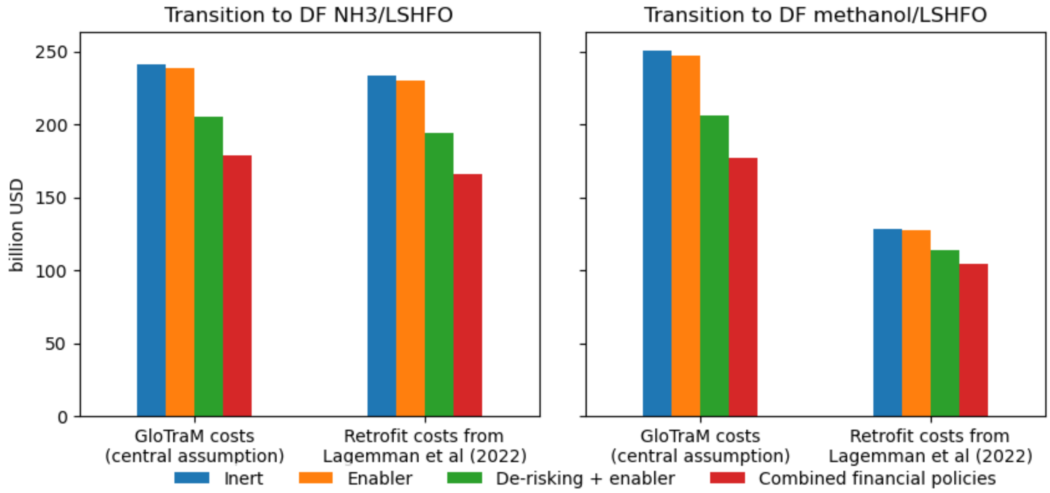

Figure K.6: Sensitivity of book loss to retrofit costs, as modelled by GloTraM

(a) Lagemann et al., 2022 provides a breakdown of retrofit cost for a range of from/to retrofit cases on the case study of a 7.5MW bulk carrier. Retrofit costs in $/kW (machinery + piping + shipyard + lost income) and $/kg bunker fuel (Tank) for each from/to combination were derived from those estimates. Newbuild costs were also adjusted to the most expensive possible retrofit cost, plus the cost of propulsion. For example, the newbuild engine cost for methanol was proxied as the retrofit cost of machinery + piping from LNG to Methanol, plus the cost of ICE propulsion.

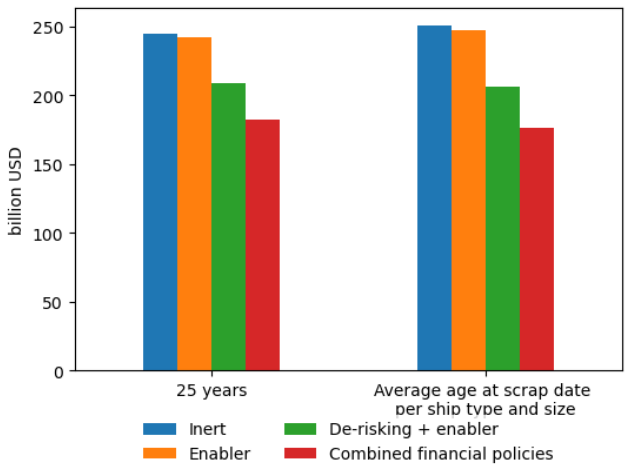

Figure K.7: Sensitivity of book loss to the age of ship at scrapping date, as modelled by GloTraM

Table K.2: Loans spreads for power generation (percentage points above LIBOR). Based on the loan spreads reported in Xiaoyan et al. (2023) and Zhou et al. (2021). 2020-2021 was calculated as the weighted average by loan volume.

