The risk of asset stranding for fossil fuel carrying ships

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Highlights

- Gas and oil tankers are facing large risk of asset stranding in a 1.5°C world.
- Up to 37% of their expected earnings up to 2050 could fail to materialise.
- Their owners and operators are fragmented and specialised in those segments.
- This makes them more vulnerable to the demand side risks.
- Coal carriers face smaller risk, as they can be used to transport other bulk cargo.

Keywords

Stranded assets, shipping, energy transition, transition risk, demand-side risk, fossil fuels

1. Introduction

Climate change creates a variety of economic and financial risks (Carney, 2015); these include physical risks from climate-related damage (Bolton & Kacperczyk, 2021; Carney, 2015), liability risks from potential claims for compensation brought forward by certain entities and countries that incurred climate-related damage (Carney, 2015; Lamperti et al., 2021) and transition risks which can broadly be defined as "the threats, possibly systemic, posed by the transition to a low-carbon economy to financial stability" (Carney, 2015)[1]. Drivers of transition risks include the introduction of climate mitigation policies that may not be anticipated early enough by economic actors (Campiglio & van der Ploeg, 2022; Monasterolo, 2020); an unexpected or very rapid technological advance(Campiglio & van der Ploeg, 2022; Dunz et al., 2018; Monasterolo, 2020) or change in the preferences of consumers, entrepreneurs, and financiers(Campiglio & van der Ploeg, 2022). All of these can render existing capital investments obsolete (Campiglio & van der Ploeg, 2022; Dunz et al., 2018; Monasterolo, 2020), lead to the discontinuation of certain assets before their scheduled end-of-life, or to their sudden devaluation (Batten et al., 2017; Caldecott & McDaniels, 2014).

The concept of stranded assets is closely linked to transition risks and is defined as assets "which have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities" (Caldecott & McDaniels, 2014).

The primary focus of this paper is on the transition risk and the subsequent risk of stranded assets for stakeholders of the shipping industry, specifically those that ship fossil fuels as a commodity. We further focus on the concept of "stranded capital" (Daumas, 2023; van der Ploeg & Rezai, 2020), i.e., assets that are projected to lose value or require costly conversion; and the expected earnings from these assets, which would fail to materialise if the shipping industry decarbonises (foregone earning streams) (Daumas, 2023; van der Ploeg & Rezai, 2020).

Ships are capital-intensive, long-lived assets with lifetimes of approximately 25 years; today, they are highly reliant on carbon-intensive fuels for propulsion, and more than a third of them in terms of deadweight (based on Clarksons World Fleet Register (WFR)(Clarksons Research, 2022)) are used to transport fossil fuels[1]. Ships that are powered by carbon-intensive fuels and that also transport fossil fuels can be impacted by two distinct types of low-carbon transitions and thus two kinds of risk of stranded assets (Smith et al., 2015):

- The transition towards zero/low-carbon shipping, aimed at minimising the carbon footprint of the ships themselves (supply-side risks), which might lead to obsolescence and devaluations of carbon-intensive ship assets.
- The transition towards a zero/low carbon of non-shipping sectors, referred to as world economy afterwards, notably in electricity generation, transportation, and other sectors and applications which implies replacing fossil fuels with renewable electricity or other low or zero carbon fuels. Although long-term world trade is largely driven by long-term GDP growth, it is also impacted by the energy pathways of the other sectors (Sharmina et al., 2017; Walsh et al., 2019). The decrease in demand and trade would result in a decrease in the need to transporting coal, oil, and fossil gas (demand-side risk, as coined by Smith et al (2015)(Smith et al., 2015)), and it might also lead to obsolescence and devaluation of certain segments of the shipping assets.

[1] 36%, calculated using the deadweight of the existing and ordered fleet of liquefied gas tankers and oil tankers, plus 17% of the fleet of bulk carriers from Clarksons WFR (Clarksons Research, 2022). 17% is the share of the coal trade in bulk trade (in tonne-miles) from Clarksons Shipping Intelligence Network (SIN)(Clarksons Research, 2023).

The decrease in demand for transport of fossil fuels might partially be replaced by demand for transporting new fuels, such as bioenergy, eventually CO_2, etc, but these are unlikely to fully offset the overall decline in energy transportation(Jones et al., 2022).

Although these two transitions are distinct, they are likely to happen simultaneously because they share similar incentives to reduce greenhouse gas (GHG) emissions and are driven by similar technological developments. Also, the decrease in shipping activity to transport fossil fuels, and consequently the emissions thereof, will contribute to reduce emissions and the efforts needed to decarbonise shipping. In that sense, the decarbonisation of the world economy would help the decarbonisation of shipping.

The transition to zero-/low-carbon shipping is attracting growing attention to the supply-side risk in both, the stranded asset literature(Bullock et al., 2020; Fricaudet et al., 2023; Jeong et al., 2023; Mitchell & Rehmatulla, 2015; Raucci et al., 2017) and the policy space. The revised International Maritime Organisation (IMO) Strategy to reach a net zero GHG shipping emissions by around 2050(2023 IMO Strategy on Reduction of GHG Emissions from Ships, 2023), which was adopted in July 2023, and the integration of shipping into the European Union carbon market framework[18] which became effective in January 2024, can be expected to further drive this attention.

Demand-side risk, which relates to the ongoing energy transition in the world economy has, so far, been largely understudied: While the general risk of stranded assets has been assessed in a growing range of sectors (see an extensive literature review in (Campiglio & van der Ploeg, 2022; Curtin et al., 2019; Daumas, 2023)), only a small body of literature exists for shipping (Bullock et al., 2020; Jeong et al., 2023; Raucci et al., 2017), and none of that literature specifically addresses demand-side risk. Indeed, the body of research on asset stranding frequently concentrates on specific sectors at high risk, notably fossil fuel extraction and electricity generation (Campiglio & van der Ploeg, 2022; Curtin et al., 2019; Daumas, 2023).

Not all shipping segments would be affected equally. Coal, mostly transported by bulk carriers, only represents 17% of dry bulk trade (based on Clarksons WFR(Clarksons Research, 2022)). On the contrary, oil and fossil gas are transported by oil tankers and liquefied gas tankers, two types of ships that are almost entirely dedicated to carrying fossil fuels. Although many studies consider that fossil gas will be used in the medium term, moving away more rapidly from oil and gas is necessary to remain within a 1.5°C compatible carbon budget. In pathways that suggest a longer use of fossil fuels or a less steep reduction, emissions would have to be captured at the point of their emission or removed from the atmosphere. The feasibility, availability, costs, and efficiency of these technologies and techniques are still highly uncertain. Hence, while it has been recognized that some level of removal will be needed to achieve climate targets, the realistic scale is being much debated(Deprez et al., 2024; MSI, 2019; Walsh et al., 2019; Wei et al., 2023). Furthermore, stronger electrification than often projected in scenarios could lead to faster declines in fossil fuel uses.

As for all industries, measuring and anticipating demand-side risk is critical for shipping, so that actors can make their investment decisions accordingly. This paper aims to broaden the knowledge of demand-side risks of stranded assets in a 1.5°C pathway for the fossil fuel shipping fleet and the actors that may be affected. It intends to answer the following research questions:

1. Who builds, owns, and operates coal, oil, and fossil gas carriers ?
2. What is the current value and age structure of the fleet ?
3. What will be the over-capacity until 2050 of oil and fossil gas carriers if the demand for transporting fossil fuels aligns with a 1.5°C pathway?
4. What would be the consequential value of stranded assets?

