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Integrated Assessment Model of the International Maritime Sector

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Sommario

Con circa il 2% delle emissioni globali di CO_2, la quota attuale delle emissioni del settore navale può aumentare fino a circa il 17% delle del totale di CO_2 emessa. Questo nonostante le norme dell'Organizzazione Marittima Internazionale (IMO), e dovuto principalmente all'aumento della domanda di trasporto marittimo e alla progressiva riduzione delle emissioni di gas serra da parte di altri settori dopo l'accordo di Parigi. L'IMO è costantemente sotto pressione per fornire una tabella di marcia per la riduzione delle emissioni di gas serra. Una comprensione più completa della potenziale evoluzione del settore marittimo, e delle conseguenti emissioni fino al 2050, è necessaria per informare i decision maker su come e quando applicare misure di riduzione delle stesse. L'International Chamber of Shipping (Ics) ha di recente affermato che mal direzionando gli investimenti nella sfida al cambiamento climatico l'industria navale rischia di schiantarsi contro un "iceberg finanziario". Attualmente la letteratura non dispone di uno studio completo che valuti l'impatto delle tendenze del mercato, degli obiettivi di riduzione dei gas climalteranti e dell'evoluzione della flotta. A tal fine, questa tesi stima le potenzialità di riduzione dei gas serra dei combustibili a basso contenuto di carbonio applicati al settore marittimo, interfacciate in un Modello di Valutazione Integrata con i vincoli imposti da un mercato in crescita. I risultati mostrano che i combustibili a basso contenuto di carbonio da soli possono fornire una riduzione delle emissioni di CO_2 per unità di carico trasportato da 1.3 a 2 volte, non sufficiente a soddisfare la riduzione del 50% delle emissioni complessive richieste da IMO nel 2050. Viene qui fornito un metodo robusto e intuitivo per testare il potenziale di futuri metodi di abbattimento tecnico o operativo, svincolato dall'utilizzo specifico che ne è stato fatto in questa tesi. Esso inoltre è esportabile ad altre modalità di trasporto, e costituisce un avanzamento rispetto alla letteratura esistente nella valutazione di misure di mobilità sostenibile.

Abstract

At around 2 % of global CO_2 emissions, the current share of shipping emissions may increase to around 17% of the total CO_2 emitted. This in spite of the regulations of the International Maritime Organization (IMO) and is mainly driven by increasing demand for shipping and emissions reduction from other sectors. The IMO is constantly pressured to provide a roadmap for lowering GHG emissions, compliant with what was agreed in the Paris Agreement. A more comprehensive understanding of the potential evolution of the maritime sector, and subsequent emissions up to 2050, is needed to inform decision-makers on how and when to apply measures to reduce GHGs levels. Literature at present lacks an all-encompassing study that assesses the impacts of market trends, emissions reduction targets and fleet evolution. To this purpose, this thesis estimates the greenhouse gas reduction potentials of low-carbon fuels applied to the maritime sector, interfaced in an Integrated Assessment Model with constraints imposed by a growing market. Results show that low-carbon fuels alone can only deliver a reduction of CO_2 emissions per unit freight transported of 1.3 to 2 times, which is not enough to meet the 50% cut of CO_{2eq} levels in 2050 requested by IMO. Here a robust and intuitive method is developed, able to test the potential of any technical and operational abatement possibilities, beyond the specific technologies selected in this thesis. Moreover, it is exportable to other transport modes, constituting a novel piece of literature for the assessment of sustainable mobility measures.

Extended Abstract

Introduction

From the early days of human civilization sea transport has driven trades between continents, nations and regions. Together with trade liberalization, telecommunication, and international standardization, maritime transport is considered one of the cornerstones which enabled the Globalization of the world (1). In years 1950-2010 maritime transport faced an increase twice as much the GDP growth, and international trade has grown five times faster than GDP as well as trade in percentage of GDP, which grew from 5% up to 24% in the period 1950-2010 (2). Like the majority of the other means of transport, ships emit greenhouse gasses (GHGs). Of the exhaust gases, carbon dioxide (CO_2) has only climate effects, while Nitrogen oxides (NOx) and methane (CH_4), have both climate and adverse local and regional environmental impacts, e.g. on human health (3). According to the Fourth IMO GHG Study 2020 (4) from the International Maritime Organization (IMO), maritime transport represented 2.89% of the world's global anthropogenic CO2 emissions in 2018. On the numerical value, 977 million tones constituted in 2012 total CO_{2eq} emissions, and in 2018 this amount grew to 1,076 million tones. On the other hand considering a longer year's span, in the period 2008-2018 emissions appear to be felt by 10% while at the same time seaborne trade experienced a 40% increase (5). Sea transport emissions are foreseen to increase by 150% – 250% in 2050 in business-as-usual scenarios (BAU), where no further mitigation measures are taken in combination to the tripling of world trade. Therefore, total emissions in 2050 are prospected to grow at 2.5 to 3.5 times today's level as reported by OECD 2010 (6) and Eyring et al. 2009 (7). To withstand the 50% – 85% reduction target set by the IPCC 2007 (8), the total seaborne emissions in 2050 should be no more than 15% – 50% of today levels. Hence, the level of CO_2 emitted per unit freight transported should be reduced from 20 gram to as minimum 4 gram per ton-nautical mile by 2050.

The only regulations currently in place mandating improvements in ship energy efficiency are the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), both enforced by the IMO. In April 2018 the IMO introduced a strategy to limit GHGs emissions from international shipping. The plan proposes to cut absolute GHGs emissions by at least 50% by 2050 and aims to eradicate them entirely thereafter. To reduce carbon intensity in the near term, energy efficiency measures along with slow steaming, are valid. Whereas over the longer term, it is crucial to develop policies able to promote the adoption of low- and zero-carbon fuels and technologies for oceangoing vessels. Because zero-emissions fuels are considerably more expensive than conventional fuels, policies are needed to bridge the price gap (9). Also, the development of abatement technology R&D should be intensified, provided that transition times are proportional to vessels lifetimes of 20-30 years (10).

A deeper understanding of the potential evolution of the maritime sector up to 2050 is needed to inform decision-makers on how and when to apply measures to cut GHGs emissions. This thesis is an important addition to the existing literature: it estimates GHGs reduction potentials of technologies applied to the maritime sector, while interfaced with the demand imposed by a growing market. This analysis will be carried out via an Integrated Assessment Model, merging a stand-alone sectoral model for the Ship Transport System in the message-ix platform, an International Trade model, and GHGs abatement technologies diffusion scenarios. The purpose of this project is to derive a forecast of CO_{2eq} emissions, determine if any strategy has a predominant effect on the results and which solutions appear at the moment feasible in a cost-effective perspective.

Method and Data

The next section presents the logical steps of the construction of the maritime emissions model. The analysis focuses on three cores: demand side, supply side, emissions side. Each one is the result of the application of econometric or mathematical models and data analysis. To give an insight of the model logic as a whole, CO_2 emission forecasts are based on freight transport-work forecasts, which in turn depend on a series of long-term socio-economic forecasts (SSPs), and are influenced by the evolutions in fleet composition in terms of economies of scale (EOS) and energy efficiency. The steps for the estimation of CO2eq emissions from shipping are listed below and presented in the form of flowchart in Figure 1:

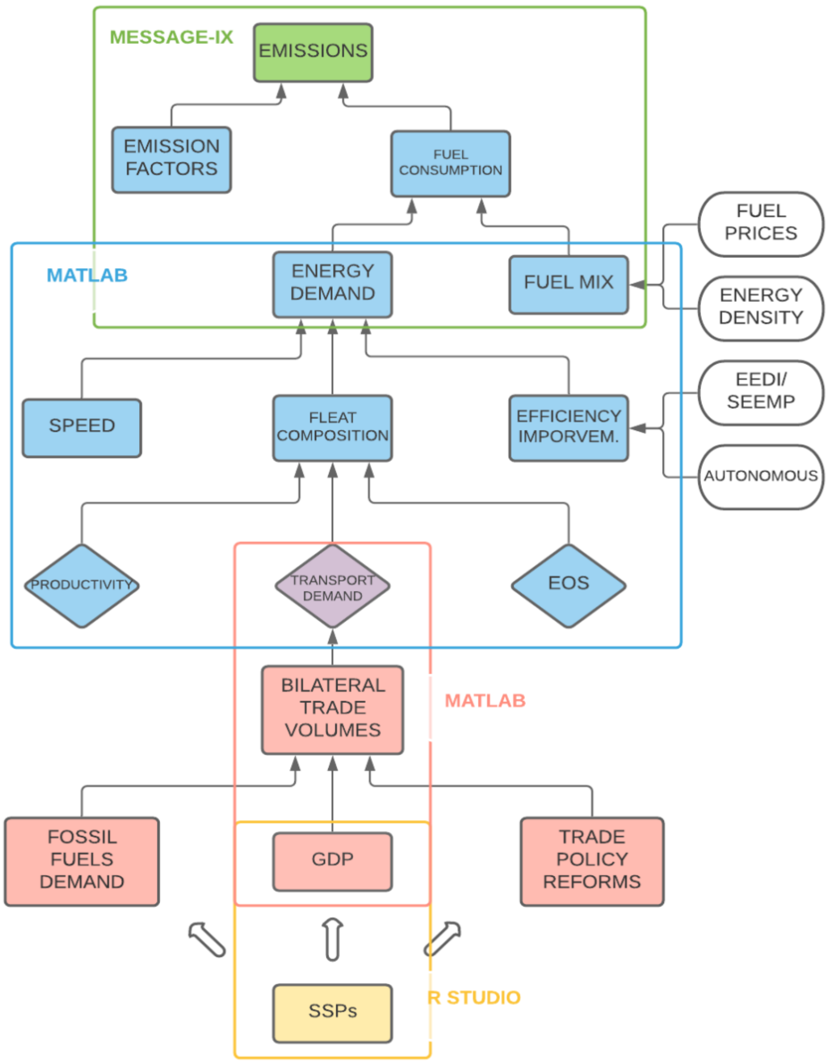

Figure 1: flowchart for overall CO2-eq projection model

1. Forecast the demand for transport of energy and non-energy products for four categories of ships (containers, bulk carriers, oil tankers and chemical tankers) in all their bin sizes.
2. Detailed forecast of the evolution of the fleet compared to base year 2015.
3. Estimate of energy consumption per transport unit (kWh/ton-nm) in the 2015-2050 horizon.
4. Assessment of the fuel mix scenarios, hence the penetration rate of zero emissions fuels.
5. Combination of data derived from points 3,4 and emissions projection in the period 2015-2050.

1. Transport demand projections

The estimate of the demand for freight transport build on forecasts in global GDP and bilateral trade, which in this study are linked together through the "gravity model". The fundamental insight of the gravity model is the direct proportionality between trade flows and the economic dimension of the countries considered, and inverse with the costs of trade itself, proxied by the measure of distance separating the countries and the resulting transport costs. In its most basic form, the gravity model can be described as follows:

$$\log X_{ij} = a + b \log GDP_i + c \log GDP_j + d \log \tau_{0,ij} + e_{ij} \qquad (1)$$

$$\log \tau_{0,ij} = \log(distance_{ij}) \qquad (2)$$

Where *X_ij* indicates trade monetary volume between countries *i* and *j*, GDP stays for country's gross domestic product and *τ_ij* represents trade costs between the two locations, which are proxied with geographical distance, and *e_ij* is a random error term. The *a* term is a regression constant, while the b, c and d terms are coefficients to be estimated. The first step in the application of the gravity model is to derive these coefficients, starting from a linear regression made using R+, and referring to data from CEPII (11). The next step after coefficients regression and calibration is to obtain the actual trade volume projections. To do this, input GDP data from the International Institute for Applied Systems Analysis (IIASA) (12) are used. Estimates of GDP trends are obtained for each SSP through the OECD Env-Growth model. For the purposes of this study a total of 625 couples in bilateral trade partners is considered, thus GDP's database provided in 32-regions resolution is used. For an insight of the results, a heat map is shown in Figure 16. Each pixel represents a certain level of bilateral trade in 2050 between two of the 25 countries, indexed to 2015 values. To facilitate understanding, black lines are inserted to delimit groups of countries belonging to the same continent. The rows represent the exporting countries while the columns represent the importers. This graphic tool is useful to capture the different evolution of some markets compared to others.

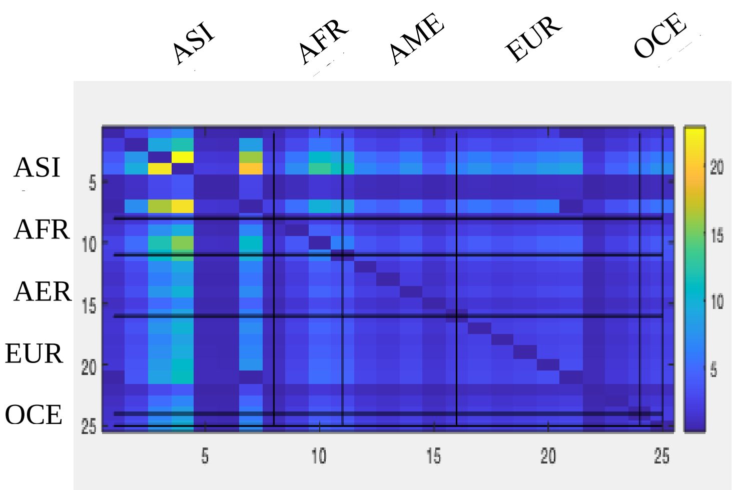

Figure 2: Heat map for SSP1, year 2050. Values are indexed with respect to 2015 level of trade.

Figure 2 refers to SSP1 scenario, and it can be noticed that in 2050 some trade routes will increase in monetary value up to 20 times compared to 2015, as visible in the top left corner which represents the import-export in Asia. This effect is mitigated by a modest or nearly zero increase in other regions, for example in the Eurozone shown in the bottom right corner, so that overall world trade is expected to be 2 to 3 times 2015's levels.

The process of converting trade volume forecasts from monetary value to unit of weight, which is essential to build the demand for freight transport (ton-nm), is based on a simple principle of proportionality. This means that the weight of goods shipped for each year after 2015 will be equal to the product of the monetary value of trade exchange by a proportionality coefficient, *r* which is computed for 2015 and assumed to be constant within the horizon. The logical approach is shown in Figure 3.

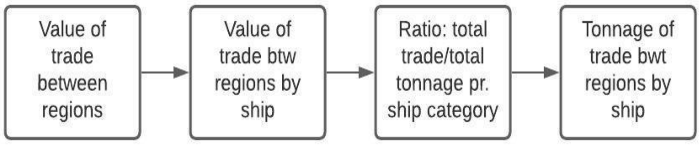

Figure 3: Flowchart for tonnage of bilateral trade estimate logic.

2-3. Fleet evolution and fuel consumption

The demand for transport is met by the use of different types of ships, in turn divided by size categories. In order to retrieve the fuel consumption estimates in the horizon, it is important to reconstruct the evolution of the fleet for the vessel's types considered. This study will use the division adopted by IMO in its Third and Fourth Report (4) (13). The main transition's drivers are the adoption of economies of scale (EOS), energy efficiency requirements, and the growing demand for transport-work. Hence, characteristics regarding the average capacity of vessels (in TEU for containers and in dwt for all other categories), the productivity (defined as ton-nm/dwt) and the total number of vessels per each size bin, are expected from literature to evolve as shown in Tables 1 and 2. For a given year the total number of vessels is retrieved dividing the demand by the total transport work of the category (ton-nm/ship) which in turn depends on the productivity from year to year. The total number of vessels is then split into size bins according to the distribution for that year. This method is used to compute the final (2050) fleet composition, while the trend in the intermediate period is derived applying a Logistic Model, whose algebraic formulation is shown in Equation 3. The logistic function typically previews a slow spread at first, steep increase in the mean part and level off towards the end of the horizon, giving rise to an S-shaped trend.

Table 1: Changes in fleet productivity indexed with respect to 2012. Source: Third IMO Report.

Ship type	Productivity		
	2012	2015	2022-2050
Liquid bulk vessels	100	113	125
Dry Bulk vessels	100	102	104
Container ships	100	109	118
General cargo vessels	100	109	118
Liquefied gas carriers	100	106	113
All other vessels	100	100	100

$$NS_{y,s,b} = \left(A_{s,b} * k_{s,b}\right) + \frac{B_{s,b} - A_{s,b} * k_{s,b}}{1 - \exp(-r * (t - \tau))} \qquad (3)$$

Where NS is the numbers of ships in year y, A is 2015's number of ships and B is the number of ships in 2050. In this model, k is 1.008 for container ships, 1.03 for dry bulks and oil tankers, and 1 for chemical tankers. The parameter t is set to be 0.2 for all the ship type, and tau is set to 2033. All values are retrieved from literature.

In order to estimate the energy consumption per each ships type, a retroactive model has been used created from the estimates of CO_2 equivalent emissions for the horizon. The criterion for choosing this approach is due to data availability, as data series on emissions by ship category were already available from previous studies. In the reference study (14) it is assumed that the fuel mix does not change in the horizon and remains equal to 90% HFO (including 5% LSHFO) and 10% MDO.

In the same way the Specific Fuel Oil Consumption (SFOC) was derived as a weighted average of 185 $\frac{g}{kWh}$ for HFO, and 175 $\frac{g}{kWh}$ for MDO. This coefficient indicates the fuel consumption per kWh of energy produced considering the calorific value of the fuel and the average efficiency of an internal combustion engine. Therefore, it is possible to derive the energy consumption for each ship type ship and size category, as shown in equation 4:

$$EC_{y,s,b} = \frac{FC_{y,s,b}}{SFOC} \qquad \left[\frac{kWh}{ton - nm}\right] \qquad (4)$$

Where FC is the fuel consumption in gram/ton-nm and SOFC is the energy provided by a gram of fuel when burnt in an engine, as explained above. At this point energy consumption is decoupled from the specification on the type of fuel used and indicates more generally the demand for mechanical energy to the main shaft. This will be the key input demand of the emission's calculations.

Table 2: Changes in ships distribution between size bins in terms of number (4).

Ship size development			
Ship type	Size Bin (dwt) [TEU for containers]	Distribution in terms of numbers	
		2012	2050
Container vessels	0 - 999	22%	13%
	1 000 - 1 999 TEU	25%	20%
	2 000 - 2 999 TEU	14%	1%
	3 000 - 4 999 TEU	19%	11%
	5 000 - 7 999 TEU	11%	11%
	8 000 - 11 999 TEU	7%	20%
	12 000 - 14 500 TEU	2%	9%
	14 500+	0,20%	6%
Chemical tankers	0-4999	30%	30%
	5000-9999	19%	19%
	10000-19999	21%	21%
	20000+	30%	30%
Oil tankers	0 - 4 999	1%	1%
	5 000 - 9 999	1%	1%
	10 000 - 19 999	1%	1%
	20 000 - 59 999	7%	7%
	60 000 - 79 999	7%	7%
	80 000 - 119 999	23%	23%
	120 000 199 999	17%	17%
	200 000 - +	43%	43%
Dry bulk carriers	0 - 9 999	1%	4%
	10 000 - 34 999	9%	13%
	35 000 - 59 999	22%	32%
	60 000 - 99 999	26%	33%
	100 000 - 199 999	31%	12%
	200000 - +	11%	6%

In the following, the results concerning the evolution of the fleet in the 2015-2050 horizon are proposed, considering the various types of ships, derived from a MATLAB model developed for this scope. Figure 4 shows the trend in the number of containerships per each size bin, taking as reference the freight-transport demand derived from input data by Shared Socioeconomic Pathway number 2 (SSP2). The SSPs are a set of storylines on possible evolution of the worlds, used as main framework when working on Integrated assessment Models. The trend within ship categories is the same also considering the other SSPs (though the axis of the ordinates is scaled according to the demand) therefore for simplicity only the one for SSP2 is shown. Figure 6 instead illustrates the trend of the total number of containers for a certain category across the SSPs. As said, it originates from the transport demand forecast for 2050, which in turn depends on the level of bilateral trade and the GDP trend. The factors of fleet productivity and the economy of scale (Figure 5) phenomenon also come into play, which have the effect of increasing the transportable cargo from the category and slightly dampening the strongly increasing trend in trade volume.