	2000-2010	2010-2020	2020-2021
renewables	1.9	2.3	1.7
fossil	1.8	2.8	2.9
renewables - fossil	-0.1	0.5	1.1

transition to renewables, such as the UK or Germany, seeing more dramatic decreases in the spread of renewables (Egli et al., 2018; Geels and Gregory, 2023). Kempa et al., 2021 finds similar results, looking at energy production rather than power generation, with renewables comprising renewable energy equipment manufacturers, project developers and biofuels, while fossil technologies include oil and gas exploration and production and pipelines. They found that the cost of debt for renewables was 0.4 percentage points higher than fossil before 2007, and around 0.9 percentage points lower afterward. Those findings validate fairly well with the results from the land-shipping SFC model: at the beginning of the transition, the model predicts that the cost of debt of green shipping is higher than the one of brown by around 1.5 percentage point (0.1 for dual-fuel, as those are able to run on conventional). An enabling behaviour leads to a decrease of this difference, with green and dual-fuel shipping being priced less than brown shipping by around 1.3 percentage points.

Based on the evidence reviewed above, the sensitivity of GloTraM results is tested by calibrating the enabler and de-risking + enabler scenarios to the evolution in the cost of debt Kempa et al. (2021), Xiaoyan et al. (2023), and Zhou et al. (2021) find. The gap in the costs of debt for zero-/low-carbon ships and conventional ships is assumed to be 0.25 percentage points in 2018 and decreases linearly to -1 percentage points by 2030.

The results in the scenarios ”Enabler” and ”De-risking + enabler” do not vary much between the central and the sensitivity analysis, as showed on Figures K.8 and K.9. This is not surprising, given that the evolution in the cost of debt and therefore the WACC are very similar between the two scenarios, and all the others input are held constant. This gives confidence in the validity of the results of GloTraM, even if one were to doubt the validity of the results of the land-shipping SFC model.