This work makes an original contribution to the fields of shipping transition and finance, and more generally of energy transitions, by providing a first top-down assessment of the risk of asset stranding for fossil fuel carriers, and the potential actors that would be affected. Like other studies, we build a forward-looking model, which compares a baseline projection with an externally imposed carbon budget constraint (Curtin et al., 2019; Daumas, 2023). In this paper, the shipping supply that exceeds shipping demand and its associated earnings is considered at risk of being stranded (see details in the methods section). These estimates serve as indicators of the vulnerability of the sector's capital stock to stranding within a given projection. While much of the literature has focused primarily on quantifying these physical asset strandings, e.g., fossil fuel reserves that cannot be extracted (McGlade & Ekins, 2014, 2015; Welsby et al., 2021) or committed emissions embedded in existing fixed assets (Bullock et al., 2020; Löffler et al., 2019; Lu et al., 2022; Pfeiffer et al., 2016), we provide a monetary estimate of stranded assets. Using the suggestion of Daumas (2023)(Daumas, 2023), we estimate the amount of:

- *Book loss*: the economic value of existing carbon-intensive assets, in this case, fossil fuel carriers, forced to be decommissioned/unexploited before their projected economic lifespan, and in line with the work of (Edwards et al., 2022; Hauenstein, 2023; H. Johnson & Andersson, 2016; Löffler et al., 2019; Mercure et al., 2018; Saygin et al., 2019; Zhang et al., 2021). To do so, we estimate the value of the fleet by estimating the newbuild value of each ship based on the parameters obtained from a regression analysis of the newbuild prices of the ships and depreciating to its second-hand value.
- *Foregone earnings streams*: the continuous reduction in financial income that firms exposed to transition risks may face in the low-carbon transition, in line with the work of (Chen et al., 2023; Mercure et al., 2018; Muldoon-Smith & Greenhalgh, 2019). We estimate the value of foregone earnings streams by extracting an average price of shipping for each of the shipping segments concerned.

Furthermore, while most studies (Lu et al., 2022; McGlade & Ekins, 2014, 2015; Pfeiffer et al., 2016; Saygin et al., 2019; Welsby et al., 2021; Zhang et al., 2021) are static in nature because they only look at the existing stock of assets to calculate the risk of assets becoming stranded and implicitly assume that no new asset will be built, we compare this conservative scenario with ones where future investments continue to take place in the near future, in line with the work of (Bullock et al., 2020; N. Johnson et al., 2015; Löffler et al., 2019; Mercure et al., 2018).

The methods used are detailed in the next section.The following provides some contextual data on the fleet of fossil fuel carriers, and the main actors that are economically involved; it describes the modelled evolution of the fleet and reports the estimated amount of stranded assets in a 1.5°C scenario. The last section discusses the implications of the results.

2. Material and methods

To answer the research questions, an estimate of the financial value of the existing stock of capital is first provided. As previously discussed, stranded capital can be monetised as book loss and foregone earnings streams (Daumas, 2023). To calculate those, the next section provides an estimate of the evolution of the fleet up to 2050, its capital value and the amount of expected earnings associated. Of the resulting fleet value and expected earnings, the following section then explains the method to assess demand-side risk. Finally, the last section explains how the data was collected.

2.1. Modelling fleet evolution, value and expected earnings

Fleet evolution

The composition of the future fleet of fossil fuel carriers depends on the retirement and newbuilding activities in the coming decades. To represent those dynamics, we model each existing and ordered ship of the fleet and assume that each of them will be operating over an average lifetime by vessel type and size before being scrapped. We further add to the existing fleet newbuilds, along the two scenarios of fleet evolution:

- **No further ordering**: in this scenario, no more fossil fuel carriers are built, apart from those already ordered at the date of data collection (January 2024).
- **Newbuild until 2030**,: newbuilds continue until 2030, with the average newbuild deadweight / fleet deadweight equal to the last decade's average.

Based on Clarksons WFR data, fossil fuel carriers take on average 2 to 3 years between contracting and delivery. To build the "Newbuild until 2030" scenario, we assume that in the coming 2 years, the newbuild ships correspond to the currently ordered ships. From 2026 on and until 2030, we assume that ships continue being built according to the past average ratio of newbuild deadweight / fleet deadweight for the years 2014 to 2023, i.e. 5% for oil tankers and bulk carriers, and 8% for LNG and LPG carriers. Those numbers are equal or above the current ratio of ordered deadweight / fleet deadweight for 2026 onward. We assume that no new fossil fuel carriers are built after 2030.

We apply this newbuild ratio NBR to each cohort, described by shipping segment s, size bin z and year of built $built$. We build a representative ship for each segment and size characterised by a deadweight dwt, a Maximum Continuous Rating mcr, powered by conventional fuel. dwt and mcr are the average deadweight and main engine MCR of all ships built in the last decade (2014-2023). Each year t, we assume that the following number of ships are built:

$$N_{s,z,t} = \frac{NBR_s \sum_{built \in [t-ScrapAge_{s,z},t-1]} N_{s,z,t}}{dwt}$$

With $N_{s,z,t}$ the number of ships of the cohort characterised by the shipping segment s, size bin z and built in t.

Fleet valuation

Let us now turn to the methods used to estimate the value of the fleet previously described at any point in time. The 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 MCR of the main engine and a series of dummies of the fuel type (conventional HFO/MDO, noted Heavy Fuel Oil (HFO), 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 regression model is summarised in the equation below, with P^{new} the newbuild price of a ship of main engine MCR mcr, deadweight dwt, S a vector of dummy variables to control for the shipping segment, F a vector of dummy variables to control for the fuel type, T a vector of year dummy variables, ϵ the residual error and a_1, a_2, a_3, a_4 four vectors of coefficients.

$$P^{new} = a_1 \times dwt \times S + a_2 \times mcr \times F + a_3 \times dwt \times S + a_4 \times T \times S + \epsilon$$

The regression variables are summarised in Table 1. 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.

Table 1: Summary statistics of the dataset used for the regression of ship newbuild values

	Count	Mean	Sd
Price	4,457	88,138,732	1.1e+08
Deadweight	4,457	101,094	79,929.8
Main engine MCR	4,457	25,185	19,221.5
Built year	4,457	2015	4.7

	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

The model is fitted using an ordinary least squares regression analysis and the results are shown in Table 2. Model (1) includes all shipping segments but no time fixed effects. The R^2 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 HFO, which is in line with expectations. Positive coefficients on ship segment $\times$ 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 $\times$ shipping segment dummies slightly increases the R^2 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 only 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.

Table 2: Regression of newbuild price results

	(1) Newbuild price	(2) Newbuild price	(3) Newbuild price
HFO # Main engine MCR	1956.9*** (0.000)	1721.5*** (0.000)	1172.2*** (0.000)
LNG # Main engine MCR	2712.1*** (0.000)	2258.2*** (0.000)	1830.9*** (0.000)

	(1)	(2)	(3)
	Newbuild price	Newbuild price	Newbuild price
Methanol # Main engine MCR	3041.4***	2337.4***	1786.7***
	(0.000)	(0.000)	(0.000)
Bulk carrier # Deadweight	100.7***	136.8***	173.3***
	(0.000)	(0.000)	(0.000)
Chemical tanker # Deadweight	264.8***	-124.1	
	(0.000)	(0.525)	
Container # Deadweight	-31.31	113.3***	292.1***
	(0.185)	(0.000)	(0.000)
Cruise # Deadweight	54359.9***	46990.0***	
	(0.000)	(0.000)	
Ferry-RoPax # Deadweight	12346.2***	12889.1***	
	(0.000)	(0.000)	
General Cargo # Deadweight	699.5**	934.2**	
	(0.019)	(0.039)	
Liquefied gas tanker # Deadweight	1143.5***	1601.3***	1768.1***
	(0.000)	(0.000)	(0.000)
Miscellaneous - other # Deadweight	177.3*	200.3	
	(0.065)	(0.656)	
Offshore # Deadweight	6924.8***	5860.4***	
	(0.000)	(0.000)	
Oil tanker # Deadweight	143.0***	102.0***	144.8***
	(0.000)	(0.000)	(0.000)
Other liquids tanker # Deadweight	106.8	-901.0	
	(0.839)	(0.585)	
Ro-Ro # Deadweight	677.5***	-56.63	
	(0.000)	(0.832)	
Service - other # Deadweight	1861.2**	2146.3	
	(0.024)	(0.230)	
Vehicle # Deadweight	1692.0***	-2586.0***	
	(0.000)	(0.000)	
Constant	9302448.7***	16289922.5***	19642173.8***
	(0.000)	(0.000)	(0.000)
Shipping segment x Year FE	No	Yes	Yes