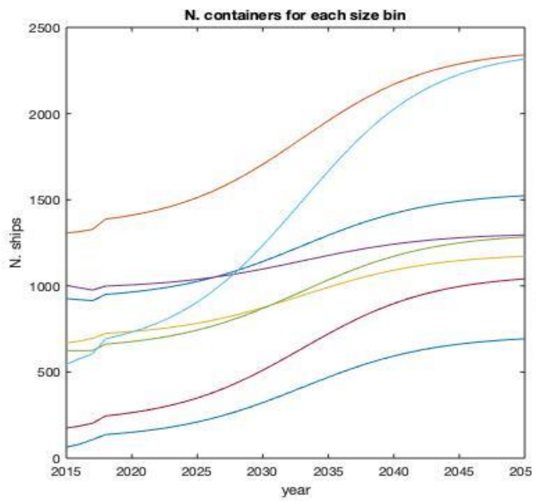

Figure 4: Number of containers every year for each size bin.

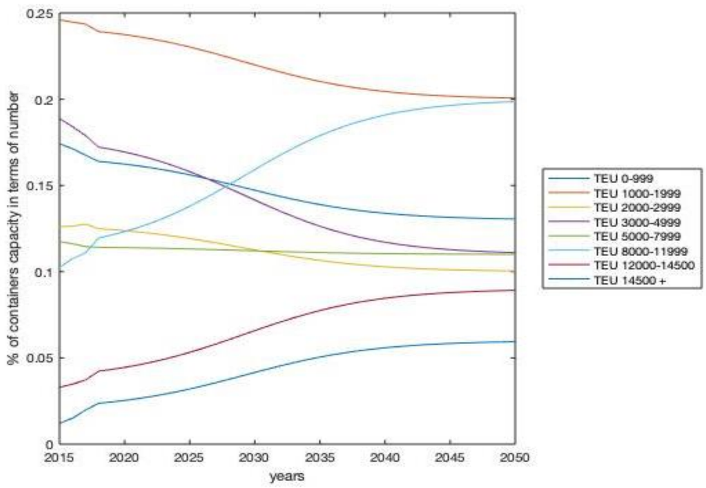

Figure 5: Expected distribution of containerships in terms of numbers over size categories.

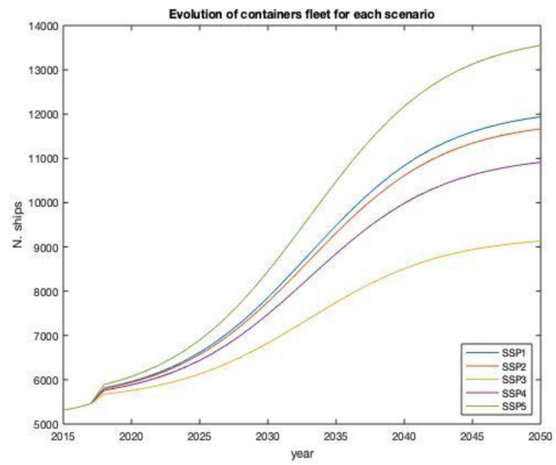

Figure 6: Different evolution in containers number per each SSP.

4. Emissions projection

Technologies have already been outlined in the literature that are assessed as more promising in terms of cost and emission reduction potential than others. The possibilities to reduce GHGs emissions range from solutions concerning the design of the vessel, its operational parameters (such as the reduction of auxiliary consumption or slow steam), the installation of alternative technologies for propulsion and the use of alternative fuels. Low emissions fuels, in particular, present a CO2 abatement potential by 2050 of 64.08% (4), a clear gap compared to all other solutions (the second highest value is 3.95%). For relevance, therefore, in this study it is chosen to consider only the transition to alternative fuels as a method of reducing emissions.

The energy demand can be met through the use of conventional energy carriers such as HFO or VLSFO, MDO or LNG. Alternatively, one can use a selection of alternative fuels (at least theoretically) that call for the use of internal combustion engines (ICE), fuel cells (FC) or steam turbine systems. Low carbon fuels considered in this study are bio-methanol (Bio-MEOH), hydrogen and ammonia. Below are the data concerning GHGs emissions in operational and production phases, for all the fuels involved.

Table 3: Operation and Upstream emissions per each GHG of alternative and conventional fuels. Sources: Bio-MEOH: Lisboa et. al. 2011 (15). Conventional fuels: Smith et. al. 2014 (13).All others: Gilbert et. al. 2018 (16).

Fuel type	**Emission specie**							
	CO_2 (g/gfuel)		CH_4 (g/gfuel)		N_2O (g/gfuel)		CO_{2eq} (g/gfuel)	
	Upstream	Operation	Upstream	Operation	Upstream	Operation	Upstream	Operation
HFO/LSHFO	0,338	3,114	0,0032	0,00006	0	0,00016	0,4276	3,158
MDO	0	3,206	0,0032	0,00006	0	0,00015	0,0896	3,247
LNG	0,511	2,75	0	0,051	0	0,00011	0,511	4,212
BioMeOH	2,034	0	0	0	0	0	2,034	0
LH2 ren.	1,798	0	0	0	0	0	1,037	0
LH2 fossil	14,38	0	0	0	0	0	10,375	0
NH3 elec.	0,231	0	0	0	0,00001	0	0,233	0

In the estimation of specific emissions per unit of fuel, the method by which these emissions are calculated is important. In particular, the value can change considerably if a Life Cycle Assessment is considered. This aspect becomes even more important if alternative fuels are examined because in most cases, they are "emissions free" at the consumption time, but to assess whether they are actually effective for abatement purposes one must consider the entire life cycle. In fact, it is possible that in an LC perspective the emissions from a fuel considered "clean" are actually equal or more than traditional fuels, having only "anticipated" them from operational to upstream phase. Figure 7 from Gilbert et. al. 2018 (16) which highlights this aspect. It can be noted that for hydrogen emissions are all upstream and only in the case of production from renewable sources they are equal or lower than those of traditional fuels. Since the reported aspect is particularly relevant to this study, it was chosen to include upstream emissions of all fuels in the analysis. It is beyond the boundaries of this thesis using a comprehensive LCA approach, so I limited to a Well to Wheel (WtW) analysis.

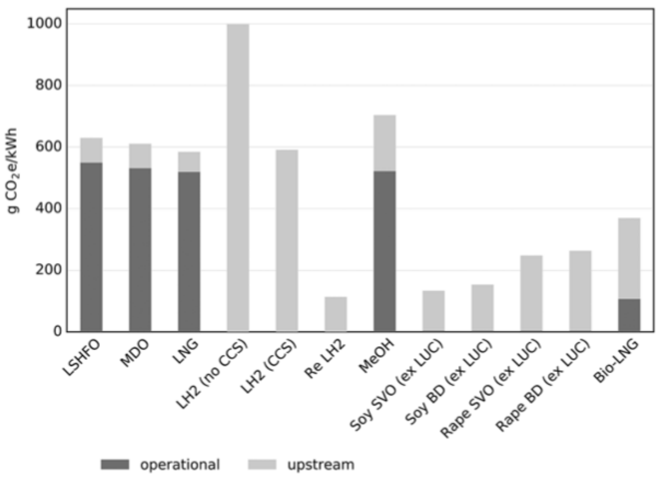

Figure 7: Emissions per kWh of shaft output per each fuel type. Source: Gilbert et. al. 2018 (16).

The model for the estimation of annual CO_{2eq} emissions from maritime transport, consists of a dynamic system least-cost optimization problem. The tool used is message-ix, an open framework for the integrated analysis of energy, climate, environment and sustainable development policies. It was originally formulated for strategic energy planning and integrated assessment of energy-engineering-economy-environment systems (E4). The framework can be used to run models which can range from very simple to very detailed ones, such as the MESSAGE-GLOBIOM global model (17). The framework can be applied to analyze scenarios of transformation of the energy system under technical-engineering constraints and socio-economic considerations. It also includes the possibility to incorporate the effect of price changes on the demand for energy goods and services (18). The model aims to satisfy the demand value of a given commodity in a node (i.e. a region, country, or globally) at the lowest total cost. The most relevant equation is number 5, which shows the mathematical formulation for computing emissions:

$$EMISS_{n,e,y,t} = \sum_{y} ACT_{n,t,y} * emission\_factor_{t,y,e} \qquad (5)$$

Where the *emissions factors* are derived from Table 3 and *ACT* is the activity in kWh delivered by each fuel.

To estimate the penetration rates of technologies that involve the adoption of alternative fuels, IMO set two different scenarios assuming different levels of spread for 2030 and 2050, as shown in Table . This because high cost occurring nowadays along with technical immaturity makes quite difficult to exactly estimate penetration rates for these novel technologies, which are rather or not at all spread by 2018. It is out of the scope of this thesis to assess which one is most likely to happen, rather it was chosen to analyze both. From now on the "optimistic" Scenario 1 is referred to as S1, and "conservative" Scenario 2 as S2.

Table 4: Penetration rates for alternative technologies. Source: Fourth IMO Report.

Technology		**Penetration rates (% of ships applying a technology)**				
		Scenario 1			Scenario 2	
		2018	*2030*	*2050*	*2030*	*2050*
Alternative fuels with carbon	LNG + ICE	1.0%	55.0%	0.0%	1.5%	20.0%
	LNG + FC, Methanol + ICE	0.0%	54.0%		0.05%	
Alternative fuels without carbon	Hydrogen, Ammonia ecc.	0.0%	0.1%	100%	0.05%	20.0%

Results and Discussion

In this section the most interesting results are proposed. The reader is invited to look at the full text if willing to have further explanation of the presented results and other scenarios not discussed here. The graphs resulting from the seaborne energy consumption estimates are presented below. In particular, in Figure 8 the values are indexed to the year 2015 and broken down into the various ship types. The graph in question refers to the SSP2 scenario but the behavior is similar for all the other SSPs considered. Figure 9 instead presents the aggregated values (considering the fleet as a whole) for each SSP.

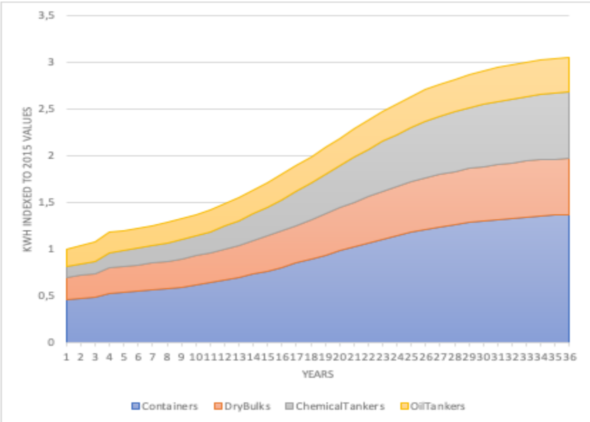

Figure 8: Energy consumption split into ship category, SSP2.

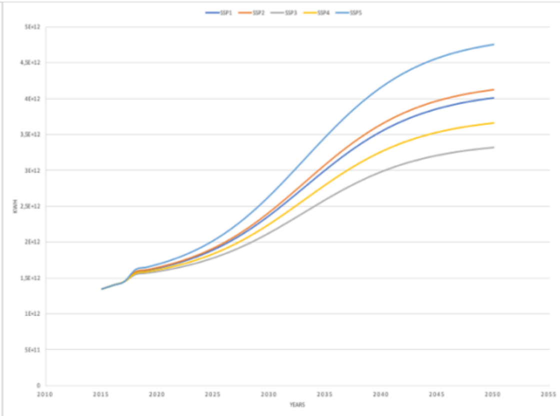

Figure 9: Total energy consumption resulting from fleet evolution model per each SSP.

It can be noted that the trend in energy consumption follows the pattern of the total number of ships in the different categories. This phenomenon is due to the fact that, for the estimation of this value, the forcing factors are the trend in the number of ships (increasing), the productivity of each ship in ton-nm/ship (weak growth) and the energy consumption factor per transport work unit kWh/ton-nm (weak decrease). The last two parameters therefore compensate for their growth and degrowth and induce the number of ships to follow the shape of the transport demand.

Business as Usual Scenario

This section presents the projections of CO_2 emissions of shipping up to 2050 in business-as-usual (BAU) scenarios. In the context of this study, BAU refers to the shipping sector. The definition of BAU is that no new regulation will be adopted for shipping that has an impact on emissions or energy efficiency. The assumption adopted to build the BAU scenario is that conventional and alternative fuels follow the actual market share, hence 99% for Fuel Oils, 1% for LNG and zero for all the others. Figure 10 shows the activity of the different technologies in the hypothesis of an evolution according to business as usual. Then activity graphs for the SSP2-S1 and SSP2-S2 scenarios, in which different levels of technology penetration are set are shown in Figure 11 and Figure 12. The projection of emissions resulting from the three models are compared in Figure 13.

The following considerations can be made from the images below:

- The BAU and S2 scenarios run parallel and, towards the end of the horizon, S2 even bypasses the BAU. The result is justified by the fact that LNG has a higher CO2-eq emission factor than HFO and MDO, and its greater diffusion in S2 compared to BAU scenario implies that overall emissions are also higher.
- The use of alternative fuels, though produced with conventional methods (Steam Methane Reforming), does not contribute to the decrease in emissions and indeed the value stabilizes just below the BAU curve. This is explained by the fact that upstream CO2-eq emissions due to their production are of the same order of magnitude as the operational emissions of conventional fuels. Moreover, with the exception of hydrogen, capacity factors are lower than those of fuel oils and consequently higher fuel consumption is required. In this study capacity factors are defined as the energy shaft output per gram of fuel (in kWh/g).

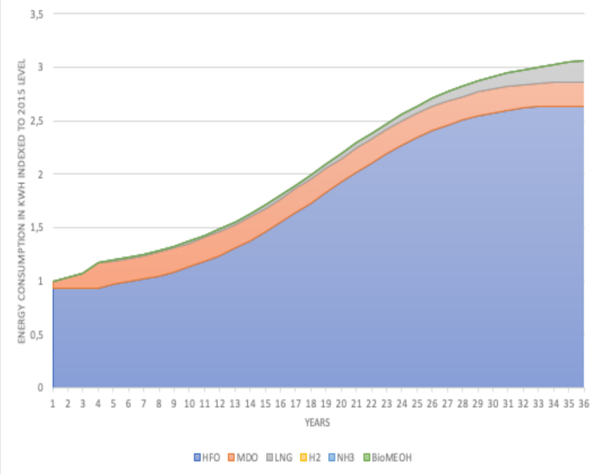

Figure 10: Activity of technologies in a Business As Usual scenario. Values in kWh indexed to 2015

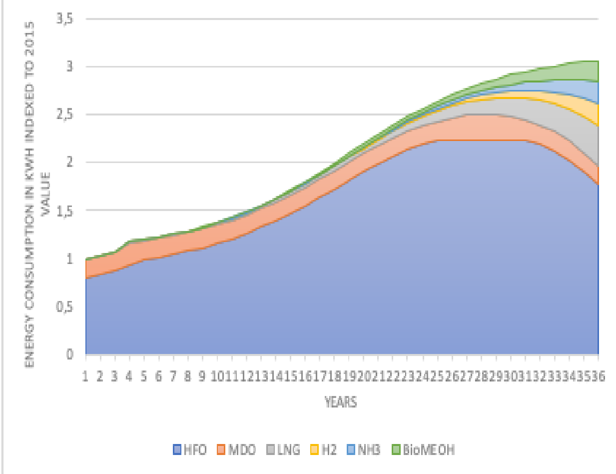

Figure 11: Activity of technologies in Scenario 2. Values in kWh indexed to 2015 levels.

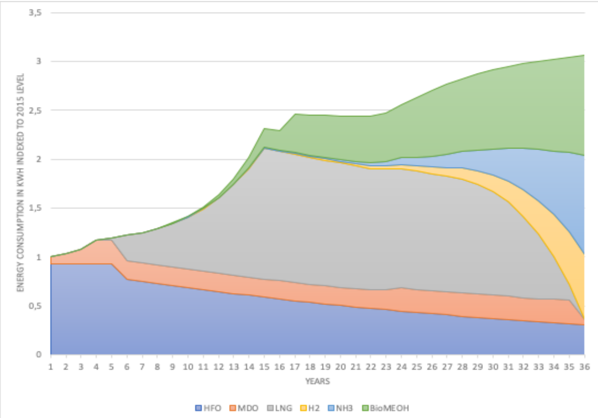

Figure 12: Activity of technologies in a Scenario 1. Values in kWh indexed to 2015 levels.

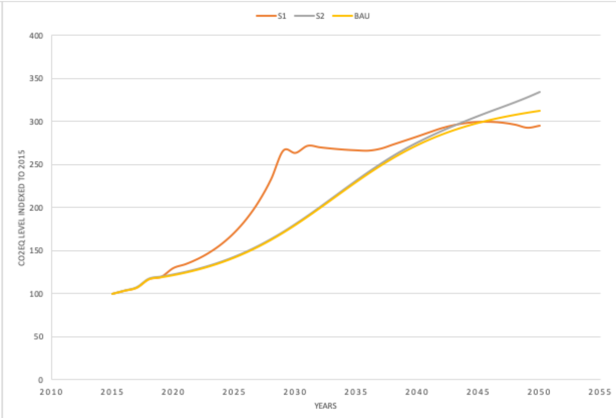

Figure 13: CO2-eq emissions for S1, S2 and BAU starting from SSP2. Values in million tons indexed to 2015 level.

Production of ZEF from Renewable Energy Sources

It is of interest for the above considerations to study the impact of more sustainable production of alternative fuels. This hypothesis has been implemented starting from SSP1 because this scenario, differently from SSP2 analyzed previously, underlies the hypothesis of a rapid and constant detachment from fossil dependence. Below the first two graphs present the share of CO_{2eq} emissions under the hypothesis that hydrogen and ammonia are produced through Water Electrolysis (WE) or Biomass Gasification (BG) (Figure 14) using renewable energies in all phases of the process (Figure 15). For hydrogen, the total emission factor drops from 14.4 to 1.8 gCO_{2eq}/g, while for ammonia it goes from 0.23 to 0.17 gCO_{2eq}/g *(16)*. On the other hand, the overall emissions trend given by the new set-up is reported, together with the scenarios already analyzed previously SSP1-S1 and S2 (Figure 16).