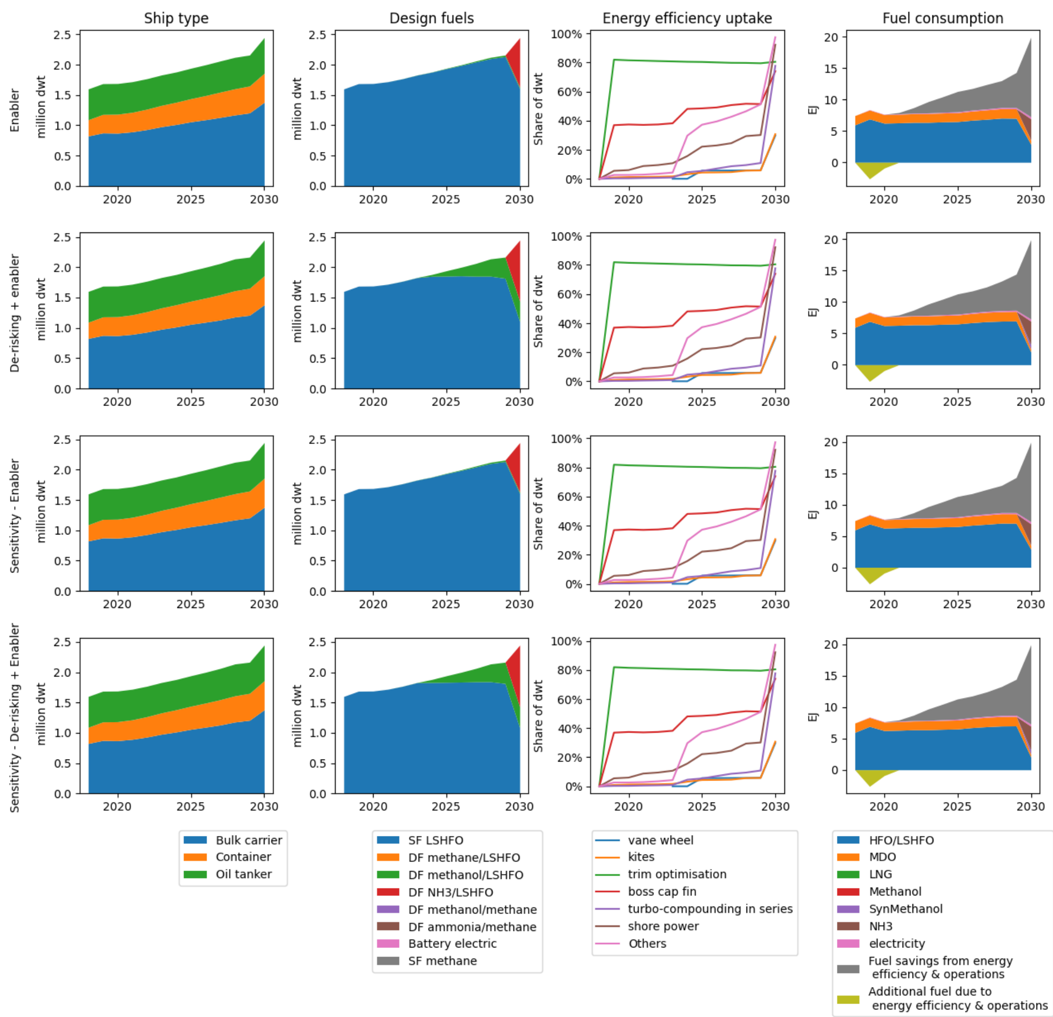

Figure K.8: Sensitivity of fleet evolution to the WACC input assumptions, as modelled by GloTraM

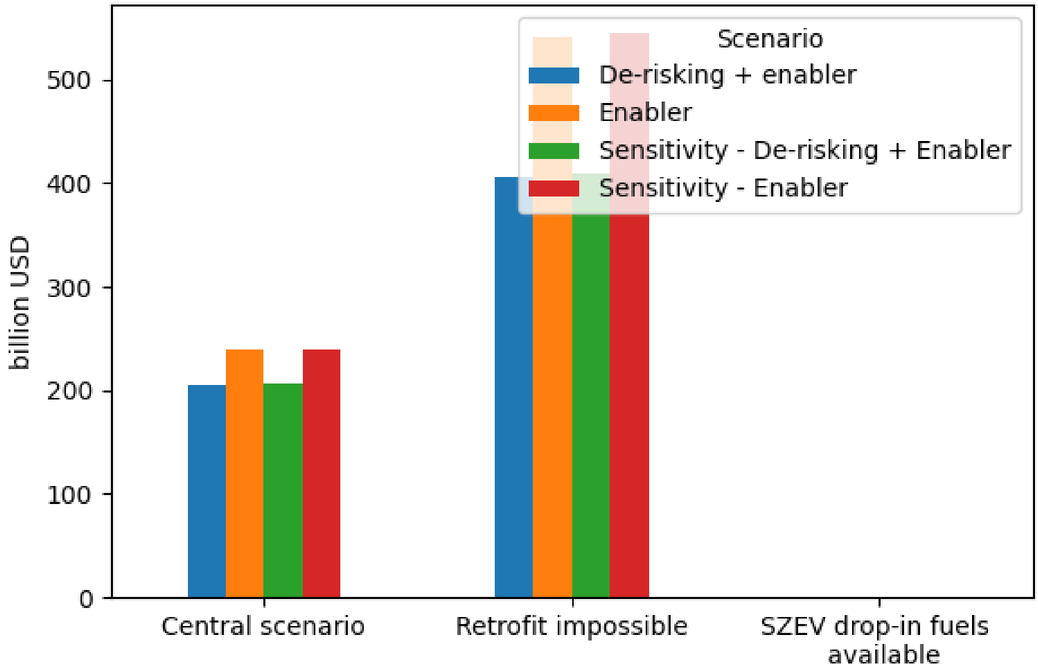

Figure K.9: Sensitivity of stranded capital to the WACC input assumptions, as modelled by GloTraM