	(1) Newbuild price	(2) Newbuild price	(3) Newbuild price
R-squared	0.937	0.959	0.930
N	4457	4457	3772

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:

$$P^{new} = a_1 \times dwt \times S + a_2 \times mcr \times F + \ a_2 \times dwt \times S$$

With a_1, a_2, a_3 three vectors of coefficients, S a vector of dummy variables to control for the shipping segment, 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 (Figure 1). The resulting second-hand value is computed as follows:

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

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

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

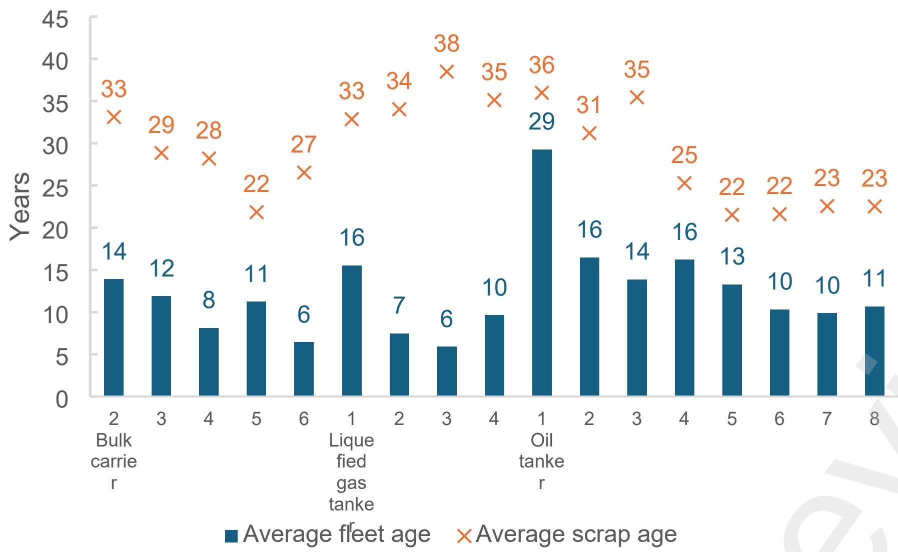


Figure 1: Average scrap age and average fleet age (including orderbook) per shipping segment and size bin. Calculated using Clarksons WFR data.

The numbers on the x-axis correspond to the 4th IMO study size bins

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 et al., 2017; 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(MSI, 2019), whose slope depends on the second-hand market. In contrast, Hong et al (2022) implicitly assume 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)(Hong et al., 2022), an assumption that is also supported by Adland et al (2023) (Adland et al., 2023), and Merika et al (2019) find a broadly linear decreasing curve between age and the log of second-hand value using a non-parametric regression(Merika et al., 2019), which, when converted into absolute value, suggests that depreciation is linear[2]. The resulting curve is close to linear. Third, it might be that the ships depreciate to an earlier date than their scrapping age. The validity of those assumptions is sense-checked against the depreciation curves induced by second-hand prices reported in Clarksons Shipping Intelligence (SIN)(Clarksons Research, 2023). The results, discussed in the supplementary materials, broadly support the validity of those two assumptions.

Finally, the estimated value of the fleet validates well with the estimates from Clarksons Shipping Intelligence Network (SIN) (see the supplementary materials). This gives confidence that although individual ship second-hand market prices might differ from their estimated value, given the limitations mentioned above, the method is adequate to estimate the total fleet value.

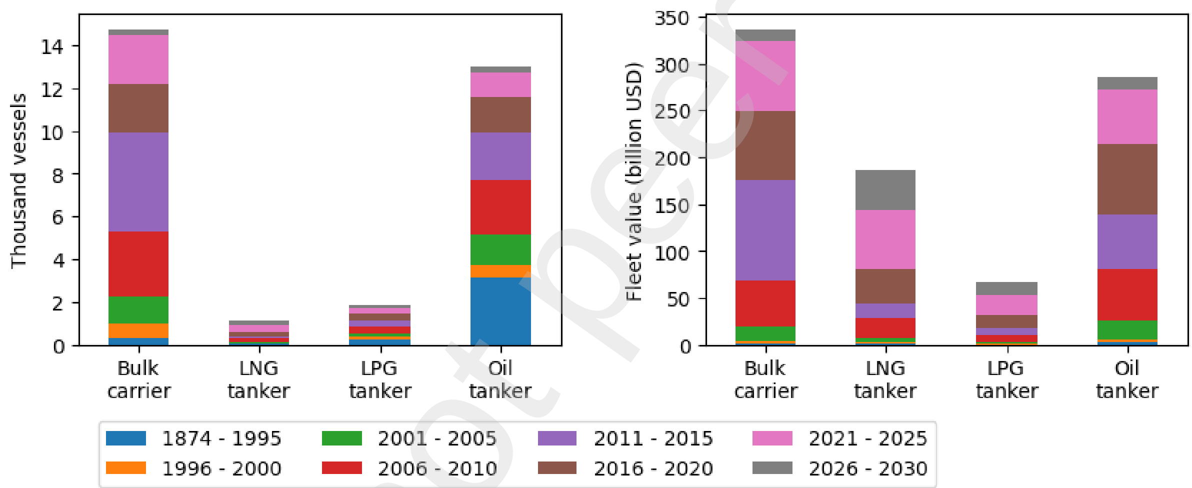


Figure 2: Sunk capital: fleet value by segment and build year in 2023, under the scenario “No further ordering”

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

Valuing expected earnings

Let us now turn to the estimation of expected earnings over a ship’s lifetime and at the time of investment. We 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

[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

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 the following equation:

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

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. We assume that each ship is built in year $built$ 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. When aggregating for all ships, the expected supply for each segment is calculated as follows:

$$CS_s = \sum_{i \in F_{s,z}} \sum_{t \in [t0, t_0 + ScrapAge_{s,z} - Built_i]} CS_{i,t}$$

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

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, we assume that she expects to collect future earnings as follows:

$$\tilde{\Pi}_i = \sum_{t \in [t0, t_0 + ScrapAge_{s,z} - Built_i]} CS_{i,t} \times P_s \times EarningsRatio$$

with P_s the price of shipping, expressed in USD/tonne-mile and $EarningsRatio$ the average earnings as a share of revenue. It is assumed that she expects the earnings and earning share to remain constant and equal to its long-term trend. The authors acknowledge 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:

$$\widetilde{\Pi}_s = CS_s \times P_s \times EarningsRatio$$

2.2. Methods for calculating demand-side risk

Let us now turn to the estimation of the scale of demand-side risk. Demand for transportation of fossil fuels is expected to fall if the world economies decarbonise. This means that part of the shipping activity and the earnings that the shipowner expects from ship i at the time of investment may not materialise should the world economy decarbonise. 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. At any time t, shipping supply that exceeds shipping demand is considered at risk of being stranded on the demand side. The stranded supply $S^{Stranded,D}$ is summed throughout the period, as follows:

$$S_c^{Stranded,D} = \sum_{2018}^{2050} CS_{s,t} - D_{s,t}$$

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

$$\Pi_c^{Stranded,D} = S_c^{Stranded,D} \times P_s \times \mathrm{EarningsRatio}$$

Calculating book loss is less straightforward and requires an allocation of stranded supply to individual ships. We do so 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 we scrap all ships starting from those with the lowest ratio, until the sum of their cumulative committed supply reaches the amount of stranded supply $S_c^{Stranded,D}$. As a robustness check, we also allocate the stranded supply to the older ships first. The results are reported in the supplementary materials; they show a higher amount of book loss for oil tankers, but similar for liquefied gas tankers. The results for oil tankers show that the estimates presented in the results are conservative, as a less than the optimal allocation of stranded supply to ships would result in a higher amount of book loss.