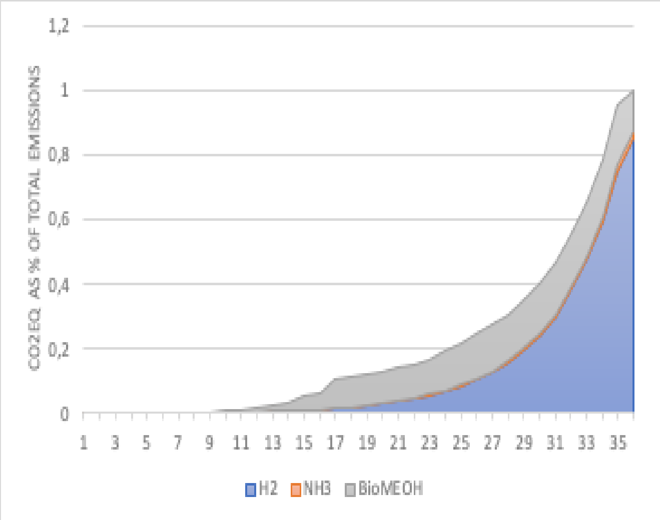

Figure 14: Impact on total amount of upstream emissions from ammonia, hydrogen and Bio-methanol in a scenario where they are produced with conventional methods. Values as a share of total CO2-eq emissions.

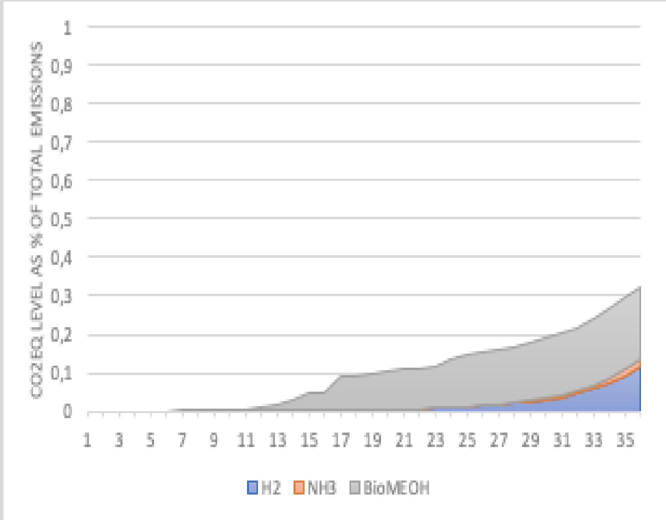

Figure 15: Impact on total amount of upstream emissions from ammonia, hydrogen and Bio-methanol in a scenario where they are produced from renewable energy sources. Values as a share of total CO2-eq emissions.

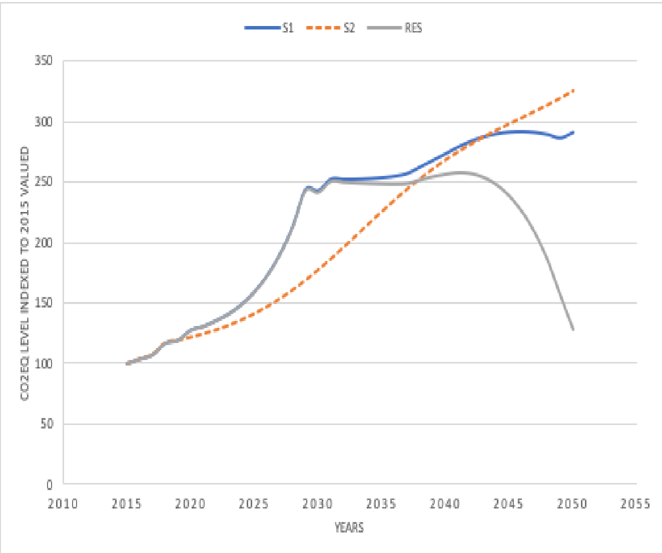

Figure 16: CO2-eq emissions for SSP1 for Zero emissions fuels production starting from RES, plus SSP1-S1/2. Values in million tons indexed to 2015 level.

A more sustainable production of hydrogen and ammonia can reduce their impact on global emissions by 70%. Particularly significant is the behavior of hydrogen, which with WE or BG is able to reduce its share of estimated emissions from 82% to 11% in 2050. As a consequence, while fuel activities remain those typical of the S1 scenario, final CO_{2eq} levels are also 56% lower than in S1 and 60% lower than in S2. Moreover, this means that at the end of the horizon GHGs emissions will be 25% higher than the 2015 values, instead of reaching 300% as in the other scenarios.

Conclusions

One of the goals of my research was to investigate whether and how the fuel transition, combined with the expected tripling of world seaborne freight, could allow emissions reductions by 2050. My studies show that it is difficult to ensure reductions in greenhouse gas emissions and progress towards decarbonization. According to the IIASA SSPs scenario, this projected growth in sea transport is based on global GDP growth that will lead maritime trade to increase by 250-300%. With these assumptions, freight volume will increase from 41 000 billion ton-nm in 2007 to a minimum of 106 000 billion ton-nm in 2050 for SSP3 to a maximum of 153 000 billion ton-nm for SSP5, according to the results of my analysis, which is consistent with the Linstad 2013 projections (2). If freight work is supplied with the current fuel mix (here referred to as 2015 fuel mix in a BAU scenario), the emissions will follow the path of the freight work, thus increasing of three times 2015 levels. This despite the fact that 2050 fleet will undergo efficiency improvements, due to Economy of Scale and productivity increase. Considering modest zero emissions fuels share and rely of LNG to achieve GHG reductions proves completely inadequate, as proven in S2 which gives total sea transport cargo emissions ranging between 2 470 and 3550 million tons of CO_{2eq}in 2050 depending on the SSP evaluated. This equals a 250%-400% increase in emissions compared to the 1 billion ton of CO_2 emitted in 2018 (4) and for three out of five SSP the final value of CO_{2eq} emission goes beyond the BAU's estimate (Figure 41). It will also lead to increased emissions per freight unit transported since the growth, i.e. 170-220%, in freight work is lower than the increase in emissions, thus the final specific emissions would go from 19 $gCO_{2eq}/ton-nm$ up to minimum 25 $gCO_{2eq}/ton-nm$. Even in a more optimistic case where high spread of clean fuels is accounted (S1), emission projections set them close to the former results. Here only SSP5 overcomes BAU 2050 emissions levels, but still the four other SSP predict an increase between 250 and 300% with respect to 2015 CO_{2eq} levels. This led to the main conclusion that adoption of zero emission fuels is ineffective if not coupled with greed decarbonization or and a more sustainable production system.

The fuel options chosen in this paper are based on literature review, but they are not necessarily exhaustive, nor they are unique or mature paths for producing these fuels. A CAP on total carbon levels set to 2 Mt CO2-eq starting from 2030 can provide a reduction of 1.3 to 2 times of specific emissions per ton-nm, which is far from the required 5 to 6 times reduction suggested by Bouman et. al. (19). Low carbon fuels have the potential of reducing their upstream emissions by 70%. Coupled with a substantial shift in the fuel mix in 2050 (referring to S1), this would lower specific emissions per freight unit transported of 1.7 to 2 times from 2015 value. This means that if alternative fuels adoption is to be taken into account, they only prove effective if it comes with sustainable production processes, whose spread is not straightforward nor already happening on large scale. Complicating matters, this is not enough to deliver the necessary cut in global maritime sector emissions, thus it is fundamental to explore all others technical and operational measures not taken into account in this thesis, and any market-based or regulatory instrument to enhance their actuation. Efforts need to be directed at overcoming obstacles for exploitation of the low carbon potential of fuels identified or finding alternatives that are not considered here. Significant efforts will be required for any promising option, first to prove actual applicability and then to be scaled up to industrial level.

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EXTENDED ABSTRACT

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1 Introduction

1.1 Motivation

From the early days of human civilization sea transport has driven trades between continents, nations and regions. Today's trade world put its routes in the middle of the 19th century and contributed to shape the global economy. First technological improvements like steam engines in combination with the industrialization of the West in the 19th century produced a consistent growth in transport and freight trade which followed during the 20th century. More recently, together with trade liberalization, telecommunication, and international standardization, maritime transport is considered one of the cornerstones which enabled the Globalization of the world (1).

Globalization shaped international trade making it not just specific in finished goods and services but extended to components and raw materials used within the production process. This resulted in trade growing more rapidly than the global Gross domestic product (GDP) (20) . As shipping is featured by trade, it is important to understand how and with which timing trading patterns change. Increased trade capability and transport produced advantages for the emerging industry, enable access to raw materials and human capital, the spreading of skilled workforce and machinery at a competitive cost (21). The growth in years 1950-2010 show the following pattern: Population 180%, Energy consumption 470%, GDP 670%, Maritime transport 1500%, Trade 3700% (2). Thus, maritime transport faced an increase twice as much the GDP growth, and international trade has grown five times faster than GDP as well as trade in percentage of GDP, which grew from 5% up to 24% in the period 1950-2010.

The environmental drawback of international trade has risen awareness in the current climate debate. Anthropogenic emissions of greenhouse gases (GHG) have been acknowledged from the scientific community to be the main driver of global warming and temperature increase. Augmentations to more than 2°C above pre-industrial levels are likely to have catastrophic consequences on a global scale (22; 3). The Intergovernmental Panel on Climate Change (IPCC), established in 1988, estimated that in order to reach a stabilization of the temperature at 2°C above pre-industrial levels or below, greenhouse gas emissions has to be cut by around 50% – 85% in 2050, with respect to current levels (8).

The emissions attributable to shipping operations divide between greenhouse gases (CO_2, CH_4, and N_2O) and local pollutants (SO_x, NO_x, and PM). Carbon dioxide (CO_2) is seen as the most important greenhouse gas emitted by ships while other GHGs are considered less important (23). According to the Second IMO GHG Study (23) published by the International Maritime Organization (IMO), shipping sector emitted 1046 million tons of CO_2 in 2007, contributing for the 3.3% to the global anthropogenic CO2 emissions (2). More recent data presented in the Fourth IMO Report 2020 (4) show that the greenhouse gas emissions expressed in CO_{2eq} from global shipping sector (including international, domestic and fishing) have grown by 9.6% from 2012 to 2018, starting from 977 million tons to 1,076 million tons. On the total value, 962 million tons constituted CO_2 emissions, and in 2018 this amount grew to 1,056 million tons. Furthermore, the impact of shipping sector in global anthropogenic emissions has risen from 2.76% to 2.89% in the period 2012-2018 (4). On the other hand, considering a longer year's span emissions appear to be felt by 10% in the period 2008-2018 while at the same time seaborne trade experienced a 40% increase (5). Finally, from 2013 to 2015, the CO_2 intensity of freight vessels improved by 3.5% due to a 6% rise in transport demand and a 7% increase in transport supply (measured in dwt-nm in this reference) (24). The effect of these countervailing factors is the net rise in emissions observed, equal to 2.4%. In the future, as the fuel efficiency of foreign shipping rises, as the world economy grows and shipping demand intensifies, UNCTAD expect CO_2 emissions to continue to rise.

These emissions are foreseen to increase by 150% – 250% in 2050 in business-as-usual scenarios (BAU), where no further mitigation measures are taken in combination to the tripling of world trade. Therefore, total emissions in 2050 are prospected to grow at 2.5 to 3.5 times today's level as reported by OECD (2010) (6) and Eyring et al. (2009) (7). This scenario depicting GHGs emissions in rapid growth stand in sharp contrast to the global reductions required from this point on (8). Despite it is still uncertain how the greenhouse gas reductions should be distributed across sectors, the target suggests that global greenhouse gas emissions should decrease to net zero and even negative values across all sectors by 2050 (25). The decarbonization potential in each socio-economic sector is largely affected by the widespread adoption of zero emissions technologies or negative emissions measures, such as renewable or bioenergy to avoid emissions and the adoption of carbon dioxide capture and storage or afforestation, to level off sources with unavoidable positive emissions. Unfortunately, continuous and widespread deployment of negative emissions technologies is slow with respect to the required scale. As a consequence, sectors need to decarbonize in advance considering that negative emissions technologies might not be ready in time to be effective.

Assuming that all sectors should face the same percentage reductions to withstand the 50% – 85% reduction target set by the IPCC (2007) (8), the total seaborne emissions in 2050 should be no more than 15% – 50% of today levels. The picture is even more worrying considering that today's BAU scenario is rather far from being no-growth, on the contrary it's likely that the demand for sea transport work will follow the world trade, projected to triple. It can be deduced then that the level of CO_2 emitted per unit freight transported should be reduced from 20 gram to as minimum 4 gram per ton-nautical mile by 2050. This means a greenhouse gas reduction by a factor of 5 to 6, while meeting the market demand and growth objectives of sea-transport systems. It's clear that such a challenge cannot be faced with the same measures applied in the last decades but requires a paradigm shift in the maritime shipping sector altogether, issue which is also experienced in the energy production or agricultural sectors. The IMO's Fourth Study (4) highlights that the shipping industry is already working on decoupling emissions trends from growth of international trade. However, the report accomplishes that improvements in technical efficiencies alone are not enough to reach the target of halving the emissions of the sector by 2050, with respect to 2008 levels. The development of zero-emission technology remains crucial and, on this deal, proposals have been made to create an R&D fund with the goal to develop zero-carbon ships.

Ships emissions, their impact and technical improvements to reduce emissions have been treated in major studies such as: the Second IMO GHG Report 2009 (23), the Technical support for European action to reducing GHG emissions from International Transport (26), Maritime Transport and the Climate Change challenge 2012 (27) and more recently with the Third and Fourth IMO GHG Reports (2014 and 2020) (13) (4). In addition, a large number of more specific studies have been carried out to investigate the state of the art and cost-efficient technologies in terms of potential emission reductions and related costs. Among all Linstad, H. 2013 (2) and Evert A. et. al. 2017 (25) focused on reviewing the literature and categorize all the operation and technical abatement measures. On the other side literature has focused on quantifying the bound between international trade and shipping changes. On this field Anderson et. al. 2012 (28) examines how trade patterns are likely to evolve over the next two decades as a consequence of consistent economic growth in Asia and structural changes in the rest of the world. Sharmina et. al. 2017 (29) is a comprehensive assessment about the implications for international shipping of structural changes to global/regional energy systems. Walsh et. al. 2019 (30) instead addresses the evolution of shipping transport-work demand in response to climate change mitigation and adaptation solutions. The inherent complexity of the global shipping system makes difficult to predict trade volumes and patterns in the long-term, but despite the challenge some studies address the projection of fleet evolution. Apart from Third and Fourth IMO Studies, other references on this side are Linstad et. al. 2015 (31) on ships design and Linstad et. al. 2012 (32) on Economy of Scale (EOS).

The literature covers in an exhaustive way the solutions for cutting emissions, and there are numerous researches concerning the technological evolution of the fleet and the influence of commercial patterns on the naval transport volumes. In spite of this, it lacks an all-encompassing study that merges together all the three aspects presented above, namely market objectives, emissions reduction targets and fleet evolution.

A more comprehensive understanding of the potential evolution of the maritime sector, and subsequent emissions up to 2050, is needed to inform decision-makers on how and when to apply measures to reduce emissions. To this purpose, this thesis is an important addition to the existing literature, as for the first time estimates of greenhouse gas reduction potentials technologies applied to the maritime sector are interfaced in an Integrated Assessment Model with constraints imposed by a growing market. The purpose of this project is to derive a forecast of CO_{2eq}. emissions resulting from two opposing driving forces (growing trade and emissions cut), determine if one of the two has a predominant effect on the results and which solutions appear as more cost-effective. It will thus be possible to better understand if and how an 85% reduction in the sector's emissions will be possible, and at what marginal costs. This study is not intended to be exhaustive in every aspect of the question but provides an overview and a new approach to this controversial issue that can pave the way for future projects.

This analysis will be carried out via the development of a stand-alone sectoral model for the ship transport system, which in turn will interface with an international trade model, built upon the Shared Socio-economic Pathways (SSPs), and with a range of potential GHGs abatement technologies. To do that, a cluster of coding languages are adopted, alongside the Model for Energy Supply Systems And their General Environmental impact (MESSAGE). This is a process-based integrated assessment model, with a detailed representation of techno-engineering, socio-economic, and biophysical processes for energy and land-use purposes. At the moment, the maritime sector is crudely represented in the model, however, representing a significant uncertainty in the future Shared Socio-economic Pathways (SSPs). Hence an improvement in the modelling of this part of the transport system is needed. Key task include:

1. Description of trade growth trend under SSP scenarios.
2. Description and simulation of maritime sector development.
3. Emissions projection under assumption of GHGs abatement technologies measures.

The study begun in January 2020 and has not considered the COVID-19 pandemic, which is currently having a significant impact on the industry. The WTO expects a 15-30% contraction in worldwide trade in 2020, which will contribute reduce the level of emissions from shipping. However, if and to what extent the pandemic will lead to long term effect is not in the interest of this thesis.

1.2 Research Process

The research pursued in this thesis can be thought as a step by step process. The process began with a deep literature review to acquire confidence to the subject and to set the path and the objective of the analysis process. First outcomes of the literature revision were the substantial emission reduction challenge faced by the seaborne trade sector, requested to go up to 85% per freight unit transported by 2050. Secondly, the regulatory framework has been outlined and I gained knowledge about which measures are already in force to meet the greenhouse gasses reduction targets, like for example the EEDI parameter or the regulations about local pollutants, affecting also GHGs pollutants. The third outcome has been a global overview of all potential emission mitigation measures, their pros and contras and eventual barriers or boosters for the implementation. Literature agrees that if all available or experimental abatement options were added up, it is feasible to meet the IPCC 2007 (8) targets for naval sector. There's though a big gap between this large potential and the actual annual energy efficiency improvements, being less than 1% per year per freight unit transported. It's not within the scope of this thesis understating why and how social-political-economic barriers would limit the spreading of zero emissions technologies, but only how different penetration rates will affect the CO2-eq levels in 2050. The methodological strategy to achieve this has included three different perspectives of shipping.

The first perspective is the trade demand pattern, namely the transport work in tons-nautical miles that the ship sector altogether is supposed to satisfy. The demand is primarily affected by projected growth in Gross Domestic Product (GDP) and future energy consumption from fossil fuels (heavy oil and coal). In fact, about a half of the world's oil demand, a fifth of coal demand and a tenth of natural gas demand are supplied by ship, which also transport 80% of all the traded freights. Other effects that will contribute to local changes in bilateral trade routes are connected to the rapid expansion of emerging markets and the birth of new ones. To contextualize this, the example of Asian market is provided: the world's economic and industrial center of gravity appears to be shifting away from the north Atlantic, due to the fast-economic growth in Asia and other developing economies. Together with the effects of globalization, growth of emerging markets is boosting South–South trade (28). Asia's level of international freight trade has doubled since 1973, with exports over the past decade increasing three times as much as the rest of the world. The fact that China is today the first world's exporter, when 50 years ago exports of Asia altogether were below 30% is an indicator of how the uncertainty intrinsic in trade patterns, thus in shipping. The first part of this work focused on the quantitative analysis of the effects presented above, producing a dataset of five international commerce scenarios built upon SSPs storylines.

The second focus of the project is the maritime transport sector itself, that due to upcoming restriction and intrinsic evolution trends going on, will experience changes in his productivity (ton-miles/dwt), average size per ship category and in capacity (dwt/ship). Due to the long lifetime of the ships around 25 years and even higher for the corresponding infrastructure these changes are expected to be slow, but yet consistent. As an example, concerning the development of the size of the container ships until 2050, the Third IMO GHG Report (13) expect two main impacting factors to be: a trend towards larger ships due to economies of scale, counterposed to infrastructural changes. As a result of current infrastructural barriers, which can be expected to be removed by 2050, big size segments are expected to catch-up in this regard. Because ships have a long lifetime and infrastructural changes on shore need huge investments, there's a confidence that there will be no radical change in the short term. However, due to new norms becoming effective in the next years (like the EEDI threshold becoming stricter), it's not weird to consider the rapid phaseout of certain inefficient technologies that will be substituted by newer ones. One example could be the massive installation of carbon capture and storage (CCS) equipment on board, forced by the come into effect of norms for limiting GHGs emissions and the high zero emissions fuels costs on the other hand. At this stage, the goal is to obtain an overview of future numbers of ships in different categories, aggregating the effects of increased energy efficiency, economies of scale, and trade volumes to be transported.

The third perspective to complete the dissertation is the emission sector, tightly connected with the two others. On one hand this is a direct effect of fleet development, as the ships turnover and consequent modifications in fuel consumptions in turn affect the produced CO_{2eq} emissions. On the other hand, though, all the energy efficiency improvements and abatement solutions (like fuel transition, slow steam and others) bring about newer emissions that are not directly linkable to the maritime sector but comes from other supply chain levels. For instance, in bio-fuels exploitation release of emissions might incur at various stages of lifecycle. Impacts can also be associated with land-use change, even though this thesis do not deal with these effects. Failure to take upstream emissions into consideration in any sectoral assessment risks embedding carbon intensive solutions, for this reason this compart cannot be incorporated in the second core (fleet development) but need to be treated individually. In this way it is possible to adopt a life cycle approach (LCA) and account for all the secondary sources of emissions when modeling new technologies and comparing them with actual ones. Other studies who assessed the feasibility of abatement measures adopted the same logic for a more coherent comparison. In this phase the decision criteria for inclusion or exclusion of a certain abatement technology in the message-ix model are formulated. Once the selection is made the upstream and operational emissions data are collected for each technology and the penetration rate is estimated. Finally, the study proceeds with the calculation of CO_2emissions in the period 2015-2050 and the analysis of the results.

2 Background and context

2.1 Climate Change challenge

Emissions target to meet 1.5°C requirements

Climate change is, as stated from the United Nation (33), a defining issue of our times, whose impacts take place at an inherently global level with unpredicted scale. It is a well-established knowledge that the concentration of greenhouse gasses (GHGs) in the atmosphere has been steadily rising since the time of the Industrial Revolution, and the mean global temperature along with it.

Reducing GHGs emissions is hence one of the major challenges of this century and the key to avoiding the most catastrophic impacts of climate change (34). By 1995, 192 countries started negotiations to strengthen the global response and adopted the Kyoto Protocol, whose second commitment period end exactly in 2020. Aiming to provide an objective source of scientific information, the UN Intergovernmental Panel on Climate Change (IPCC) was set up, and with its Fifth Assessment Report (35) it provided a comprehensive assessment of causes and visible effects of climate change over the past few decades. Moreover, it estimated a CO_2 budget for future emissions to limit warming to less than 2°C. Nearly half of this maximum amount was already emitted by 2011. In 2015, 175 world leaders (now 186) have committed to reducing their GHG emissions under the Paris Agreement, which central aims to limit global warming to well below 2°C above pre-industrial levels. The agreement builds upon the 21st Conference of the Parties in Paris and for the first time it brings all the nations into a common cause to take action.

Another step further was reached in October 2018 with a Special Report (36), finding that a number of impacts could be avoided by limiting the global warming to 1.5°C compared to 2°C or more, and that efforts put in this direction could go hand in hand with ensuring a more sustainable and equitable community. On the other side, this limitation would require rapid and unprecedent changes in all aspects of society, with transitions starting from energy, land use, industry, buildings cities and transports. Emissions of carbon dioxide (CO_2) would need to reach the 'net zero' around 2050, eventually balancing any surplus by removing CO_2 from the air. The potential contribution of carbon capture and storage (CCS) technologies is still uncertain, hence it is estimated that greenhouse gas emissions need in any case to be cut by around 50% – 85% in 2050.

The Shared Socioeconomic Pathways

The Shared-Socioeconomic Pathway (SSP) framework are an attempt to facilitate research and assessment over a variety of research communities that can quantify the range of uncertainty in economic and environmental policies, required to achieve particular climate outcomes. They are structured into five narratives, arranged depending on the mitigation and adaptation challenges posed by climate change (37). Many impact assessment and mitigation researches, ranging from global analyses to other with focus on specific countries, sectors, or particular aspects of climate change, use these scenarios either as the scientific foundation of their approach or to provide important context information for a more precise analysis (38).

As said, the SSPs are a series of five narratives on potential trajectories for human growth and environmental change taking place in the 21st century. The SSPs are a unique tool, representing the most comprehensive set of scenarios produced so far for research on environmental preservation and sustainable development. Every SSP consists of a narrative on potential socio-economic development as well as quantitative data provided by social, economic and integrated measurement models of state-of-the-art explaining the narratives. Projections on a wide variety of subjects such as population size, urbanization patterns, incomes, energy consumption and production, agriculture and land utilization, pollution and climate change are included in the quantitative details. Overall, the package offers information on a wide variety of futures, from those that are more aligned with sustainable development trends to futures marked by a rapid rise in resource use, environmental stress and global human development challenges. (39)

Socio-economic development scenarios consist of both qualitative and quantitative components. Quantitative components provide common assumptions for elements that can be quantified and serve as inputs to models. Qualitative narratives (or storylines) describe the evolution of aspects of society that are difficult to project quantitatively. These narratives are a series of consistent, qualitative analyses of potential changes in demographics, human development, economics and attitudes, policies and institutions, technology and natural resources and the environment. The narratives are meant to provide a logic underlying quantifiable element of scenarios. (38) They explain possible potential circumstances at the level of broad regions of the planet that can serve as a framework for integrated pollutants and land use projections, as well as global warming, effects, adaptation and risk assessments.

Together, such scenarios enable, with and without climate policy proposals, the analysis of alternative futures. The SSPs are intended to be a critical instrument for connecting climate change studies across various fields, from climate change drivers to the physical climate environment, climate effects and methods for adaptation and mitigation. They can also be used on various spatial scales (global, regional and local scales) (40) or to interconnect separate sectors.

To help guarantee that the collection of SSPs actually spans a variety of results, an outcome space in which socio-economic and environmental problems are expressed on two axes is presented in Figure 1: one axis reflects adaptation-related challenges; the other axis poses mitigation problems. The rationale here is that we need to define potential socio-economic circumstances, which will make mitigation and adaptation potentially difficult or relatively straightforward, in order to characterize uncertainties.

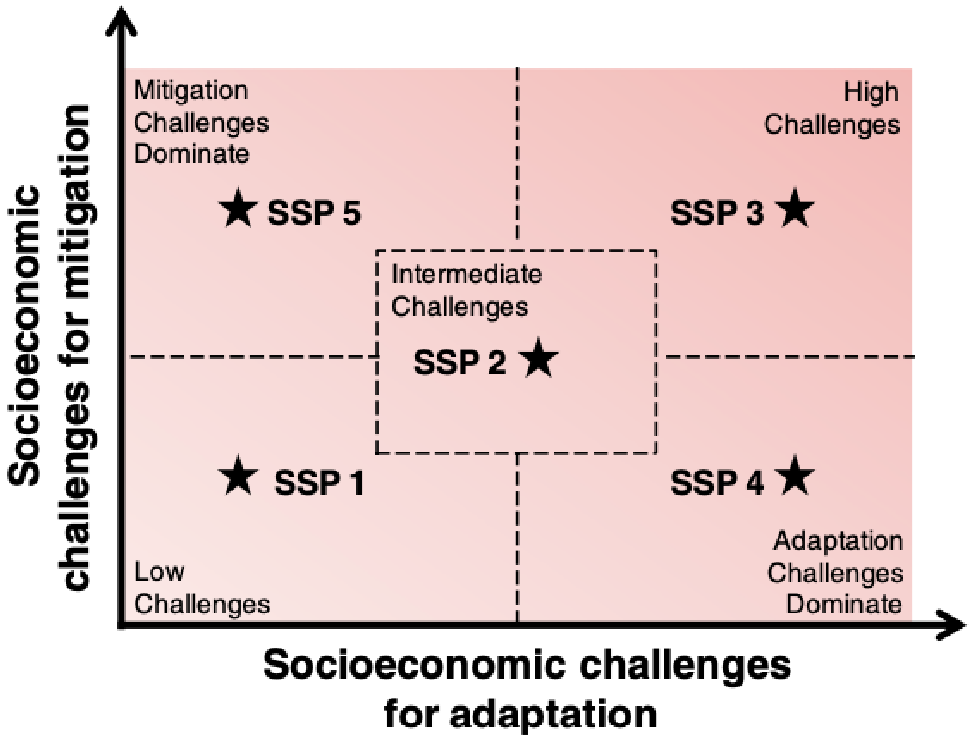


Figure 1: Five shared socioeconomic pathways (SSPs) representing different combinations of challenges to mitigation and to adaptation.

Four of the narratives (SSP1, SSP3, SSP4, SSP5) describe the numerous configurations of high or low adaptation and mitigation issues, all of which were considered sufficiently plausible to warrant the development of SSP, as is visible above.

A fifth narrative (SSP2) defined moderate problems of both types and is intended to represent a future in which development rates in either dimension is not extreme, but rather follow middle-of-the-road directions relative to the number of potential results for each component. Consequently, the narratives were not developed from climate components (30), but they were not meant primarily as a direct communication tool for climate policy advice, but rather as a tool for allowing the scientific community to create effective climate policy makers' evaluations.

Narratives shortcut

Below the five narratives are presented in a contracted form:

SSP number and name	Short narrative
SSP1: Sustainability	A world making relatively good progress towards sustainability, with ongoing efforts to achieve development goals while reducing resource intensity and fossil fuel dependency. It is an environmentally aware world with rapid technology development and strong economic growth, even in low-income countries.
SSP2: Middle of the road	A world that sees the trends typical of recent decades continuing, with some progress towards achieving development goals. Dependency on fossil fuels is slowly decreasing. Development of low-income countries proceeds unevenly.
SSP3: Fragmentation	A world that is separated into regions characterized by extreme poverty, pockets of moderate wealth and a large number of countries struggling to maintain living standards for a rapidly growing population.
SSP4: Inequality	A highly unequal world in which a relatively small, rich global elite is responsible for most GHG emissions, while a larger, poor group that is vulnerable to the impact of climate changes contributes little to the harmful emissions. Mitigation efforts are low and adaptation is difficult due to ineffective institutions and the low income of the large poor population.
SSP5: Conventional development	A world in which development is oriented towards economic growth as the solution to social and economic problems. Rapid conventional development leads to an energy system dominated by fossil fuels, resulting in high GHG emissions and challenges to mitigation.

Figure 2: Short narratives of shared socioeconomic pathways. Source: (13).

Although SSPs are differentiated on the basis of pre-specified outputs, they are built on the basis of determinants (e.g. population, economic development, technology, priorities, administrative efficiency, environment) of these outcomes. Some of these elements will be expressed qualitatively in narratives, while others will be quantitative. For the purposes of this thesis is interesting to investigate what are the differences implied in the areas that drive the assumptions in the various models, then in particular environment and technological development. These are reported in extended form below Table 1.

Table 1: Summary of assumptions regarding Technology and Environment & Natural Resources elements of SSPs. Country groupings referred to in table entries are based on the World Bank definition of low-income (LIC), medium-income (MIC) and high-income (HIC) countries. Source: O'Neill et. al. 2017 (41)

SSP element	SSP1	SSP2	SSP3	SSP4	SSP5
Technology					
Development	Rapid	Medium, uneven	Slow	Rapid in high-tech economies and sectors; slow in others	Rapid
Transfer	Rapid	Slow	Slow	Little transfer within countries to poorer populations	Rapid
Energy tech change	Directed away from fossil fuels, toward efficiency and renewables	Some investment in renewables but continued reliance on fossil fuels	Slow tech change, directed toward domestic energy sources	Diversified investments including efficiency and low-carbon sources	Directed toward fossil fuels; alternative sources not actively pursued
Carbon intensity	Low	Medium	High in regions with large domestic fossil fuel resources	Low/medium	High
Energy intensity	Low	Uneven, higher in LICs	High	Low/medium	High
Environment & natural resources					
Fossil constraints	Preferences shift away from fossil fuels	No reluctance to use unconventional resources	Unconventional resources for domestic supply	Anticipation of constraints drives up prices with high volatility	None
Environment	Improving conditions over time	Continued degradation	Serious degradation	Highly managed and improved near high/ middle-income living areas, degraded otherwise	Highly engineered approaches, successful management of local issues
Land Use	Strong regulations to avoid environmental tradeoffs	Medium regulations lead to slow decline in the rate of deforestation	Hardly any regulation; continued deforestation due to competition over land and rapid expansion of agriculture	Highly regulated in MICs, HICs; largely unmanaged in LICs leading to tropical deforestation	Medium regulations lead to slow decline in the rate of deforestation
Agriculture	Improvements in ag productivity; rapid diffusion of best practices	Medium pace of tech change in ag sector; entry barriers to ag markets reduced slowly	Low technology development, restricted trade	Ag productivity high for large scale industrial farming, low for small-scale farming	Highly managed, resource-intensive; rapid increase in productivity

The Representative Concentration Pathways

Different Integrated Assessment Models (IAMs) were used to derive quantitative scenarios on trends in energy consumption, emissions and associated changes in climate based on the combination of SSPs and Representative Concentration Pathways (RCPs) (39). The RCPs form a series of pathways for greenhouse gas and air pollutant emissions and concentrations, as well as for land use (42) and their climatic consequences (43). The theoretical framework of how the RCPs could be paired with the SSPs has been identified in the last five years. In general, many SSPs will result in the same RCP, so it is possible to create several BAU scenarios in theory (13). Nevertheless, in order to reduce the number of possibilities, while also demonstrating the spectrum of potential results, it was agreed to mix each SSP with one RCP, provided that this combination is feasible. In the following scenarios, the resulted are displayed:

- RCP8.5 combined with SSP5;
- RCP6 combined with SSP1;
- RCP4.5 combined with SSP3;
- RCP2.6 combined with SSP4/2.

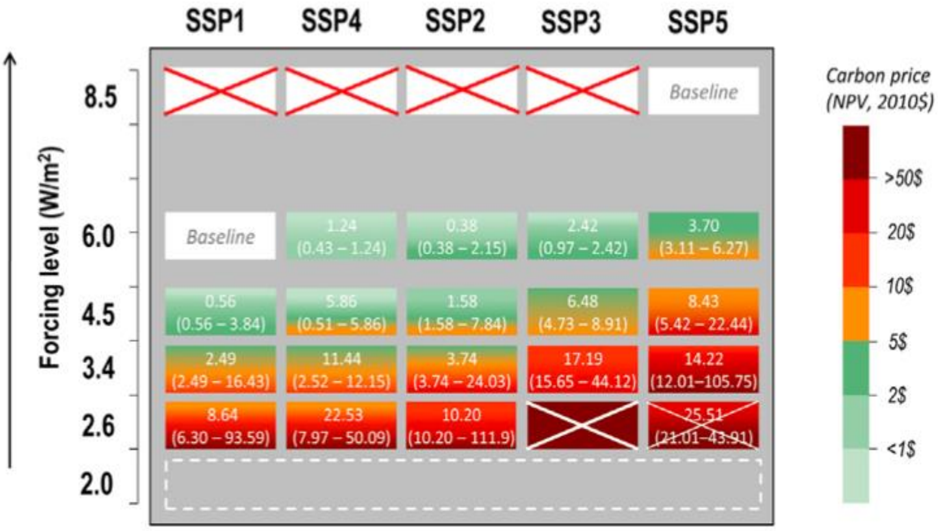


Figure 3: Carbon prices and the attainability of alternative forcing targets across the SSPs. The colors of the cells are indicative of the carbon price. The numbers in the boxes denote the carbon price of the marker scenarios with the full range of non-marker. From Riahi K., et. al. 2016 (76).

To this purpose, a scenario matrix approach was adopted that promotes the conduct of integrated climate change evaluations by the scientific community. Therefore, one dimension of the grid defines climate outcomes, represented by the four different Representative Concentration Pathways and the predictions dependent on them in the climate model. The second axis describes the Shared Socioeconomic Pathways (SSPs) as a collection of alternative model expectations for potential socio-economic development (which can lead to communities that differ significantly in terms of emissions drivers) in the absence of climate policy. Finally, as SSPs are combined in integrated scenarios with radiative forcing pathways or climate change outcomes, policy assumptions would be required to create emissions that will produce the desired climate outcomes. In reality, the mitigation effort and adaptation measures needed would highly depend on the results that policy aspires to. A third key determinant of uncertainty in results is the nature of these policy assumptions, and Shared climate Policy Assumptions (44) define strategies that could be assumed in common across studies to support the evaluation of reliable approaches (38).

2.2 Regulatory framework

Impacts of seaborne trade on global emissions

For centuries, sea transport has been a major facilitator of trades between nations, regions, and continents, accounting for about three-quarters of total freight transport activity. Ocean going vessels together with the onshore infrastructure provide crucial linkages in global supply-chains and allow all countries, including those that are landlocked, to access global markets (45). In fact, while road and rail are important for national and regional trade, more than 80% of international trade tonnage is performed by the shipping sector, while aviation is responsible for more than 50% measured in value. Plus from a global freight transport perspective, it is recognized to be the most energy-efficient mean of transportation in terms of energy use per transport work (dwt-nm) (10). Compared to road and air transport, it allows a lower fuel consumption per ton transported due to its large carrying capacity. As shipping is the main vector of international trade, their trends has always been strictly correlated, thus over the past 40 years, maritime transport has increased by 250%, following the same growth rate as global Gross Domestic Product (GDP) (25). Eskeland and Lindstad, 2016 (46) noticed how this growth was faster than the one for energy consumption (170%) and global population (90%) (25). In the sole biennium from 2013 to 2015 total transport supply (dwt-nm) increased 7% (47), while total volumes reached a milestone in 2018, when they achieved the level of 11 billion tons – the first time on UNCTAD record (24).

Among the different ship categories, dry bulk carriers followed by container ships, oil, gas and chemicals tankers, contributed the most to this growth. Together, they accounted for 86% of global transport supply (102 trillion dwt-nm) in 2015, with the highest share from dry bulk ships which made alone 42 trillion dwt-nm (oil tankers: 26 trillion dwt-nm and container ships: 21 trillion dwt-nm) (47). Last UNCTAD Annual Report 2019 (24) reported the structure of international maritime trade over the last two decades. In 2018, major dry bulk commodities, iron ore, grain and coal, accounted for more than 40.0 per cent of total dry cargo shipments, while containerized trade accounted for 24.0 per cent. Tanker trade shipments (oil, gas and chemicals) on the other side, accounted for 29.0 per cent of total maritime trade volume, down from 55 per cent nearly five decades earlier. This is indicative of how raw materials and primary energy commodities supply is to the mayor extent a sea transport business.