2.3. Data collection

Individual ship data was collected from Clarksons WFR(Clarksons Research, 2022), including :

- Demolition year and price, and build year of scrapped ships which are used to estimate c 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 supplementary materials. Figure 1 shows the average scrap age calculated for each peer group (segment $\times$ size bin) using Clarksons WFR scrapping and built dates. Size bins z are(Faber et al., 2020) based on the IMO 4th GHG study size categories (Faber et al., 2020).
- 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.

We focus on four segments, namely, bulk carriers, oil, LNG and LPG tankers. Descriptive statistics on the fleet are provided in Table 3.

Table 3: Descriptive analysis of the fleet

Shipping segment	Av. build year	Av. scrapping age	Av. remaining lifespan	Total dwt	# vessels
Bulk carrier	2012	29	18	1,049,069,115	13,652
Oil tanker	2002	30	12	620,008,859	10,311
LNG tanker	2016	38	31	94,022,569	1,108
LPG tanker	2009	33	20	42,449,307	1,838

Future shipping demand has been taken from the IMO 4th GHG study(Faber et al., 2020), which itself built on the predictions of the Institute for Applied Systems Analysis (IIASA) database. Several models were used in the IMO 4th GHG study to estimate the shipping demand, described in Table 4 (Faber et al., 2020):

- Shipping demand for energy commodities (coal, fossil gas and oil) : The shipping demand corresponding to the representative concentration pathway (RCP) RCP1.9 is used in this paper as the shipping demand aligned with a 1.5ºC carbon budget. Two scenarios were provided, one estimated using the logistic model (RCP19L), and a projection based on International Institute for Applied System Analysis projections (RCP19*);

- Shipping demand for non-energy commodities: each SSP compatible with RCP19 was used in this paper, namely, SSP1, SSP2 and SSP5. In the IMO 4th GHG study, those were estimated using a logistic model (L) and a gravitational model (G)

Table 4: Description of demand scenarios. From (Faber et al., 2020)

Non-coal dry bulk, containers, other unitized cargo and chemicals (relation between transport work and relevant drivers: Logistics, denoted by _L; Gravitation model, denoted by _G)	**Coal dry bulk, oil tankers and gas tankers**
Long-term socio-economic scenarios	**Long-term energy scenarios**
SSP1 (Sustainability – Taking the Green Road)	RCP1.9 (1.5° C) in combination with SSP, SSP2 and SSP5)
SSP2 (Middle of the Road)	RCP2.6 (2°C, very low GHG emissions) in combination with SSP1, SSP2, SSP4 and SSP5
SSP3 (Regional Rivalry – A Rocky Road)	RCP3.4 (extensive carbon removal) in combination with SSP1, SSP2, SSP4 and SSP5
SSP4 (Inequality – A Road Divided)	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)	RCP6.0 (2.8°C medium baseline, high mitigation) in combination with SSP1, SSP2, SSP4 and SSP5

It is worth noting that an infinite number of pathways are possible to remain under 1.5ºC increase in temperature, so one IIASA input scenario is only one possibility for future fossil fuel consumption among others. We estimate stranded assets in all the shipping demand scenarios available in the IMO 4th GHG study and report the resulting range of results. Using this range allows to control for 1/ the methodological uncertainty in deriving shipping demand from fossil fuel consumption, and 2/ for the effect of various socio-economic scenarios on non-energy shipping demand. It does not cover however the uncertainty in the initial dataset, i.e. the range of possible consumption of fossil fuel by the world economy under a 1.5°C scenario; nor the uncertainty linked to changes in trading patterns, e.g. re-shoring or to which extend pipelines or ship transport would be used.

Shipping demand is allocated to the shipping segments according to the mapping found in the supplementary materials. As the study does not differentiate between LNG and LPG trade, those two segments were grouped under “liquefied gas tankers”. Future shipping demand was estimated in 2018 in the IMO 4th GHG study and is based on scenarios that assume a continuous and linear decarbonisation of the world economy starting from 2018.

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

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

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 distances have been taken from the IMO 4th GHG study estimates in 2018 (Faber et al., 2020). Past and current shipping demand $S_{s,2018}$ is taken from Clarksons SIN (Clarksons Research, 2023). The results are reported in Table 5.

As Figure 3 shows, the modelled and observed shipping demand validate well for bulk carriers. 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.

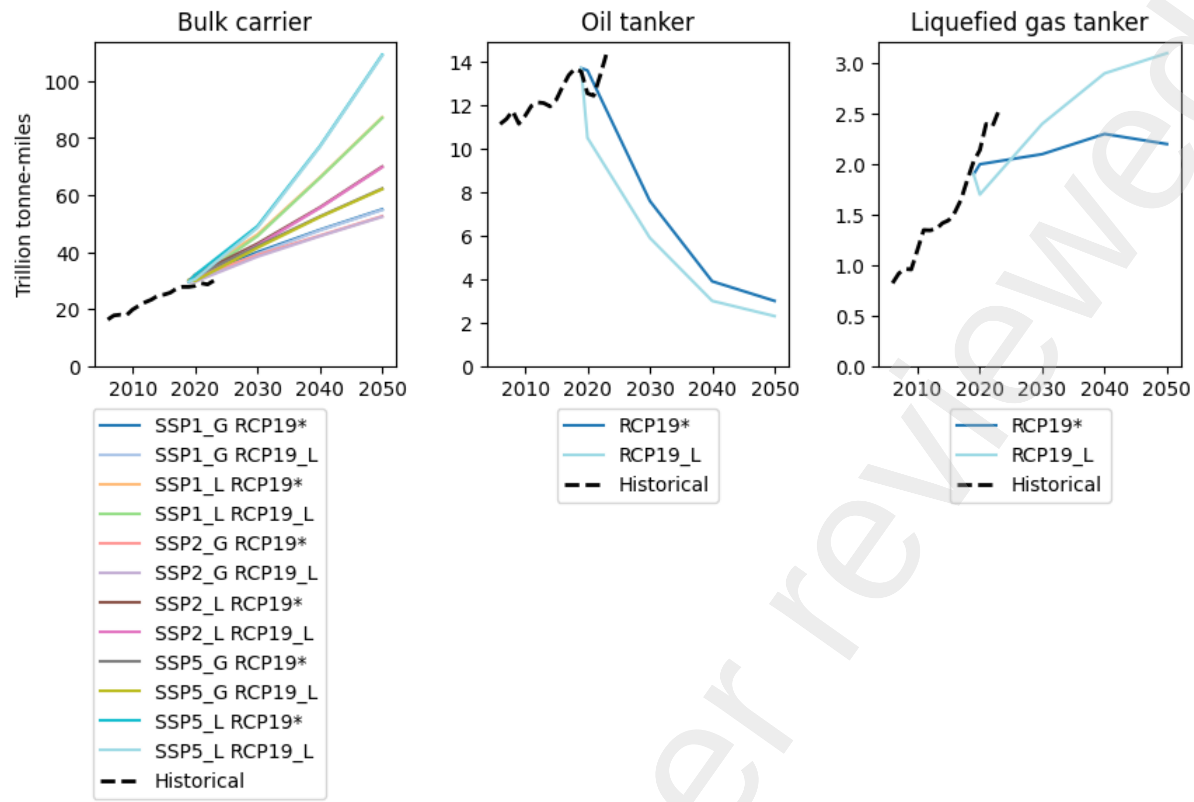


Figure 3: Validation of shipping demand

a. *Projected shipping demand is taken from the IMO 4th GHG study*

b. *Historical shipping demand is from Clarksons SIN*

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[3]. The results are reported in Table 5.

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 (Rehmatulla, 2015; Rehmatulla & Smith, 2015; 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(Rehmatulla & Smith,

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

2020). To estimate the share of fuel cost in revenue, we first estimate the average tonne of fuel burned per tonne-mile transported 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. We then use the average bunker price from Clarksons SIN of HFO and MDO from 2009 to 2019, 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. We find a ratio ranging from 0.36 for liquefied gas tankers to 0.48 for oil tankers (see Table 5).

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. We find that larger ships 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, we use the average for each shipping segment and find non-fuel to revenue ratios ranging from 0.23 (bulk carriers) to 0.22 (oil and liquefied gas tankers) (see Table 5).