All the data reported above support the evidence that maritime shipping demand is certainly not foreseen to decrease in the next decades, on the contrary it's expected to resemble the world trade trend which is expected to triple in business as usual scenarios (BAU) (2).

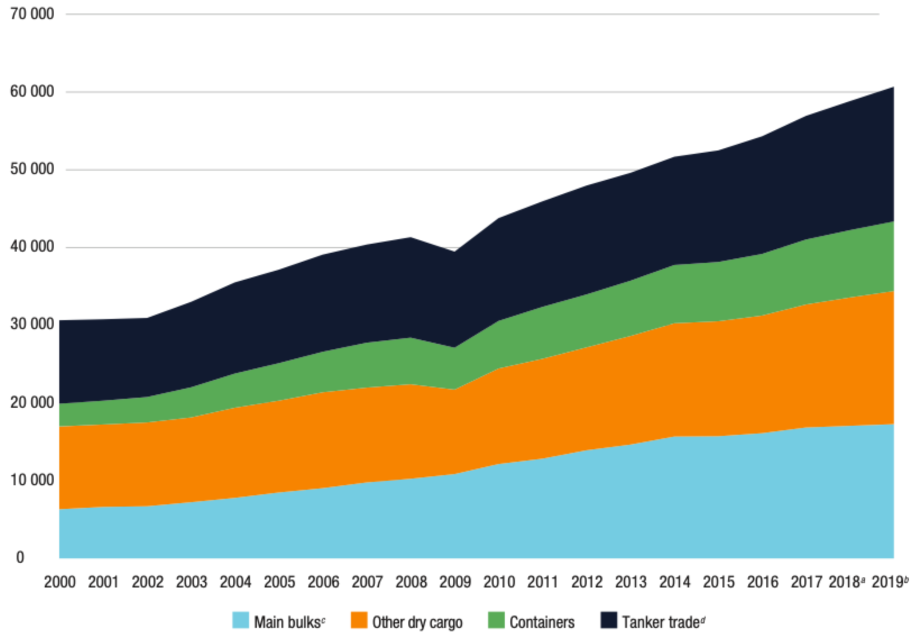


Figure 4: International maritime trade in cargo ton-miles, 2000-2019 estimated in billion tonne-nm. Source: UNCTAD, based on data from Clarkson Research, Shipping Review and Outlook 2019.

Like the majority of the other means of transport, ships emit greenhouse gasses (GHG). The main source of emissions from sea-going vessels is the exhaust gas from burning fuel in the ship's combustion engines dedicated to propulsion, with a number of byproducts. Of these exhaust gases, carbon dioxide (CO_2) has only climate effects, while Carbon monoxide (CO), Sulphur oxides (SO_x), Nitrogen oxides (NO_x), methane (CH_4), Black Carbon (BC) and Organic Carbon (OC) have both climate and adverse local and regional environmental impacts, e.g. on human health (3).

Ships emitted slightly less than 1 billion tons of $CO_2$and GHGs per year, on average from 2007 to 2012 (13). The yearly value decreased and then rose again in the last decade, increasing from 928 in 2013 to 932 million tons in 2015 (47). According to the Fourth IMO GHG Study 2020 (4) for the International Maritime Organization (IMO), maritime transport represents 2.89% of the world's global anthropogenic CO_2 emissions in 2018. Within the global fleet, a few key ship classes account for the majority of CO_2 emissions: container ships accounted for the largest share (23%) and together with bulk carriers, and oil tankers account for over half (55%) of the nearly 1 billion tons of CO_2 emitted every year (47). Figure 5 shows the distribution of CO_2 emissions from total shipping (international + domestic + fishing) for 2015. Major shipping routes are clearly visible.

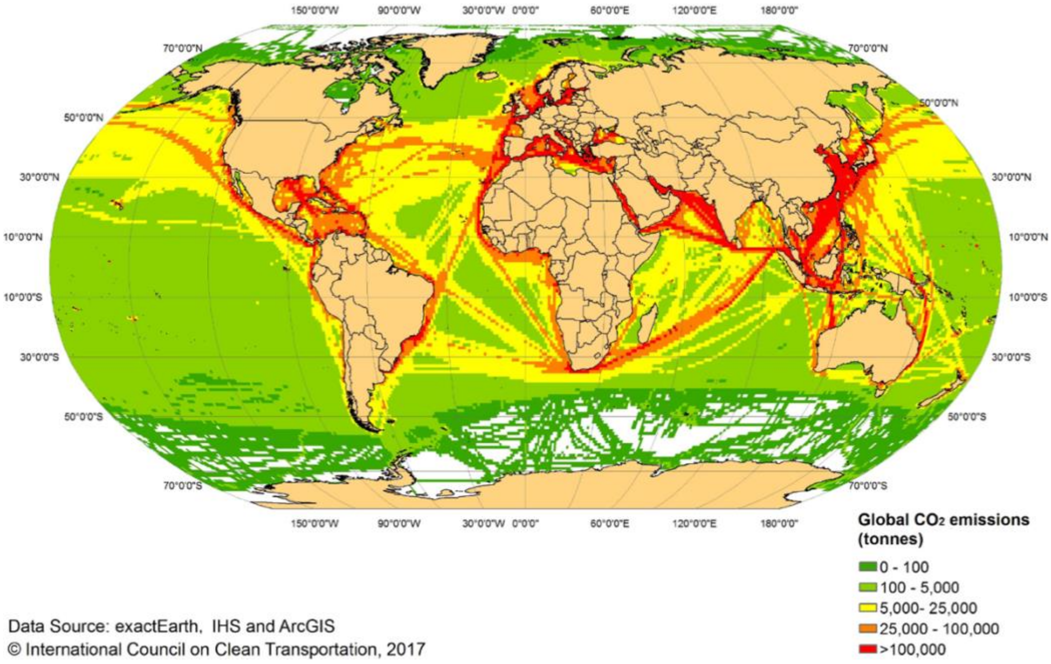


Figure 5: Heat map on major emission routes in 2015.

Along with the transport demand, also ship emissions are expected to increase in both absolute terms and in shipping's share of global CO_2 and GHG emissions. A study carried out by the International Council for Clean Transportation (ICCT) delineated a number of factors driving the increase shipping emissions, referring to the biennium 2013-2015. Key findings include:

- The number and size of the global fleet is rising. From 2013 to 2015, the world fleet of ships used for foreign trading grew by 1.5%, with fleet size for chemical tankers, general container ships and liquefied gas tankers increasing. Following the trend of large vessels replacing several smaller ones, the number of bulk carriers, cargo vessels and oil tankers dropped marginally.
- The biggest vessels are increasingly engaged. Operating hours grew significantly for general cargo ships (+12%), and chemical tankers (+7%), but not for bulk carriers or container ships.
- The main engines are becoming bigger. With the highest gains in chemical tankers (+10%), general cargo ships (+6%), and container ships (+6%), the main engine capacity for many ship types increased in the biennium. The main engine power remained unchanged for bulk carriers and oil tankers.
- The largest ships are accelerating. In the years following, the average cruising speed of the commercial fleet remained relatively unchanged. The biggest container ships and oil tankers are accelerating, though. The report indicates a rise in speed over ground (SOG) of 11.4% for the largest container ships and a lower, but still relevant, rise in SOG of 3.8% for the largest oil tankers. Due to the fact that the power needed from the main engines (ME) is equal to the speed to the power of three, even a slight increase will lead to a substantial increase in the consumption of fuel and hence in the exhaust gas produced.

If no action is taken, these emissions are projected to rise by 150%-250% in 2050. As stated by OECD 2010 (6) and Eyring et al. 2009 (7), gross emissions in 2050 are estimated to be at 2.5 to 3.5 times today's level in a business as normal scenario (BAU) as described previously. These growth rates for greenhouse gas emissions stand in direct contrast to the overall global reductions required by the IPCC, 2007 (8). Nonetheless, the question of how annual greenhouse gas emissions reduction is to be pursued across industries remains a critical one. One approach to reconcile shipping emissions with international commitments on climate change is to handle the shipping industry as if this were a sovereign country that contributes to carbon budgets in a proportionate manner (25). Along with this strategy, where all industries support the same percentage reductions, it is necessary to minimize gross shipping emissions by at least 85% compared to 2010 by 2050 (48), to meet reduction targets set by the IPCC 2007 (8). Furthermore, if demand for sea transport meets the expected tripling of world trade, it follows that CO_2 emissions per unit freight transported (gCO_2 per ton-nm) would have to be lowered by a factor of 5 to 6 times by 2050 even in a no-growth situation (2). Anderson and Bows 2012 (48) concludes that nothing short of an immediate “Scharnow turn” is necessary if the sector will not target wider actions to keep the rise in global temperature below 2°C.

In order to achieve such a substantial cut, it is important to ensure an absolute drop in the sector's annual CO_2 emissions, as the continuing potential growth of maritime transport offsets the gains achieved on an individual base. Furthermore, the remaining difficulty is to be able to accomplish the necessary reductions in GHG, while at the same time satisfying customer needs and remaining competitive compared to other modes of transport, such as road, rail and aviation. Thus, how to realize the necessary sectoral evolution in a cost-effective way is the controversial subject and origin of debate in the science community, and as will be thoroughly explained in the next section, the solution is likely to be a mixture of several distinct technical and operational improvements (2).

Existing and potential policies

Seaborne trade contributed for around 2% of global energy-related CO_2 emissions in 2019 (10). Historically, emissions from shipping were not perceived as an issue since vessels sailed at sea far from people. In the 1970s when several studies confirmed the hypothesis that air pollutants could travel thousands of kilometers before deposition and damage occurred, also ships were acknowledged to produce impacts.

The Kyoto Protocol established in 1997 invites Annex I countries (49) to pursue the limitation or reduction of greenhouse gas emissions from shipping via the International Maritime Organization (IMO). Headquartered in London and established in 1948 by the United Nations (UN), IMO promotes cooperation among governments and the shipping industry to improve maritime safety and to prevent marine pollution (10).

IMO began its work on the reduction of air pollution from ships in the late 1980s (2) and the Appendix (VI) on air pollution was attached to the International Convention on the Prevention of Pollution from Ships (MARPOL) in 1997. Annex (VI) sets out rules for the emissions of nitrogen oxides (NOx) and sulfur oxides (SOx) in the exhaust gas. In the same year (1997), advances in controlling marine carbon dioxide (CO2) emissions began.

Since then, IMO consistently tightened the emission limits for NO_x, SO_x and CO_2 (50) to mitigate the impact of these pollutants. First, IMO has defined the coast around North America and the North Sea and the Baltic as Emission Control Areas (ECA) with stricter SO_x rules beginning in 2015, i.e. the Sulfur emissions has to be less than 0.1% of the emissions content by weight. Globally the Sulfur rule becomes stricter from 2020, requiring shipping vessels to either use maritime fuels with a maximum sulphur content of 0.5% compared to the present cap of 3.5% or install a scrubber (10). Second, IMO requires that new-built vessels from 2016 onwards which operates fully or parts of their time in the North American ECA shall reduce their NO_x emissions by 75%, i.e. less than 3.4 g (IMO tier III) compared to less than 14 g globally (IMO tier II). While these regulations can further help minimize air pollution and contribute to mitigate the health consequences on people living in or near major ports and the environmental pressures on the oceans, there is a possibility that investments in fossil fuel infrastructure will be blocked and the transition to carbon-neutral fuels will be postponed (10). In facts, current regulations provide emission limits for CO2 for its climate change effects and for NO_x and SO_x for their health and environmental effects (31), but NO_x and SO_x emissions have been proven to mitigate global warming (51) (52). On the other side, other unregulated emissions, i.e. BC and CH_4, enhance global warming specifically in local areas (42, 79, 80). For example, the albedo of certain substances such as snow and sea ice are lowered by the precipitation of black carbon over these highly reflective surfaces, thus increasing their surface temperature. In turn, this contributes to increased melting and further decreases in the amount of snow / sea ice and hence further decreases in surface albedo, leading to a major negative feedback loop (81, 82, 83). Complicating the issue, emissions in one region may contribute to a direct climate forcing that varies in magnitude from the same amount emitted in another region. This is because of geographic variations in the level of sea ice, solar rays and optical patterns in the atmosphere.[1]. Region-specific global warming potential (GWP) characterizations are therefore needed to more accurately quantify the dislocation effects.

The IMO GHG strategy

The only regulations currently in place mandating improvements in ship energy efficiency is the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), both enforced by the IMO. The SEEMP proposes to target the energy efficiency of ship operations, while The EEDI sets standards for new ships and mandates vessels designs to become more energy efficient over time. The EEDI entered into force in 2013 and applies to many of the largest ships engaged in international shipping. The Index adopt a formula to evaluate the CO2 emitted by a ship per unit of transport based on a fully loaded vessel as a function of vessel type and size, thus thresholds have been agreed upon for major ship types. Essentially, this indicator requires new vessels entering the fleet to emit less CO2 per unit of transport-work, typically measured as gCO2/dwt-nm. Ships built between 2015 and 2019 are asked to be 10% more efficient than the baseline, constituted of ships sailing between 1999 and 2009. On the same principle, ships built between 2020 and 2024 must be 20% more efficient, and those built in or after 2025 must be 30% more efficient than the baseline (31).

In April 2018 the IMO introduced a strategy to limit GHG emissions from international shipping in order to align the industry with the environmental targets set by the Paris Agreement. The plan proposes to cut absolute GHG emissions by at least 50% by 2050 and aims to eradicate them entirely thereafter. It also seeks to decrease the carbon intensity of international shipping by at least 40% by 2030 and to pursue measures to reduce the greenhouse gasses emissions by 70% by 2050, relative to the baseline for 2008. To this end, the Data Collection System (DCS) legislation for the fuel oil use of ships came into force in January 2019. Both ships with a gross tonnage of 5 000 tons and above are mandated by the Legislation to produce annual reports on their fuel oil use and transport activities. The goal of this framework is to create a solid database that can be used to track and monitor international shipping energy consumption as well as measure CO2 emissions (13).

Improving carbon intensity

Strategies to comply with the Paris Agreement have been defined by the IMO, but policies to promote the alignment with these ambitious goals (to reach carbon neutrality in the second half of the century) are still needed. The EEDI targets mandated from 2015 to 2025 fall short compared to historical improvement rates, as energy use by the global sailing fleet per ton-nm declined annually by an average 1.6% between 2000 and 2017 (10). This implies that, although the new EEDI formulation will avoid slipping back on improvements in energy efficiency, it does not stimulate advancements above historical rates. Not only will the results of this measure be far-reaching, but energy efficiency approaches alone are also most likely to be inadequate to reverse the increasing path of CO2 emissions from ships (9) (13). In any case, because the EEDI only applies to new ships, it cannot meaningfully reduce GHGs from the sector in the short term. Even in the long-term, the index as currently designed, is not expected to reduce shipping's cumulative CO2 emissions by more than 3% over the period 2010-2050 (13). Therefore, to reduce carbon intensity in the near term, energy efficiency measures along with slow steaming, are valid. Slow steaming is the practice of operating cargo ships at significantly less than their maximum speed, typically used to save money on fuel. Whereas over the longer term, it is crucial to develop policies able to promote the adoption of low- and zero-carbon fuels and technologies for oceangoing vessels.

As a result, some organizations are pressing the IMO to tighten the EEDI requirements, in order to promote the introduction of emerging technology that would boost vessels in an important jump forward. Among the others, the OECD delegation's submission to the IMO recommended numerous measures to align international shipping with the sustainable development goals (SDS), including the implementation of Phase 3 (30%) EEDI standards from 2025 to 2022 and then creating a new, more stringent "Phase 4" EEDI standard for 2025. Another advice is to reduce emissions from the existing fleet, given that today's policies will take a long time to work their way through the in-service fleet. One way is to implement an operational efficiency standard to secure that vintage fleet still in use in 2030 are nearly 20% more efficient than the EEDI baseline.

Because zero-emissions fuels are considerably more expensive than conventional fuels, policies are needed to bridge the price gap to encourage their adoption (9). One such policy mechanism consists of operational CO_2 standards (also called a goal-based mechanism) that set mandatory objectives for ships to reduce their operational carbon intensity per unit of transport work. Set at stringent enough levels, operational carbon intensity objectives gradually drive the uptake of zero-carbon fuels. These could help to reduce the carbon intensity of marine fuels by almost 10% by 2030, and by nearly 50% by 2050 compared to 2015. Operational carbon intensity requirements provide industry players with the ability to select the most convenient and acceptable mitigation plan while reducing the CO_2 intensity of vessels progressively. Further measures are required by zero-emission vessels or by a CO_2 pricing program for marine fuels: restrictions forcing ships not to release GHGs during activities in such cases, such as while they are in the Emission Control Areas (ECAs) or at sea, or to pay a charge per gram of CO_2 in exhaust gasses. Zero-emission mandates generate demand for zero-carbon fuels and drive cleaner technologies to be commercialized. In addition, they gradually introduce zero-carbon fuel use in protected areas/environments. Initially, mandates for the most suitable ship types should be introduced in geographically restricted areas and, if proven viable, applied to other areas and other ship types, thus eventually becoming more ambitious. As the innovations needed to achieve the SDS goals have not yet been commercialized, the development of maritime fuel and technology RD&D should be intensified. It is important to commercialize zero emission vessels (ZEVs) and to begin installing the associated refueling facilities in this decade, provided that vessels have lifetimes of 20-30 years (10).

In the Getting-to-Zero-Coalition, committed to commercializing deep-sea zero-emission vessels (ZEVs) by 2030 along with the related facilities, many companies from the marine transportation, power and facilities value chains have already joined hands.

2.3 State of the Art on GHGs abatement solutions

Potential reduction of CO_2 emissions from shipping

In this section, I reviewed the literature describing fleet-wide abatement scenarios to identify high CO_2reduction potential measures and quantify the maximum joint potential. The studies considered focus on emission cut achievable at fleet level, trough the adoption of available or developing measures within my horizon. The main studies which have been used as reference for follow-up papers are the Second and Fourth IMO GHG Study (23) (4). The main idea coming out from these studies is that it is possible to gain energy efficiency and cut emissions in a cost-effective manner (26) (23) (53), but Rehmatulla et. al. 2017 (54) points out that at present only a low number of measures are deployed at sufficient scale. Industrial Research and Development projects related to emissions reduction, fuel efficiency, along with policies for monitoring air emissions (2) helped in rising the expertise, but still the quantification of a theoretical maximum potential for GHG reducing measures is thwarted by technical, logistic, economic and political barriers for spread (55) (19), and also uncertainties in applicability of measures for different ship types and ages (55) (32).

To transit towards low carbon shipping, the sector has plural technological and operational measures at its benefit. Technical measures focus on energy savings strategies, dealing with design solutions, propulsion and power system improvements, and fuels switch. Operational measures instead aim at cutting emissions during ship or fleet operative conditions (19).

Six main groups of solutions are (54):

- Hull design. This deals with aspects related to hull dimensions, shape and weight, which aim to improve the hydrodynamic performance and minimize resistance.
- Economy of Scale. It is another mean of reducing emissions, as larger vessels are seen to be more energy-efficient per freight unit. Typically, when cargo-carrying capacity is doubled, the required power and fuel consumption increases by about just two-thirds.
- Power and propulsion. This involves the design of power systems and equipment, hybrid power solutions, improved efficiency of propulsion, recycling of waste heat, and reduction of the demand for on-board power by energy-saving devices such as kites and sails. Hybrid power systems allow different energy sources to be used effectively, such as combining batteries with combustion engines to make the best use of each technology.
- Reducing speed (above mentioned as slow steaming). Speed refers to the vessel's operating speed, as well as its design speed. Because the power requirement is proportional to the product of speed and resistance, this means that fuel consumption is reduced when a ship decreases its speed.

- Fuels and alternative sources of energy. This measure encompasses all aspects related to the replacement or complementation of alternative energy sources to conventional marine fuels. CO_2 emissions can be minimized by converting directly and across the entire fuel cycle, including production, processing and refining, to fuels with lower total emissions.
- Post combustion abatement measures. This is a short-term measure which involves scrubbers and carbon capture and storage (CCS) technologies. To this regard a recent study from Chryssakis et al., 2017 (56), emphasized that while scrubbers could be a financially attractive choice to comply with the upcoming global 0.5 percent fuel sulfur limit in 2020, such a strategy would not enable substantial reductions in GHG emissions as ship owners would be 'locked in' over the life of the ship to use carbon-intensive bunker fuels.
- Operational measures. Include speed optimization depending on sea and weather conditions, fleet management, voyage planning, on-board energy management and weather routing and scheduling.

Some measures can be used as retrofit measures, while others would only be taken into account in the case of new ships. For any ship type, current or newly constructed, operational measures are adequate. It is necessary to bear in mind that not all mechanisms of reduction are additive and can be implemented at the same time. Many of the options, indeed, are mutually exclusive. In addition, due to the interdependence of the steps, some reduction potential is not strictly additive. Nonetheless, a significant number of combinations of steps are realistic and economically feasible. To make the reader grasp the extent of capability of individual technologies, the estimates obtained by Bouman et. al. 2017 (19) are proposed in Figure 6.

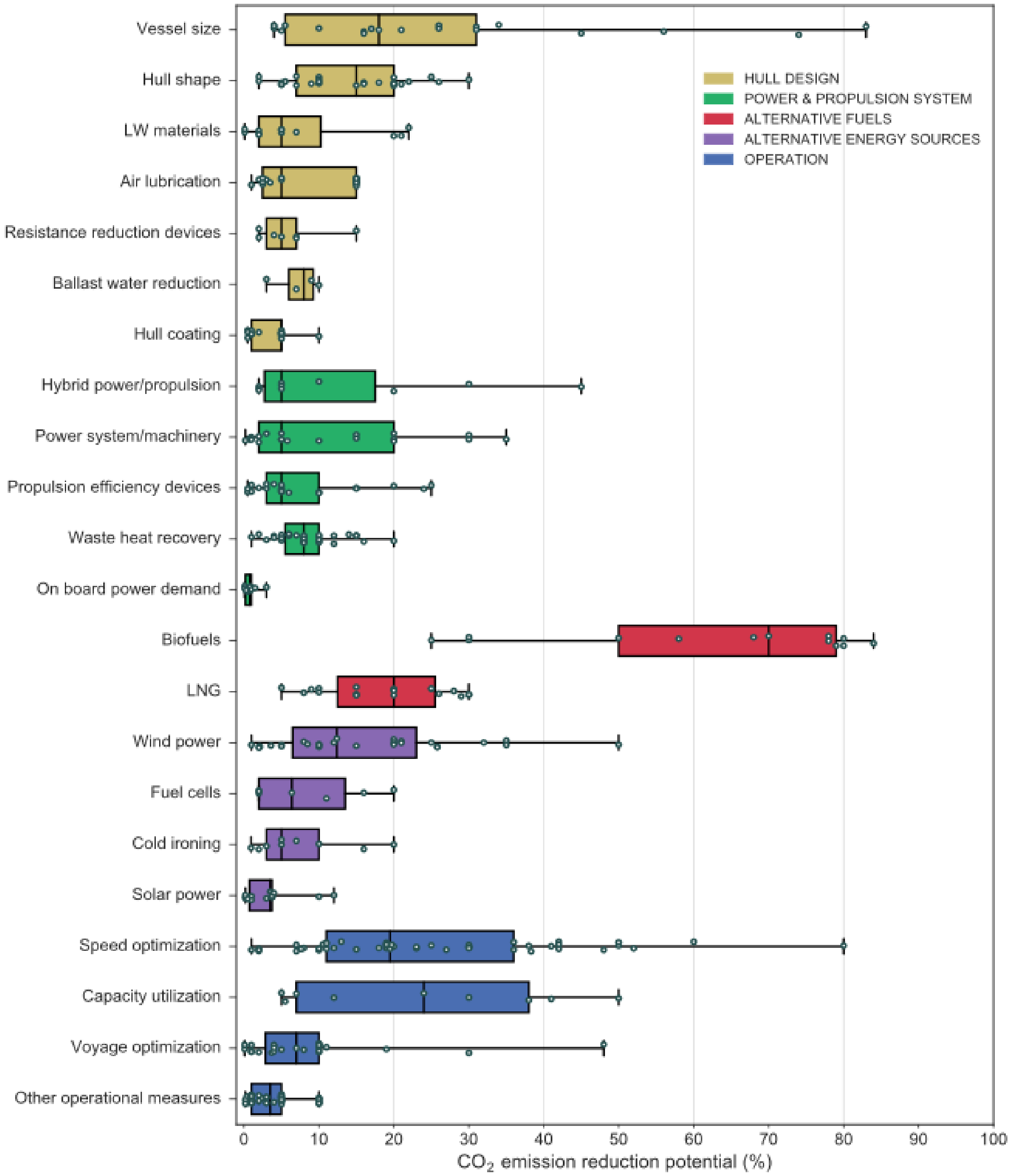


Figure 6: CO_2 emission reduction potential from individual measures from Bouman et. al. 2017 (19).

Review of possible CO_2 emissions abatement measures

Hull design

With recent research and state of the art design practice in terms of structure, a general weakness is that it is focused on slightly enhancing existing designs and solutions rather than truly challenging practice today. Seagoing vessels have historically been planned and optimized to run at a standardized maximum economic velocity. Despite the fact that the calm sea is the exception in shipping, it usually refers to design speed with design loads in still water conditions. The maximum economic speeds represent the highest speed that is appropriate to operate a vessel of specified fullness and length independently of the cost of fuel. The hydrodynamic explanation is that when the hull reaches its boundary velocity, the still water drag coefficient, which is almost constant at low velocities for any hull shape, increases rapidly (57). This boundary speed could be less than 10 knots for a small boxed shaped shoe style, whereas it could be 25 knots or more for a long and slender frigate. Historically, the cost of fuel has been poor. Compared with the fixed cost of a vessel, fuel costs have traditionally been low. This has rewarded owners for optimizing the carrying capacity of the cargo at the lowest possible construction cost and shoebox-shaped vessels with high resistance even in calm sea have been the result. With today's high fuel costs and the expansion of the Panama Canal lock from 2014, it may be more economical to build slimmer vessels, by extending overall dimensions and keeping the dead weight tonnage (dwt) constant. Awareness of these relationships is not recent (57), although there is a lack of research on the link between the slenderness of the vessel and its speed as a function of the price of fuel.

Economy of Scale

Economies of scale are another possibility for reducing emissions, since larger ships require less fuel per freight unit thus tend to be more energy efficient than smaller vessels (2). The main insight is that when the cargo carrying capacity of the ship is doubled, the required power increases by two-thirds of the increase in the size of the ship, which means that fuel consumption per unit of cargo is decreased when the size of the ship is increased. There has been a shift towards the use of larger ships due to economies of scale (13). Ships of 10.000 TEU and above, mostly in the range of 2.800-5.000 TEU, have replaced smaller ships, and ships of 1.000-2.000 TEU have been largely displaced by 2.000-2.700 TEU ships. Among container fleet analysts, there is wide consensus that "mid-size" ships (those in the 4.000-5.000 TEU range) are becoming almost obsolete as they are being replaced by bigger, more powerful ships. Lindstad et al., 2012a (32) explores the impacts of economies of scale on direct shipping costs and pollution. The potential of economies of scale was measured by contrasting the current fleet average with what can be done by replacing the existing fleet with a smaller fleet maintaining the total capacity unchanged. The findings show that at a negative cost of reduction, emissions can be decreased by as much as 30%. The comparison is based on 2007 levels of trade and 2050 projections. It could take as long as 25 years to replace the entire fleet, so the reduction in pollution will be achieved progressively as the existing fleet is renewed.

Power and propulsion system

Ships' power core design and optimization has historically focused on the number of engines or generator to be used, based on the total power needed when working under design load conditions and design speed. The most economical way to generate the power necessary to achieve the design speed, was to operate engines between 75% and 90% of the maximum power output available. The reason is that in this load region, combustion engines that burn marine diesel oil (MDO) or heavy fuel oil (HFO) have the highest performance, and that the engine's capex cost increases almost linearly with the engine's size. More recently, the conventional method of working at constant high power no longer offers the lowest cost for all sea and loading conditions as a result of higher fuel prices and lower freight rates (2). Various challenges and boundary conditions come along with the introduction of more innovative measures. A fully integrated hybrid drivetrain, for instance, deviates greatly from a traditional set-up. It is difficult for such early stage technologies to meet all the requirements needed for optimal deployment and high emission reductions. In recent decades, substantial changes have already been made in some of the more traditional steps, such as efficiency-enhancing machines, and further improvements are likely to remain limited as the physical limits are reached. (31).

Low Carbon Fuels

Emissions of CO_2 can be cut by switching to fuels with lower total emissions across all life cycle including production, refining and distribution (16) (23). The area in which the fuel is produced has a specific effect on the transport distance and pollution factors associated with the use of electricity and the maturity of technology. An environmental penalty or benefit can also result from the conversion pathway. Therefore, any substitute fuel must follow a set of requirements in order to become a viable option. Main among them is the condition that over the complete life cycle it will achieve emissions reductions.

Compared to more conventional hydrocarbon fuels such as marine diesel oil or heavy fuel oil, liquefied natural gas (LNG) has a higher hydrogen to carbon ratio, which results in lower CO_2 emissions (23). Furthermore, LNG is a pure, sulfur-free fuel that prevents the release of sulfur oxides and almost all debris. The downside is that there will be leakage of un-burnt methane (CH_4) when LNG is used on standard low-pressure gas engines or dual-fuel engines, lowering the total greenhouse gas emission reductions from 25 % to 15 % (58). There will be almost no methane leakage if LNG is instead used as a diesel on two or four-stroke high-pressure engines, although the downside is nitrogen oxide emissions that do not meet the pollution criteria for newly constructed vessels in the Baltic from 2016 onwards. However, this can be overcome after the exhaust gas is treated. Taking into account that the residence time of CO_2 in the environment is thousands of years and that there is a carbon budget linked to the targets set out in the Paris Agreement, a one-sided emphasis on LNG as a mitigation alternative risks the sector being forced into a high-carbon infrastructure that is not compatible with the long-term commitments expected (16).

Biofuels is one such option which can be considered as an alternative to fossil fuels and there are various studies that examine the feasibility (2). Bengtsson et al. 2012 (81) derive a conclusion that the biofuels are one potential measure to reduce the effect of transportation on global warming, but with other impact classes, it may be at the cost of greater environmental impact. Bouman et. (19) state that the potential for pollution reduction for the use of biofuels varies from 25 to 84%. The structural implications of large-scale biofuel adoption, however, stretch well beyond reducing CO_2 emissions during combustion. The CO_2 reduction capacity of biofuels is determined by two major factors. First, in type and quality, the bio feedstock varies and is processed in various ways. Due to improvements in feedstock, practices, efficiencies, etc., fluctuations in CO_2 reduction capacity exist. The second element applies to the way the potential for decreases is measured. Biological emissions are traditionally considered to be carbon neutral as biofuels are of renewable origin and carbon is sequestered during biomass growth. The assumption of carbon neutrality, however, greatly depends on the rotating times of the source crop, the position of the crops, and the direct and indirect albedo changes due to harvesting, both of which have an effect on the atmosphere. Thus, bio-derived fuels theoretically demonstrate the highest reduction in CO_2 emissions, but operational emissions are counterbalanced only if the biomass feedstock consumes ambient CO_2 that otherwise would not have been consumed. Moreover, non-climatic problems, such as competition for finite land resources, make the analogy excessively simplistic in terms of CO_2 emissions alone (59). The addition of emissions from land use changes will significantly alter the balance of greenhouse gases, with findings subject to considerable uncertainty and highly dependent on the method of processing of feedstock.

Hydrogen is the most abundant element in the planet, but it is seldom present in its pure form. Although it is possible to obtain it from different sources, such as biomass or electrolysis, nowadays it is mostly produced from natural gas (60). Furthermore, hydrogen liquefaction needs a very low temperature of −253 °C, which carries on screen the high cost of liquefying and storage device. Indeed, the major obstacles are the high price of fuel and restricted availability for maritime activities. As stated, direct combustion of hydrogen has the lowest environmental effect and is useful when considering the development of energy by fuel cell technology. No nitrogen oxides, sulfur oxides or contaminants are observable in contrast to conventional combustion. The key assumptions and procedures are the same as the process steps, including liquefaction, for LNG processing. From here, the production process follows, with steam reforming of the natural gas and CO_2 shift and further purification. The quantity of natural gas for output of H2 is 3.5 kg LNG / kg H2 (60). In the case of H2 with CCS, during the processing stage, CO_2 is captured and processed, with a capture rate of between 80 and 90 percent. It is delivered on a cryogenic truck after the storage of liquid H2 and it is converted in a fuel cell. The key life-cycle hot-spots include the option of liquefied or compressed H2, the energy intensity of the grid, the demand for natural gas and the reliability of carbon capture. Instead, when considering renewable hydrogen (H2 derived by renewable energy sources), the main life-cycle hot spots are the efficiency of the electrolysis process, the option of liquefied or compressed H2 and the efficiency of the fuel cell. Hydrogen has no CO2 emissions from operations. In the baseline scenario, though, the resulting

CO_2 levels from the life cycle are substantially higher than for traditional fuels. Important advantages are only realized where complete life-cycle emissions are taken into account if CO_2 emissions from its feedstock and from the supply of input energy are minimized or eliminated; either by the efficient introduction of CCS and decarbonization of input electricity or through the use of renewable energy inputs in electrolysis production. Ship Fuel Cell Technology (FCSHIP-project) has explored the use of fuel cells on board ships for both main propulsion and auxiliary applications. The Viking Lady offshore supply vessel has a fuel cell mounted and the goal is that some of the energy generated by the auxiliary engines will be produced by the fuel cell. This is the first fuel cell device to work on a merchant ship and shows that on-board service can be tailored to safe, high performance, low-emission fuel cells. But the production of hydrogen demands a significant amount of energy. For these purposes, when evaluating the use of hydrogen as a fuel, assessment of advanced hydrogen development and production dependent on renewable sources such as wind energy is of high importance. There are also other barriers and issues, regarding logistic aspects like transport and storage of hydrogen (16).

Ammonia has been regarded as one of the potential carbon-free fuels for ships to tackle with environmental issues (61). Bicer et. al. 2016 (60) explains that in marine engines, the use of ammonia as a dual fuel will minimize overall greenhouse gas emissions by up to 34.5 % per ton-kilometer. Centered on rapidly developed technology, ammonia-fueled power systems are presumed to be more promising. A new initiative to build the world's first ammonia-fueled fuel cell on a vessel was launched in January 2020, with funding from the European Union (EU) (62).

The volumetric energy density of liquid ammonia is greater than that of liquid hydrogen, which is an on-board fuel storage attraction. In comparison, the storage conditions for ammonia are close to those of propane, with ammonia at room temperature in liquid form (25° C) when pressurized to 9.9 atm or temperature at ambient pressure of −33.4° C (61). When opposed to H2, the key advantages of using NH3 as fuel are as follows.

- In terms of fuel costs, NH3 is a cost-effective option which also has developed facilities (approximately 10.6-30.2 times cheaper than H2).
- The volumetric hydrogen content of NH3 is substantially higher than that of H2 (approximately 1.7 times more than liquid-H2).
- Transportation and storage technologies for NH3 already exist and they are available today (annually, more than 18 Mt of NH3 is traded internationally).
- NH3 is easy to detect due to strong smell, so safety measures are commonly practiced against its acute toxicity.
- A carbon capture system (CCS) for NH3 production plant is already a feasible option.

The most typical application of ammonia is as a fertilizer and the Haber-Bosch process is its main industrial method of production. This ammonia would mostly be used in an engine or fuel cell as fuel (2). For engines: it is noticeable that pure ammonia has low specific energy, high auto-ignition temperature, and limited flammability limits (15-28 % by volume in air), so combustion conditions are unpredictable at very low and very high engine speeds. Concerning fuel cells, the solid oxides fuel cell (SOFC) has the advantage that it can use NH3 directly as fuel (60). However, the SOFC is constrained in how easily it can raise the rate of fuel supply according to the demand for power. The energy storage system (ESS) is then used as a supplement (back-up) power to compensate for the SOFC's poor dynamics during transient operations and can also be used as a source of cold-start energy. The SOFC and ESS are the most eco-friendly systems (up to 92.1 %) when contrasting the traditional and proposed systems (16). Owing to the high CAPEX, though, it is the most costly option than the others. The International Transport Forum (ITF) assumes that hydrogen and ammonia account for about 70 % of the fuel demand in the event of an 80 % drop in the carbon component. To show the viability of ammonia as a ship fuel, a variety of additional problems should also be addressed. First of all, the biggest theoretical downside is the problem of protection (corrosion, toxicity, low flammability, etc.). Ammonia, however, has been treated in ships as a liquefied gas cargo, a refrigerant, and an SCR reduction agent, so efforts could provide for the next step in allowing ammonia as a safe fuel. In terms of logistics, since ammonia has already been produced and shipped in large amounts around the world, the current infrastructure of the industry could be used in the future to realize bunker areas for ammonia-fueled ships (60).

Alternative energy sources

High wind power mitigation potential and low solar potential are observed for initiatives based on renewable energy sources. In wind-assisted ships, interest has re-emerged. Usually, these are intended to work in the manner of wind-assist or motor sailing in which the speed is kept independent of wind speed and direction. Wind conditions vary between countries, such that wind power in some regions and routes is more attractive than in others. For a vessel speed of 10 knots, fuel savings were usually about 20%. The use of sails, kites, and photovoltaic cells to collect these additional sources of energy depends heavily on the case of the ship in which the equipment is used. Such measures are most successful on particular routes with high solar incidence and wind potential for smaller ship sizes, as the total amount of energy that these measures can produce on board is limited by the surface area needed by each of these measures. Inversely, theoretically, cold ironing can be applied to ships of any size. It can significantly reduce local air pollution, especially in countries with a clean mix of electricity. However, there seems to be little consensus between studies on its potential for CO2 reduction, but the shipowners are not persuaded and there is a need to build models to measure the benefits of different wind assistance options on emission reduction for different ship types, routes, and ship speeds (2).