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

Table 5: Utilisation, price and cost of shipping, by shipping segment

	Utilisation	Price of shipping ($/tonne-mile)	Fuel cost / revenue	Non-fuel OPEX / revenue
Bulk carrier	0.5123	0.0026	0.42	0.23
Oil tanker	0.4038	0.0044	0.36	0.22
Liquefied gas tanker	0.2765	0.0119	0.48	0.22

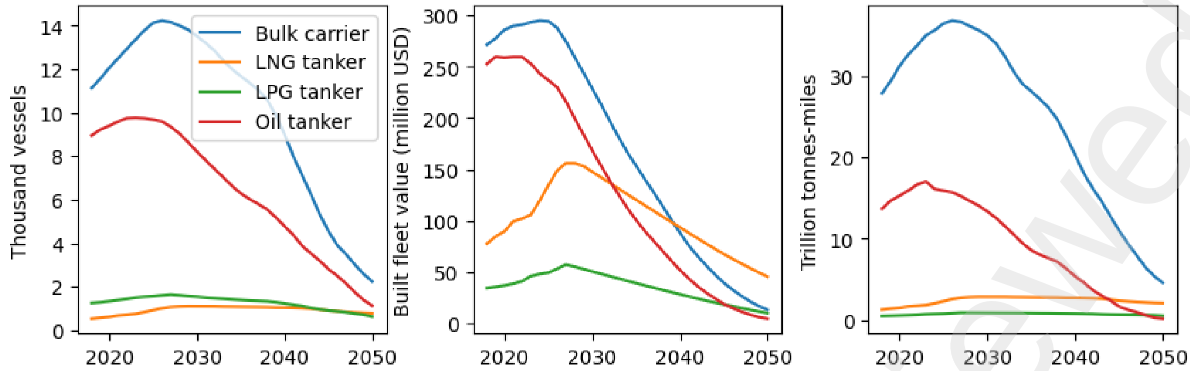


Figure 4: Fleet natural evolution, under the scenario "No further ordering"

3. Results

3.1. A myriad of actors concentrated in space

Let 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 fossil fuel carriers is largely fragmented, with oil tankers and bulk carriers spread across thousands of owners and operators, and Liquefied Petroleum Gas (LPG) and Liquefied Natural Gas (LNG) tankers spread across hundreds (see Figure 5). Oil tankers and bulk carriers are particularly fragmented, while LNG tankers constitute the most concentrated segment. The top 10 owners in each segment, oil tankers, LPG tankers, and bulk carriers, own together less than 17% of the number of ships (both existing and ordered) and no single owner owns more than 3% of the fleet (see Figure 5). The top 10 owners of LNG tankers own together 36% of the number of ships (see Figure 5).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 6), 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 6). 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 7). 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% of the bulk carrier fleet 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 fossil fuel carriers is much more concentrated with fewer actors and geographies. The top 10 shipyards build more than 60% of the existing and ordered capacity (in terms of deadweight but not number of ships) of oil, LNG, and LPG tankers. The construction of bulk carriers is somewhat more dispersed (see Figure 5). Nearly all fossil fuel carriers are built in China, Japan, and Korea, with China building nearly half of the bulk carriers, 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 (Figure 6). This diversification would make shipbuilders less sensitive to the materialisation of demand-side risks.

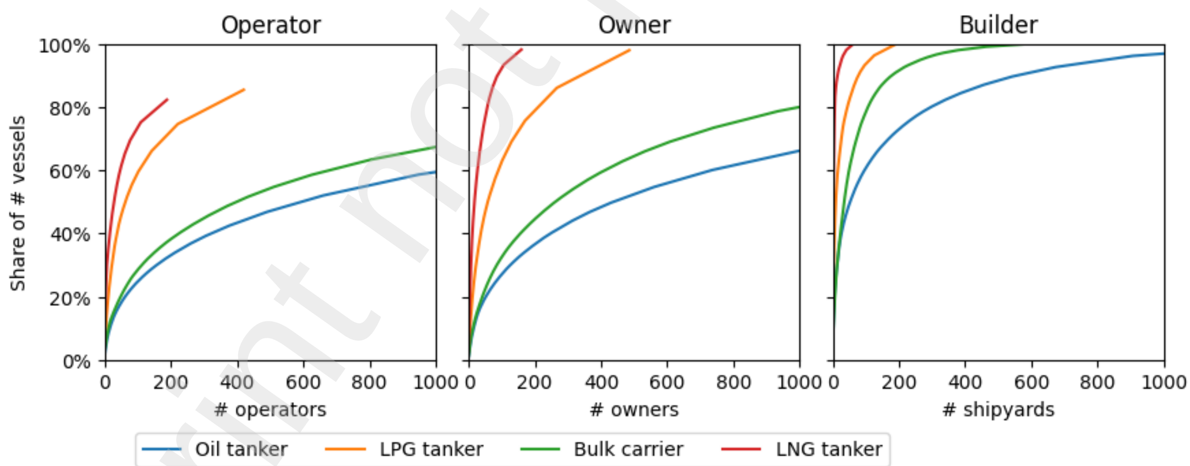


Figure 5: Concentration of fossil fuel carriers by operators, owners and builders