Speed optimization

As ship resistance is directly correlated with shipping speed, it is no surprise that speed optimization is another measure where relative high reductions in fuel consumption and emissions can be achieved (54) (50) (2) (31). A key insight is that a function of the speed to the power of three to four is the power output needed for propulsion. This essentially means that the fuel consumption per freight work unit is lowered when a ship decreases its speed. An increasing interest in the relationship between speed and reductions in emissions has emerged. Corbett et al. 2009 (63) considered whether the lowering of speed can be a potentially cost-effective CO_2 mitigation option for ships calling at US ports. They found that a fuel tax of about 150 USD per ton would lead to average speed-related CO_2 reductions of approximately 20% – 30%. Plus, Sea at Risk and CE Delft (2010) (64) studied how, in 2009, over-capacity could be used in major shipping markets to slow steaming and thereby minimize emissions. It has been estimated that dry bulk, tanker and container vessel emissions can be decreased by approximately 30%, compared to the situation in 2007, by using over-supply to minimize speed. Limiting ship speeds will instantly minimize GHG emissions in the short term and could be coupled with other measures as propulsion efficiency and routing for the weather. Reducing emissions by speed reduction can be achieved by reducing the design speed by installing a smaller engine, reducing the speed of operation, or a combination of both. Speed reduction by engine de-rating and engine tuning are common techniques for reducing fuel consumption (54). De-rated engines are possibly being adopted, although comparatively costly, since they have lower Specific Fuel Oil Consumption (SFOC). The second IMO GHG study (23) describes how it is possible to use de-rating and engine modifications to theoretically reduce the SFC of an engine by approximately 4.3 % and up to 3%.

Global emission reduction potential from the sector

On the introduction of operational cost-effectiveness initiatives, Rehmatulla et. 2017 (54)shows that only three steps, general speed reduction, fuel consumption control and weather routing, were the subject of the implementation of cost-effective operational measures. Just a number of attempts have been made with respect to introducing technological energy saving initiatives. In particular, the results show that while there is a good spread of implementation across the various measures, only a select number of measures are implemented on a sufficient scale in each of the categories. Secondly, high-implementation initiatives tend to be those with limited ship-level gains in energy efficiency, and the adoption of CO2-reducing technologies, especially alternative fuels, is low despite their high potential to reduce CO2 emissions. Linstad et. al. 2015 (3) suggest that no single solution is, on its own, adequate to achieve substantial sector-wide reductions. On the other hand, it concludes that by rapidly implementing and integrating a large number of individual based and independent steps, a substantial emission reduction of over 75 percent is achievable. In other words, GHG emissions can be decreased by a factor of 4-6 per freight unit transported within 2050 using current technologies. The maximum potential for reducing pollution varies from 20% to 77%, and the estimates for 2050 are in line with the estimated maximum potential of the Second IMO Study (23). Furthermore, Gilbert et. al. 2018 (16) analysis shows that there is currently no widely available fuel to deliver GHG emission reductions, but some alternative fuel solutions have the potential to resolve main barriers. To achieve reductions in greenhouse gas emissions, hydrogen or other synthetic fuels rely on decarbonization of both energy inputs for production and other feedstock materials. Likewise, bio-derived fuels can be a reduction alternative, but only if land-use transition can be ensured while developing biomass does not have a broader effect on potential savings and the sector is able to compete adequately for their use. These examples demonstrate that in the respective fuel life cycle, critical obstacles are located upstream and that the way to resolve them might be beyond the reach of the shipping sector alone. LNG is a promising choice to meet current requirements, but it is not a fuel with low emissions of greenhouse gases. Otherwise the industry would find itself addressing its near-term targets for local pollutants, at the cost of setting itself up to address longer-term greenhouse gasses goals.

3 Method

3.1 Introduction

This chapter explains all the statistical models, assumptions and hypothesis used in the data analysis, the calibration process and database creation ultimately used in message-ix. To give an insight of the model logic as a whole, CO2 emission forecasts are based on transport-work forecasts, which in turn depend on a series of long-term socio-economic forecasts (SSPs), and are influenced by the evolution in the composition of the fleet in terms of economies of scale (EOS) and energy efficiency.

The next section deals with the presentation, in order, of the following models: for the demand side the gravity model for the estimation of bilateral trade volumes between two countries, the transport demand model that converts the monetary value of trade into transported volumes and consequently into maritime transport demand (therefore from USD to ton-nm). It should be noted that in this thesis all monetary units are in United States dollar (USD), all tons are metric, all other measurements are metric apart from nautical miles. On the supply side we will present the scenario of evolution of the fleet, the model for the estimation of energy consumption of each type of ships and subcategories for each size bin, and finally the theory for the prediction of emissions in the horizon 2015-2050. It is necessary to point out that in this chapter the models will be discussed only on a theoretical and conceptual level. Their application for the purposes of the project is discussed in the next chapter, which deals in more detail with the illustration of databases and codes formulated ad hoc starting from the general models presented here.

3.2 Demand side

3.2.1 Selection of projection scenarios

In this project a sector model of the naval sector has been built, which can be considered as standalone and presents possibilities of integration with the global model in message-ix. Although it is a standalone model, it is necessary to refer to global development scenarios recognized by the scientific community that deals with Integrated Assessment on Climate Change. Consequently, it was decided to use the Shared Socioeconomic Pathways (SSPs) as global reference scenarios from which to derive data on GDP projections for the regions.

3.2.2 Model for bilateral trade projection

For the estimation of trade volumes in monetary terms, it was first necessary to study the historical correlation between trade volumes on the one hand and demand drivers on the other, such as total GDP, GDP per capita or population of the countries considered.

In this regard, the gravity model has proved to be particularly suitable both for the type of application and for its robustness, whose source of reference in this thesis was *The gravity model of international trade: a user guide* by Ben Shepherd (65) (66). In fact, in the last half century this model has become the workhorse of research applied to international trade and econometric models, giving rise to a series of studies concerning different regions, periods and sectors. It is therefore a key tool for interesting research in the analysis of market policies, and their impact on the sector itself. In recent years the model has been extended to cover not only the material goods market but also the services market (e.g., Kimura and Lee, 2006), due to the increasing availability of data.

The fundamental insight of the gravity model is the direct proportionality between trade flows and the economic dimension of the countries considered, and inverse with the costs of trade itself, whether they are approximated by the distance separating the countries and the resulting transport costs. This intuition constitutes the heart and the traditional mathematical formulation of the model, to which in the last decade has been added with increasing importance a more structured theoretical content. In its most basic form, the gravity model can be described as follows:

$$\log X_{ij} = a + b \log GDP_i + c \log GDP_j + d \log \tau_{0,ij} + e_{ij} \qquad (1)$$

$$\log \tau_{0,ij} = \log(distance_{ij}) \qquad (2)$$

where X_{ij}indicates exports from country *i* to country *j*, *GDP* stays for country's gross domestic product, $\tau_{0,ij}$ represents trade costs between the two locations, which are proxied with geographical distance, and e_{ij} is a random error term. The *a* term is a regression constant, while the *b*, *c* and *d* terms are coefficients to be estimated. The definition "gravity" comes from the fact that the conceptual form of equation 1 resembles Newton's law of gravity: trade values are directly proportional to the exporting and importing countries' economic "mass" (GDP), and inversely proportional to the distance between them (hence coefficient *d* is expected to be negative). Consequently, gravity suggest that larger country pairs will trade more, but at the same time countries that are further apart are seen to trade less, mainly because transport costs between them are higher.

The model is clearly a robust starting point for research applied to international trade, however, it is not without flaws when considering more advanced concepts of trade policy between countries. Banally, it is not able to capture the effect of a preferential trade agreement between some countries rather than others. A second problem arises when one is to model a reduction in the costs of trade at a global level, for example due to a drop in oil prices: the traditional gravity model would respond to this eventuality by unitarily forecasting an increase in trade volumes, whereas in the absence of changes in relative prices one would expect consumptions patterns to remain constant.

To overcome the problem that the basic model makes rougher predictions than standard econometric models, over the last decade theory has acquired an increasingly important part of gravity modeling, and applied researchers now have the choice among a number of commonly used theoretically grounded gravity models. An example in this regard is the Anderson and Van Wincoop (2003) model, which introduces two additional variables to the basic formulation to capture the dependence of import-export between two countries on the costs of trade with all other possible partners, namely outward and inward multilateral resistance.

While agreeing with the limits of the basic gravity model, for the purposes of this project it was chosen to use the latter with respect to more extensive formulations, mainly for two reasons. The first is that the detailed study of the drivers that guide the projections of international trade value evade the purpose of this project, whose objective is to predict the emissions resulting from it. Secondly, and as a result of the above motivation, a less stringent level of accuracy is required for the analysis, and therefore the drawback of having more raw results typical of a preliminary approach, is offset by the lower computational effort for the implementation and calibration of the coefficients.

A clarification is necessary in this regard: the model presented here for the estimation of commercial volumes is not the only one suitable for this purpose, although it is particularly effective and robust. In particular, another model that can be applied in Fourth IMO GHG Report (4) is the logistic curve description, also called S-curve, according to which the transport work goes through a phase of slow initial growth and then undergoes a rapid increase, and finally a mature stage in which growth stabilizes. The main difference with the gravity model is that the S-curve can better describe the peculiarity of demand for different types of cargo and commodities. On the other hand, it is based on global data, so it does not capture the specificities of bilateral trade between individual countries. In this study, the first model was preferred over the one now presented on the basis of this difference: the peculiarities of transport demand for the various types of cargo is estimated with a model built ad hoc that will be discussed in the next paragraph, while at this stage it is more important to have a detailed picture, albeit preliminary, of the trend of trade relations of individual countries.

Secondly, it is specified that in this study the forecast of trade volumes has not been differentiated between energy products (like coal, oil and gas) and non-energy products. The former has a greater influence on the activity of coal dry bulk, oil and gas tankers, while the latter affects the demand for container ships and chemical tankers of non-energy products. Consequently, for a more accurate analysis it would have been necessary to use the gravity model only for the estimation of non-energy goods and to estimate the demand for fossil fuels starting from a linear regression on IPCC data on the evolution of energy consumption in the countries considered. This may to some extent be a limit to the accuracy of the forecast and will be better discussed in section 6.2 Possible improvements.

3.2.3 Model for transport-work projections

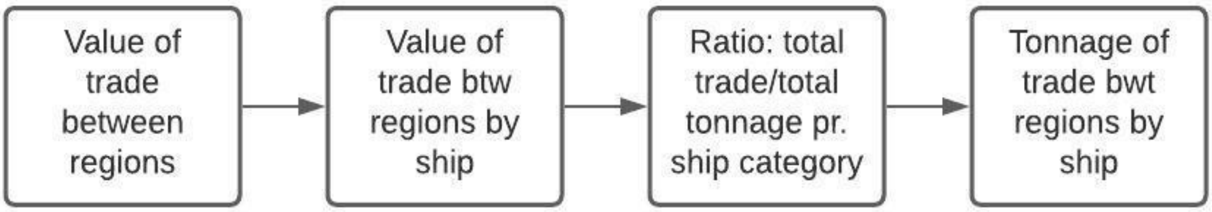


Figure 7: Flowchart for tonnage of bilateral trade estimate logic.

The process of converting trade volume forecasts from monetary value to unit of weight, which is essential to build the demand for freight transport (ton-nm), is based on a simple principle of proportionality. This means that the material volume of goods shipped for each year after 2015 will be equal to the product of the monetary value of trade exchange by a coefficient of proportionality, here indicated as *r*. The logical scheme of the model is shown synthetically in Figure 7, while below is reported the algebraic formulation that estimates this coefficient.

First, it is necessary to aggregate the trade value at continental level, accordingly:

$$X_{c1,c2,y_0} = \sum_{i \in c1} \sum_{j \in c2} X_{ij,y_0} \qquad [USD] \tag{3}$$

Where the reference year y_0 is 2015, *c1* and *c2* indicate respectively the continent of export and import while *i* and *j* refer to the individual countries selected in the analysis belonging to a given continent. X_{ij,y_0} finally, is the value of trade between two countries in the year 2015 obtained from equation (3).

Then the bilateral trade data between two continents is divided in the sum of the contributions for each type of ship, as described by the equation, where the index *s* includes the types of ships considered (see Section 3.3.1):

$$\begin{aligned} X_{c1,c2,y_0} &= X_{c1,c2-container} + X_{c1,c2-drybulk} + X_{c1,c2-chem} + X_{c1,c2-oil} \\ &= \sum_{s} X_{c1,c2-s,y_0} \qquad [USD] \end{aligned} \tag{4}$$

Once the value of X in different types of ships has been partialized, it is possible to calculate the coefficient *r* given by the ratio between the trade value *X(c1,c2-ship)* and the volume of transported goods for the year 2015 and the corresponding ship category *T(c1,c2-ship)*:

$$r_{c1,c2-s} = \frac{X_{c1,c2-s,y_0}}{T_{c1,c2-s}} \text{ , es. } r_{c1,c2-s} = \frac{X_{c1,c2-container,y_0}}{T_{c1,c2-container}} \qquad \left[\frac{USD}{ton}\right] \tag{5}$$

From here intuitively, the volume of goods transported for each year of the horizon can be derived as the ratio of the exchange values provided by the gravity model, for the coefficient *r* described above.

$$T_{c1,c2,y} = \frac{X_{c1,c2,y}}{r_{c1,c2,s}} \qquad \forall\ y_n > y_0 \qquad [ton] \tag{6}$$

Where all the elements of the formula refer to the previous equations. In the next Chapter 4 is contained the details of the data series used to derive the coefficient *r* and the MATLAB codes developed ad hoc for this purpose.

3.3 Supply side

3.3.1 Model for fleet development

The demand for transport is met by the use of different types of ships, in turn divided by size categories. This study will use the division shown in the table, with reference to the method followed by IMO in its Third and Fourth report.

Table 2: Size bin distribution and relative unit for each ship category

Ship type	Size distribution	Unit
Dry Bulks	0 - 9999	dwt
	10000 - 34999	
	35000 - 59999	
	60000 - 99999	
	100000 - 199999	
	200000 +	
Containersn	0-999	TEU
	1000-1999	
	2000-2999	
	3000-4999	
	5000-7999	
	8000-11999	
	12000-14500	
	14500+	
Chemical Tankers	0 - 4999	dwt
	5000 -9999	
	10000 - 19999	
	20000 +	
Oil Tankers	0 - 4999	dwt
	5000 - 9999	
	10000 - 19999	
	20000 - 59999	
	60000 - 79999	
	80000 - 119999	
	120000 - 199999	
	200000 +	

To each size bin of all categories of vessels correspond specific characteristics regarding the average capacity of the vessels (in TEU for containers and in dwt for all other categories), the productivity (defined as ton-nm/dwt) and the total number of vessels belonging to the group. It is expected that in the horizon analyzed all these characteristics will evolve. In particular the distribution of the number of vessels for each size category will vary as a consequence of the number of scrapped ships, new ships entering the fleet and their respective size. As already discussed in the introduction, many types of ships have seen their size vary in the past years due to the effect of the Economic of Scale (EOS) which foresees an increasing number of small and medium size ships replaced with a few vessels of large or maximum size. That said, the size of a new vessel entering the fleet can be influenced by various technological and economic factors, it depends on the demand of the type of cargo transported and the trade pattern concerning the cargo itself, i.e. the geographical location of the areas of supply and demand. In addition, it is subject to physical restrictions due to the size of ports and canals and terminal equipment. All these concomitant factors can lead to a large uncertainty in future fleet modeling; however, this is a key element for the prediction of global energy consumption in the whole fleet, which is intrinsically dependent on the average vessel size.

Although most ship types are not expected to experience significant changes in size distribution in the future, the notable exceptions include two of the four categories analyzed in this study: containers and bulk carriers. This is primarily due to a fast-growing market and economies of scale factors, but even then, significantly larger ships are not expected to enter the market due to port infrastructure constraints.

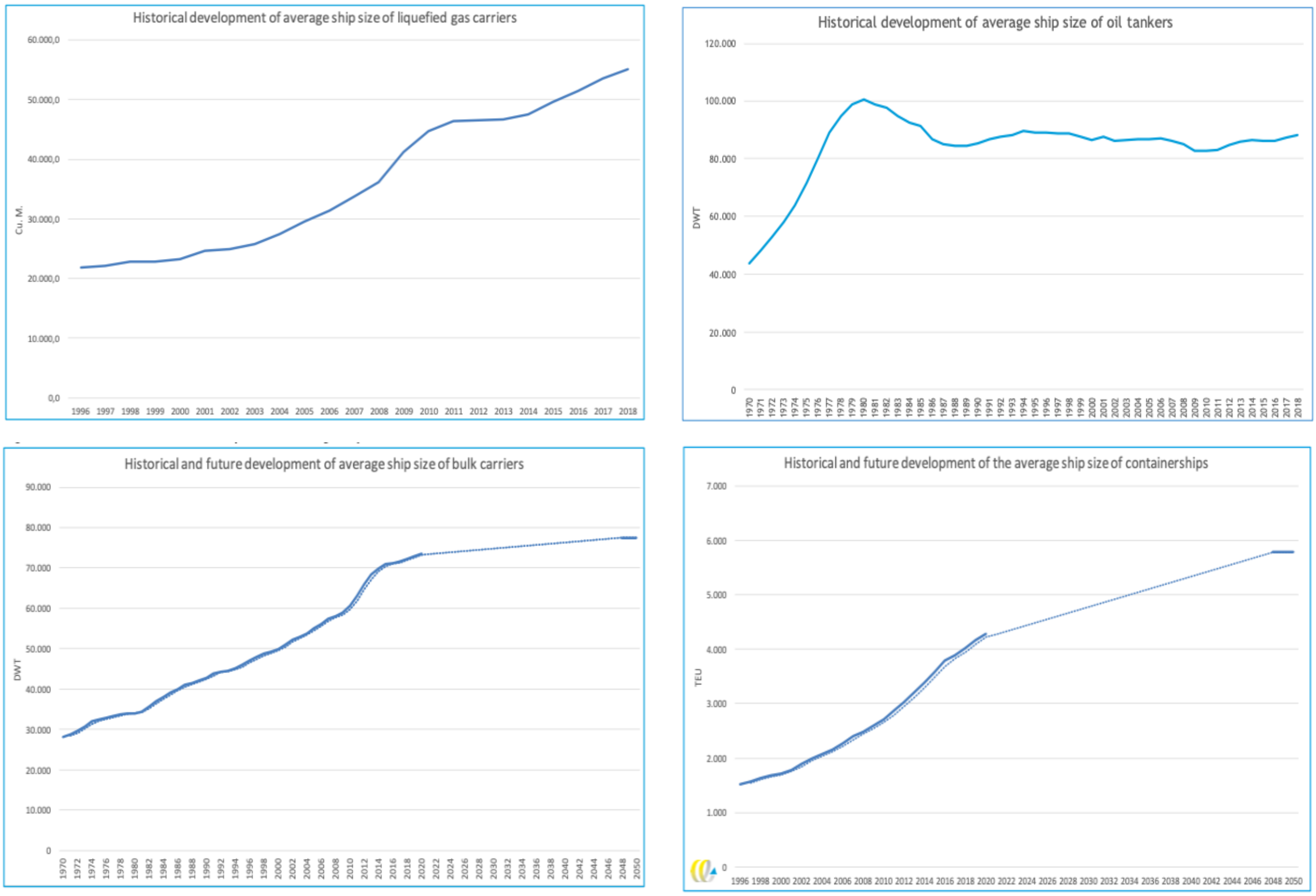


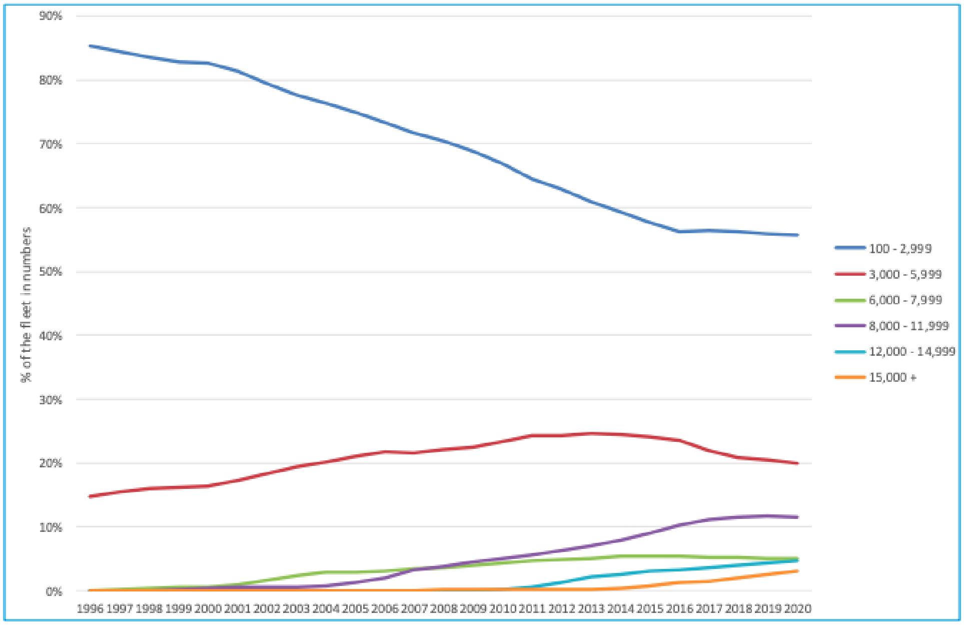
Figure 8: First row. Development of average capacity of liquified gas and oil up to 2018. Second row. Historical and future average size of bulk carriers and containerships up to 2050.