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.*

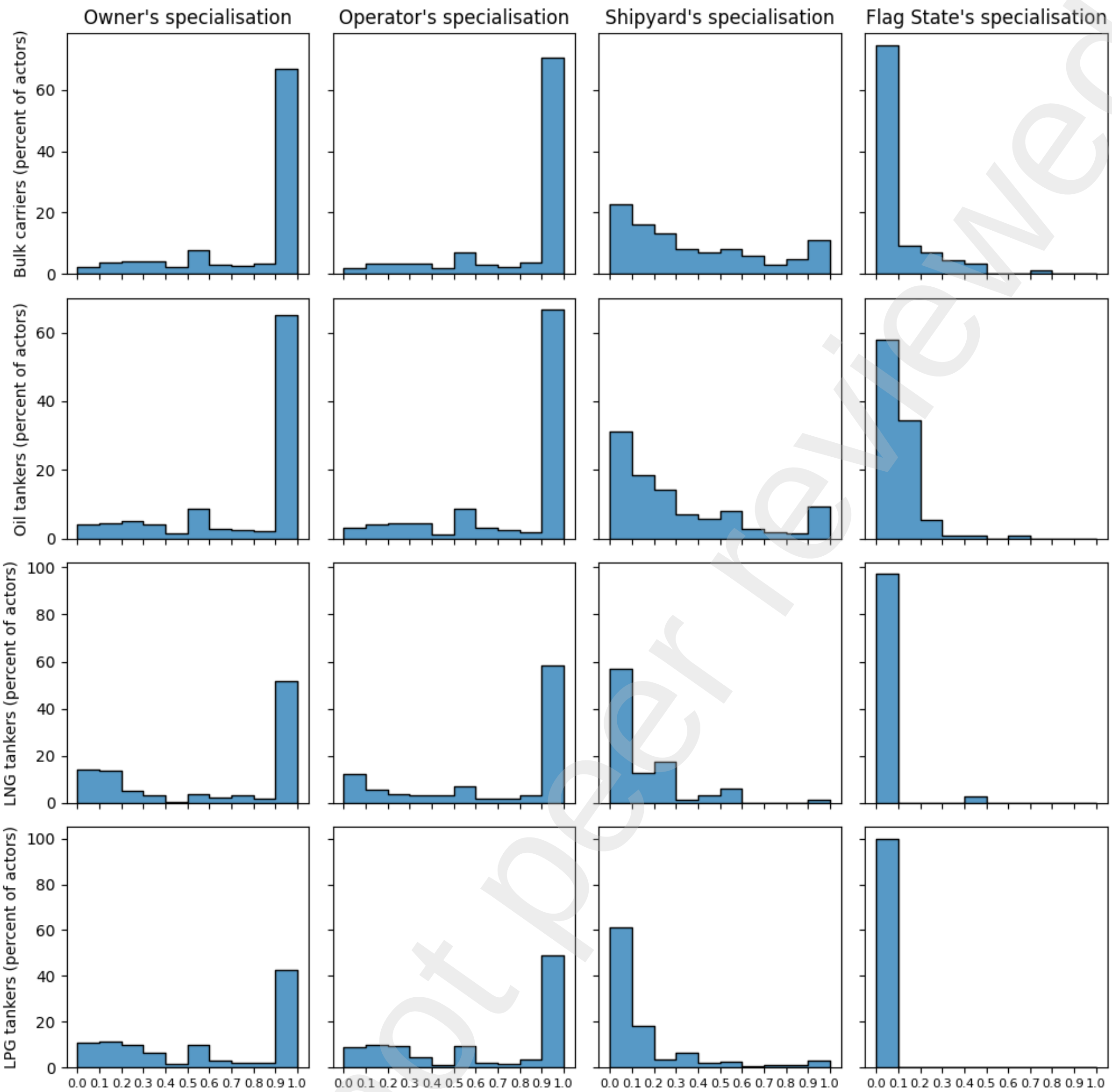
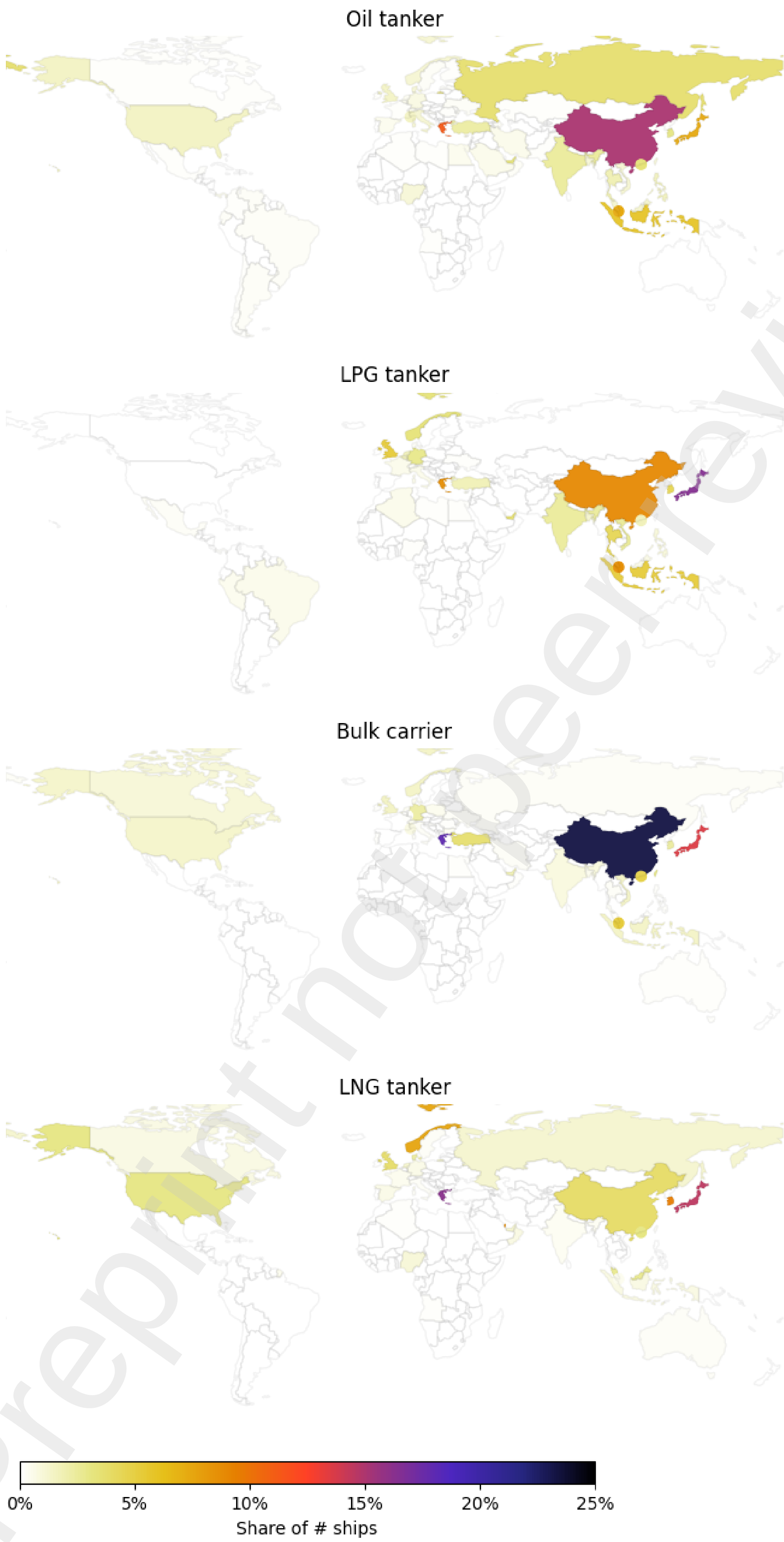


Figure 6: Distribution of actors, by degree of specialisation in fossil fuel carriers

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.*



Oil tanker
LPG tanker
Bulk carrier
LNG tanker
0%
5%
10%
15%
20%
25%
Share of # ships

Figure 7: Share of the fleet of fossil carriers (number of ships), by country of ownership

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

3.2. The fleet of fossil fuel carriers will grow in the short term

Using a combination of regression analysis to estimate newbuild prices and linear depreciation for second hand/existing vessels, we value the current and ordered fleet to be worth around USD 875 billion in 2023, with the bulk carrier fleet (both coal and other bulk) estimated to be worth USD 336 billion, oil tankers USD 286 billion, LNG tankers USD 186 billion and LPG tankers USD 67 billion (Figure 2). They are expected to generate earning stream of USD 1.3 trillion before they retire (USD 571 billion for bulk carriers, 278 for oil tankers and 461 for liquefied gas tankers). The current and ordered capacity of fossil fuel carriers mostly includes bulk carriers and oil tankers, with LNG and LPG tankers representing only a small share of vessels and deadweight (Figure 2). However, because those tankers are more expensive than bulk carriers and oil tankers, the fleet value is more evenly distributed. The 2011-2015 generation of bulk carriers represents a disproportionally large share of the fleet, due to intense ordering at the end of the first decade of this millennium. This is not the case for the other segments, however. Finally, the current orderbook for bulk carriers and especially for oil tankers is fairly limited (9% and 7% of the current fleet deadweight respectively); however, the current orderbook for LNG and LPG tankers is large (55 and 28% respectively), so that new ships or ships to be built (2021-2030 generations) represent more than half of their respective fleets' value (Figure 2).

In the coming few years and in the "no further ordering" scenario, the natural scrapping of older ships is expected to be at least compensated for by the arrival of new ships currently on the orderbook, so that the supply of shipping (in tonne miles), the fleet capacity (in thousand vessels), and the fleet value (in USD) are not expected to decrease. On the contrary, the high level of ordering of bulk carriers, LPG carriers and even more so LNG carriers, means that these fleets are expected to grow up to shortly before 2028 (Figure 8). Furthermore, as LNG and LPG tankers are on average relatively new and have a long lifespan (see Figure 1), the supply and capacity of this fleet are expected to decrease significantly only after 200.

As oil tankers have a faster natural replacement rate, their fleet value remains stable, and the annual supply of transportation decreases already from 2024 on in the "no further ordering" scenario (Figure 8). The decline is fairly rapid because the average remaining lifetime of the oil tankers is short (see Table 3). This is the result of two dynamics: small oil tankers (under 20,000 deadweight) have, with on average 30 years, long lifespans (see Figure 1 in the methods Section), but they are, on average, older (see Figure 1 and Table 3 in the methods Section). Also, larger oil tankers on average have a short lifespan (around 22 years; see Figure 1), but are, on average, younger (see Table 3 in the methods Section).

3.3. A large portion of the fleet of fossil fuel carriers is at risk of being stranded

Let 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, even in the "No further ordering" scenario (Figure 8). The demand for transporting oil products decreases constantly after 2018 (the scenario was produced in 2018; see experimental procedures), 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. However, if further oil tankers are ordered, the committed supply does not fall before 2032 and the oversupply of oil tankers is much larger (Figure 8, "newbuild until 2030" scenario).

On the contrary, the large orderbook and long lifespans for liquefied gas tankers[4] result in their committed supply increasing dramatically until 2029 even in the "no

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

further ordering” scenario, 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 future demand for transporting fossil gas, so the results are also subject to a large uncertainty. However, the committed supply remains much larger than all scenarios aligned with 1.5°C target. Further ordering makes the gap somewhat larger and means that the liquefied gas tanker fleet is in oversupply until 2050 (Figure 8, “newbuild until 2030” scenario).

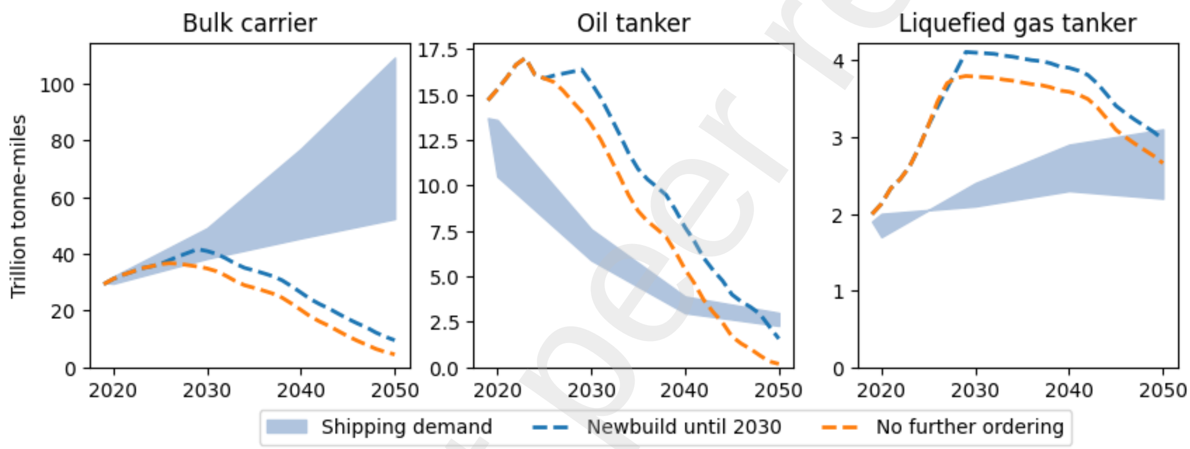


Figure 8: Projected shipping demand and committed supply

a. The blue area represents the range of shipping demand estimates in various demand scenarios.

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 uncertain effect of growth in fossil fuel consumption on trade. 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 of the conservative “no further ordering” scenario, up to USD 10 billion of oil tankers’ annual earnings and USD 8 billion of liquefied gas tankers’ annual earnings fail to materialise (Figure 9). The share of oil and fossil gas shipping demand which does not materialise is found to increase until 2030; by then, it represents 36 to 55% of the total expected supply, depending on the demand scenario (Figure 9). Those annual foregone earning streams reduce fairly rapidly until 2040 for oil tankers, and slowly until 2050 for liquefied gas tankers. Further newbuilds exacerbate the annual foregone earnings: up to USD 11 to 13 billion for oil tankers or 50 to 60% of their annual expected earnings, and to USD 9 to 10 billion or 43 to 49% of expected earnings for liquefied gas tankers in 2030 and in the “newbuild until 2030” scenario. They also lengthen the period during which earnings are foregone.

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 and under the “no further ordering scenario”, 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, and USD 59 to 66 billion or 27 to 31% of the fleet value for liquefied gas tankers in 2027/2028. 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. Further ordering increases the value at risk to USD 41 to 55 billion and USD 65 to 78 billion respectively.

For the bulk carrier segment, our 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 8). As a consequence, bulk carriers 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 in the “No further orderings” scenario, and a few years later in the “newbuild until 2030” scenario (Figure 8). Only in some of the demand scenarios does the bulk carrier fleet become slightly underutilised, and the scale of this is limited (Figure 9) as is the number of potentially unused ships (Figure 10).

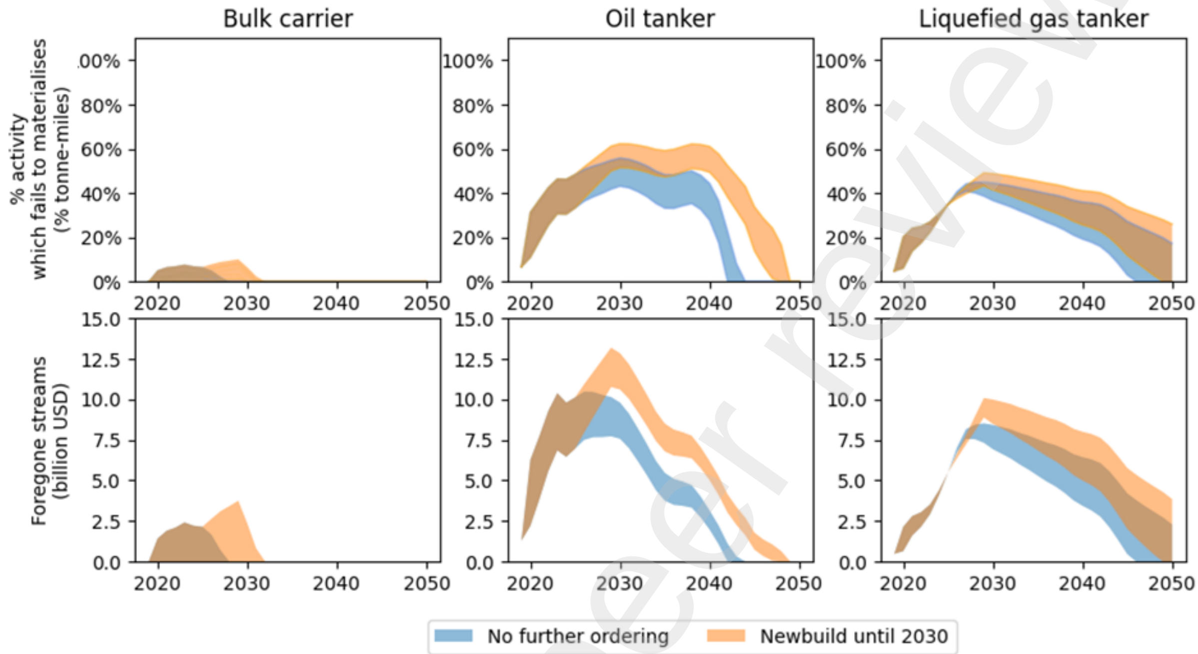


Figure 9: Demand-side risk and foregone earnings streams

a. The areas represent the range of estimates in various shipping demand scenarios taken from the IMO 4th GHG study.

b. Results from 2018 onwards, as the demand was estimated in 2018 for the IMO 4th *GHG study* (Faber et al., 2020)

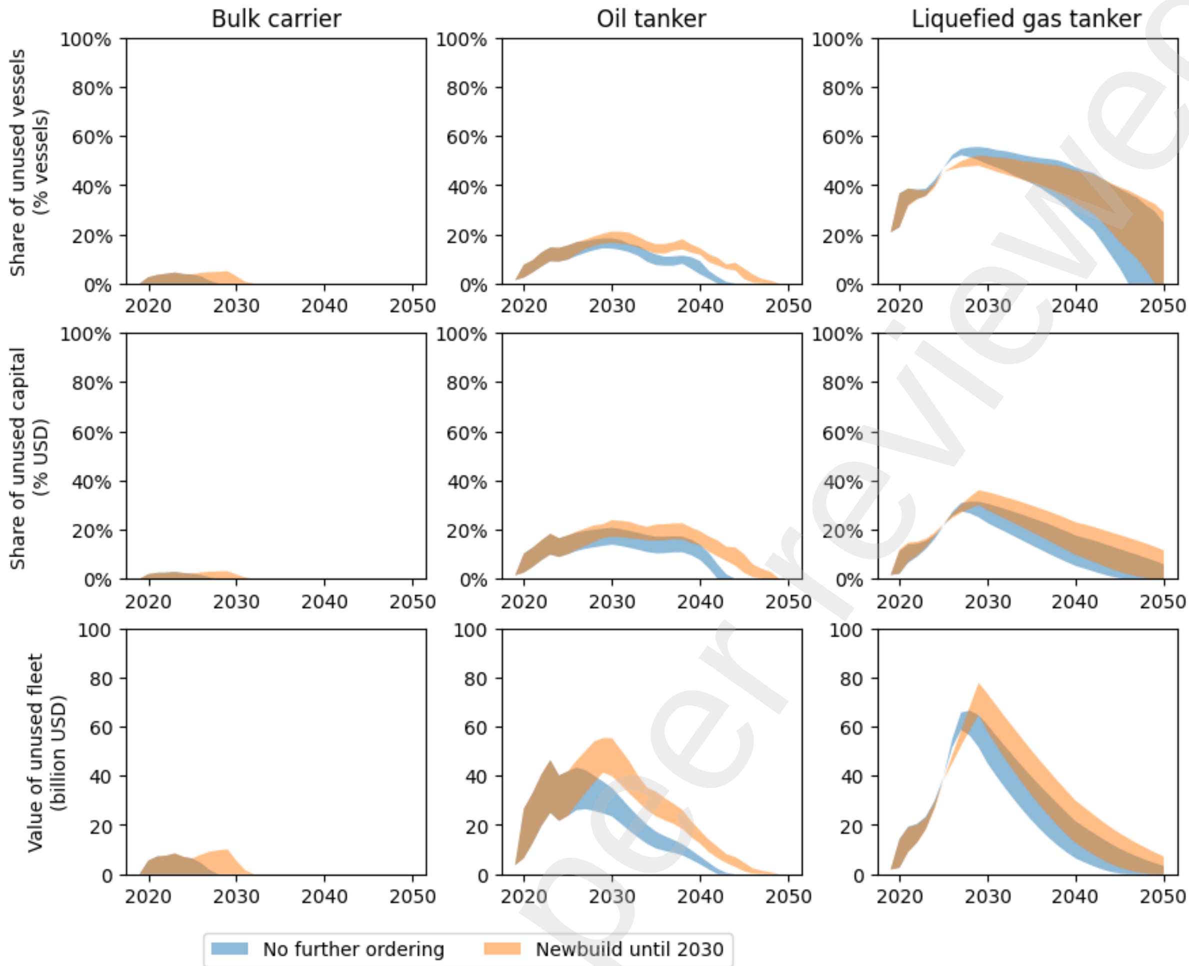


Figure 10: Demand-side risk and book loss

a. *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.*

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 11). 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 if no new carriers are ordered, an amount which increases to USD 373 billion if further ships are ordered. 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, if no new ships are ordered, could amount to USD 92 to 100 billion in 2027 representing around 21 to 23% of the fleet value. This amount further increases to up to USD 120 billion in 2030, if further ships are ordered.

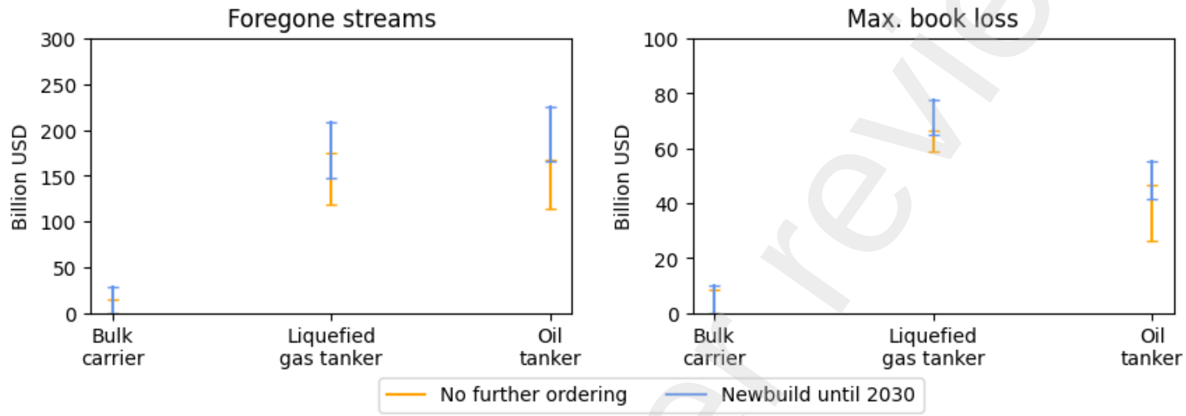


Figure 11: Cumulative demand-side risk until 2050

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. Discussion

This article 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 under two scenarios. These estimates were compared to the energy transition 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. The results indicate that even if no new fossil fuel carriers were ordered from 2024 onwards, 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; Lu et al., 2022; McGlade & Ekins, 2014, 2015; Welsby et al., 2021). Up to USD 100 billions of capital are at risk of being stranded due to demand-side risks.

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. Additional ordering up to 2030 makes the risk even greater, with cumulative foregone earnings streams reaching USD 373 billion or 37% of their expected earnings over the 2018-2050 period. 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 (Walsh et al., 2019). 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; Walsh et al., 2019)); while 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).

Furthermore, 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, 2022) as we write this article, 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, 2022). We estimate that LPG tankers only represent 21% of the committed supply of liquefied gas tankers (see Figure 4), 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 & 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, our results show that ownership, construction and operations of fossil fuel carriers 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 risks on their financiers, for example of 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 fossil fuel carriers, which makes them vulnerable to demand-side risks, 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, 2021; Daumas, 2023), what Daumas (2023) referred to as "stranded paper" (Daumas, 2023).

The results suggest that investors are not looking at long-term trends but are rather driven by short to medium term trends, which is in line with the results of (Fricaudet et al., 2023). However, although much of the potential stranded assets are already built or ordered today, our analysis shows that if investors refrain from investing in certain segments in the coming decades, they can reduce the scale of the risk. This suggests that shipowners and their financiers can mitigate these risks by refraining from investing in ships where future transport demand is largely uncertain, or at least could price this risk into the expected returns at the potential expense of their competitiveness.

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, as the stranded demand estimated in this article represents between 1.8 and 2 billion tonnes of CO2-eq emissions until 2050 if no new ships are ordered, and up to 2.6 billion tonnes if newbuilds continue being ordered[5]. 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(Comer & Carvalho, 2023) 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.

This paper was limited in several ways, which offers 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., 2018) and consequent transportation of fossil fuels has not aligned with a 1.5°C trajectory. Our results therefore likely overestimate the amount of stranded assets in the early years of the study period (2018-2050), 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

[5] Using the carbon intensity, Energy Efficiency Operating Indicator, from the IMO 4th GHG study (Faber et al., 2020), and assuming a ratio well-to-wake to take-to-wake of 1.21 (Comer & Carvalho, 2023)

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 for alternative cargoes was only qualitatively and partially discussed; as the quantitative estimates ignore these possibilities, the estimates should therefore be considered as the maximum value at risk. Daumas (2023) shows that this limitation is shared by various other studies, with exceptions including Bullock et al (2020) and Lu et al (2022)(Daumas, 2023; Lu et al., 2022), who, however, do not monetise stranded assets or retrofitting cost; and Saygin et al (2019) who focusses on the building sector only(Saygin et al., 2019).

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 et al., 2019; Walsh & Mander, 2017). On the contrary, the estimates of shipping demand in the IMO GHG study and therefore the demand used in this paper largely ignore the potential uptake of new commodities such as biofuels, CO_2, 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.

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.

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Authors Contributions

Conceptualisation: MF, SS; methodology, data curation, analysis, writing – original draft, visualisation: MF; writing – review & editing: SS, TS, NR; supervision: TS, NR

Declaration of interests

The authors declare no competing interests.

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