Source: Fourth IMO GHG Report (4).

In its Third and Fourth Reports (4) (13), the International Maritime Organization (IMO) has outlined the main trends of this development, and part of the data there reported will be used in this study. From the review of the reports we know the following for the 2015-2050 horizon:

- The average size of ships by size category;
- The distribution of ships over the size categories in terms of numbers and,
- The expected change in productivity (ton-nm/dwt) for each size bin in every ship class up to 2050;
- It is assumed that, per size category, the average size of the ships will not change, whereas the number of ships per size bin will change compared to 2015.
- The total capacity per ship type, given a certain productivity level (in ton-nm per dwt), is therefore assumed to be sufficient to meet the projected transport demand.

The historical distribution of containers for every bin size by number is shown in the following graph.



Source: Clarksons World Fleet Register March 2020.

Figure 9: Distribution of containerships in terms of numbers over size categories in the period 1998-2018.

Based on this reference, two alternatives (67) have been considered to derive the future number of ships in the fleet:

1. For each year of the time horizon derive the total number of vessels needed to meet the transport demand in ton-nm, dividing the above demand by the total transport work of the category (ton-nm/ship) which in turn depends on the productivity increase from year to year. The total number of vessels is then divided into size bins according to the estimated distribution for that year. Since this approach is based on annual demand, it will be called the Demand Approach.
2. Another method is named as Logistic Approach and assumes an evolution of the fleet according to a logistic curve, taking 2030 as the median year of trend reversal. Unlike the Demand Approach, in this case the total number of ships is obtained only for the year 2050, with the same method described above, and the trend in the intermediate period follows the characteristic S-curve of the logistic model.

The criteria for choosing the model were mainly consistency with historical trends and forecasts in other literature references. The Demand Approach in this regard proved to be inadequate because it presented a development trend in contrast to the sources mentioned above. The limit in referring only to the present transport demand is in fact to estimate only the number of ships strictly necessary to satisfy it, without taking into account the actual number of ships already existing (for example, the theoretical value of containers in 2015 was 630 against a real figure of 5313).

Therefore, the Logistic Approach won the match that is more in line with the trend of recent years. It is necessary to point out that although the trend thus defined is more consistent with the forecasts in the literature, the final number of ships used in the logistics model depends, as in the case of the Demand Approach, solely on estimated transport demand for 2050. Consequently, it does not take into account potential changes in the market or infrastructure constraints. In reality each country meets its own import-export demand with vessels sailing under its own flag. There are also political-commercial reasons why with a larger fleet a country has more possibilities to compete in the market. Finally, from the logistical point of view, it is well known that there are periods of the year with peaks in demand compared to other months, and although we can predict demand and organize the voyages in advance, the fleets must be sized on the peaks of demand. These are some of the main reasons for the gap between results and historical series. Thus, it is inevitable that the estimated distribution of ships up to 2050 is associated with a high degree of uncertainty, making it difficult to draw accurate conclusions from past trends, which could last as well as stop.

Another hypothesis, verified with the use of the previous model, is that for each year the transport work required by ship category is satisfied. Since the theoretical number of ships estimated to meet the demand is much lower than that obtained from the Logistic Approach in all the horizon except 2050, the hypothesis can be considered always true.

Below is reported the algebraic content of the Logistic Approach used here.

$$P_{y,s,b} = P_{2015,s,b} * \Delta P_{y,s,b} \qquad \left[\frac{ton-nm}{dwt}\right] \tag{7}$$

The equation indicates that productivity each year is the productivity of ships in 2015 multiplied by the variation in productivity in that year (in the project will be used to derive productivity in 2050).

$$TWS_{y,s,b} = P_{y,s,b} * \overline{DWT}_{y,s,b} \qquad \left[\frac{ton-nm}{ship}\right] \tag{8}$$

The transport work per ship in each year, segment and size category is calculated as a product of productivity for the average size of the ship.

$$TWS_{y,s} = \sum_{b} TWS_{y,s,b} \qquad \left[\frac{ton-nm}{ship}\right] \tag{9}$$

Intuitively, the transport work per ship total of the category is the sum of the contributions of individual size bins.

$$NS_{2050,s} = \frac{TW_{2050,s}}{TWS_{2050,s}} \qquad [\#vessels] \qquad (10)$$

Here is derived the total number of ships in 2050 for each ship category calculated as the ratio between the estimated transport work for 2050 (derived from the previous model), and the transport work per ship in 2050.

Once the total number of ships in 2050 for each category is known, the development of the fleet can be calculated using a generalized logistics function.

$$NS_{y,s,b} = \left(A_{s,b} * k_{s,b}\right) + \frac{B_{s,b} + A_{s,b} * k_{s,b}}{1 - \exp(-r * (t - \tau))} \qquad [\#vessels] \qquad (11)$$

The numbers of ships in year y is calculated by using the initial number of ships (A) times a rate (k) plus the final number of ships in 2050 (B) minus the initial numbers of ships, divided on 1 minus the exponential of the negative rate multiplied with the year.

In this model, k is 1.008 for container ships, 1.03 for dry bulk carriers and oil tankers, and 1 for chemical tankers. The parameter t is set to be 0.2 for all the ship type, and *tau* is set to be 2033. All the values used have been retrieved from previous studies.

3.3.2 *Estimate of fuel consumptions*

In order to estimate the energy consumption of the various types of ships, a retroactive model has been used starting from the estimates of CO_{2eq} emissions for the horizon taken as reference.

The criterion for choosing this approach is due to the availability of data, as the data series on emissions by category were already available from previous studies.

In the reference study as well (14) it is assumed that the fuel mix does not change in the horizon and always remains equal to 90% HFO (including 5% LSHFO) and 10% MDO. This data will be used to derive the fuel consumption from the final emissions data.

Below are the equations used to derive fuel consumption estimates.

$$FC_{y,s,b} = \frac{EF_{y,s,b}}{e_f} \qquad \left[\frac{g}{ton - nm}\right] \qquad (12)$$

The formula highlights how, starting from the emission factors on nautical ton-mile for each size and category of ship, it is possible to trace the fuel consumption, through the use of data on specific emissions of CO_{2eq} per gram of fuel e_f. In this case, the value of e_f was derived from the weighted average of specific emissions of HFO and MDO, considered the only components of the mix in the reference study.

$$e_f = 0{,}9 * e_{f,HFO} + 0{,}1 * e_{f,MDO} \quad [\frac{g_{CO_2}}{g_{fuel}}] \tag{13}$$

Where $e_{f,HFO} = 3{,}114$ *ed* $e_{f,MDO} = 3{,}206 \quad \frac{gCO_2}{g_{fuel}}$, having considered only emissions in the operational phase.

In the same way the Specific Fuel Oil Consumption (SFOC) was derived as a weighted average of 185 $\frac{g}{kWh}$ for HFO, and 175 $\frac{g}{kWh}$ for MDO. This coefficient indicates the specific fuel oil consumption per kWh of energy produced considering the calorific value of the fuel and the average efficiency of an internal combustion engine, equal in the reference paper to 0,5.

$$EC_{y,s,b} = \frac{FC_{y,s,b}}{SFOC} \quad \left[\frac{kWh}{ton - nm}\right] \tag{14}$$

$$ED_{y,s} = \sum_b EC_{y,s,b} * NS_{y,s,b} \quad \left[\frac{kWh}{ton - nm}\right] \tag{15}$$

It is therefore possible to derive the energy consumption for each type of ship and size category, which at this point is decoupled from the specification on the type of fuel used but indicates more generally the demand for mechanical energy to the crankshaft. This will be one of the key components for the construction of the model in message-ix.

The assumption in the estimates used is that in the period 2015-2050 the efficiency of the fleet, and consequently the emission value on transport work, will be reduced by 10% in each type of ships. In general, the efficiency improvements are the result of changes in the average vessel size, concomitant with a change in the fuel mix. This change is associated with restrictive emission standards for other pollutants which results in more ships using MGO, VLSFO, LNG or HFO combined with a scrubber. Some solutions chosen will result in higher CO_2 production, others in lower production. In addition, there is the influence of the introduction of the Energy Efficiency Design Indicator (EEDI), already discussed in the introduction. The assumptions of the Third and Fourth IMO Reports (2014-2020) agree that the operational efficiency of new ships will exceed the requirements of the EEDI for the first three quarters of the period but will fall behind in the fourth.

3.4 Emissions side

3.4.1 Selection of alternative fuels end specific emissions

Some technologies have been outlined, reviewing the literature, as more promising in terms of cost and emission reduction potential than others. In fact, as discussed in the introduction, the possibilities to reduce GHG emissions range from solutions concerning the design of the vessel, its operational parameters (such as the reduction of auxiliary consumption or speed reduction), the installation of alternative technologies for propulsion and the use of alternative fuels. The latter presents a CO_2 abatement potential by 2050 of 64.08% (4), a clear gap compared to all other solutions (the second highest value is 3.95%). For relevance, therefore, in this study I have chosen to model only the transition to alternative fuels as a method of reducing emissions.

Once the energy demand of all types of ships has been calculated, we know that it can be met through the use of conventional fuels such as HFO or VLSFO, MDO or LNG. Alternatively, one can use a wide selection of alternative fuels (at least theoretically) that call the use of Internal Combustion Engines (ICE) or other energy production technologies such as Fuel Cells (FC) or Steam Turbine systems (ST). One of the aims of this project is precisely to understand how the choice and penetration of one low-emission technology rather than another influences the total CO_{2eq} emission projections on the horizon and whether they are economically feasible.

Since the study of the impact of each alternative fuel is too large in relation to the size of this project, I have chosen to focus only on the most promising energy sources. The analysis then examines the following fuel types:

Table 3: List of conventional and alternative fuels considered in the analysis.

Conventional fuels	HFO (LSHFO) MDO LNG
Alternative fuels	Ammonia Hydrogen Bio-methanol

Some considerations to justify the choices:

- Liquified Natural Gas (LNG) has seen in the period 2012-2018 a growth in consumption of 0.9% (4) and especially for some types of vessels such as Liquified Gas Tankers are proposed as a viable alternative to conventional fossil fuels, having a higher hydrogen to carbon ratio resulting in a lower specific emission of CO_2 and not containing sulfur (23). On the other hand, however, it is estimated that its emission reduction potential is dampened from 25% to 15% (58) if we consider the emissions of CH_4. When burned in conventional low-pressure methods in fact it is possible that there are leaks of unburned methane being this the main component of natural gas. The problem of leaks can be mitigated in the future by technological progress, although there are still some uncertainties in this regard. Despite these, it is recognized that LNG has become a conventional fuel and is therefore included.

- Biofuels in general are considered to have a high potential to reduce emissions between 25 and 84% according to Bouman et. al. 2017 (19), since it is assumed that emissions at the time of burning are offset by CO_2 captured in the growth phases of the plants from which they are produced (beet, sugar cane, etc.). The use of bio-methanol will therefore be considered in this study, although it is not the only possible solution. It should be remembered, however, that the large-scale use of a biofuel brings with it potential side effects, for example, the consumption of soil due to cultivation for energy purposes competes with agricultural exploitation (59). The discussion will be resumed in Chapter 6, although a quantitative estimate of the soil demand to meet the demand for Bio-methanol eludes the purpose of this project. An effect that will be discussed in the next section is instead that of upstream emissions: depending on whether or not these are taken into account the specific emissions of a biofuel can change significantly.
- Hydrogen is considered by many studies as a promising solution, Gilbert et. al. 2018 (16) for example evaluates very relevant the use of hydrogen as a fuel within a fuel cell especially when associated to an innovative production based on renewable resources, because its production is normally very energy intensive. Clean fuel options with hydrogen for sea transportation also argues that hydrogen is a potential alternative to traditional fuels once overcome infrastructure barriers for its distribution, technical-economic and safety. Some vessels that use hydrogen also already exist, as for example the Vikings Lady that uses a fuel cell.
- Kyunghwa et. al. 2020 (61) argues that ammonia is a possible alternative fuel, as its volumetric energy density is higher than liquid hydrogen, it does not present particular safety problems for storage on board. Moreover, ammonia has other benefits such as an already existing infrastructure, a transport and storage system already available today that make it a more cost-efficient solution. In addition, a study conducted by Nick Ash concluded that ammonia production without any associated emissions at any point in its life cycle is a technologically feasible solution. Finally, also a report of the International Energy Agency (9) has estimated that hydrogen and ammonia have the potential together to meet the environmental targets in the marine industry, despite their production costs are high in relation to oil-based fuels.

It is necessary to remember, when talking about hydrogen and ammonia, that at the moment there are no commercial engine technologies applicable to large vessels. This will be an element that will be taken into account in the construction of the message-ix model, discussed later. Also, in this case the CO_{2eq} reduction potential is initially lower, as they are assumed to be produced with conventional methods (Steam Methane Reforming) exploiting fossil compounds.

In the estimation of specific emissions per unit of fuel used, the method by which the emissions are calculated is important. In particular, the value can change considerably if we consider the Life Cycle Assessment (LCA) of the fuel itself. For the purposes of this study it is interesting to evaluate the emissions resulting from fuel's production and not only those in consumption phase, hence a Well to Wheel (WtW) approach for the fuel supply chain is adopted (which is less extended than an LCA approach). This aspect becomes even more important if alternative fuels are examined because in most cases, they are emissions free at the time of consumption, but to assess whether they are actually effective in abatement we must consider the entire production cycle. In fact, it may be that including also the CO_2 emitted in the production and transport phases (for bio fuels also the cultivation process itself), the final emissions of a fuel considered zero emissions actually produce the same or more than traditional fuels, having only "anticipated" them from burning to production. Below is an image from Gilbert et. al. 2018 (16) which highlights this aspect.

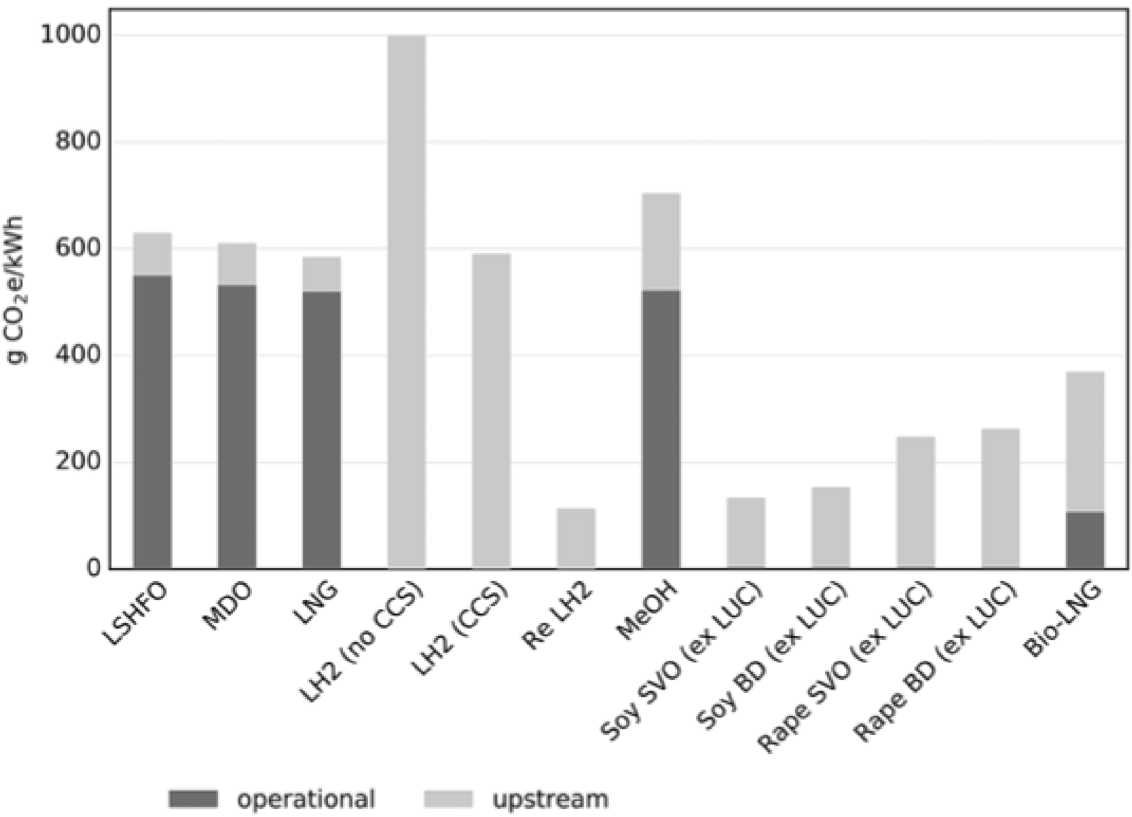


Figure 10: Emissions per kWh of shaft output per each fuel type. Source: Gilbert et. al. 2018 (16)

The image shows GHG emissions per kWh of shaft output, per life cycle stage, and includes all alternative fuels considered in this study. It can be noted that for hydrogen emissions are only upstream and only in the case of production from renewable sources are equal or lower than those of traditional fuels.

Since this aspect is particularly relevant to this study, it was chosen to include upstream emissions of all fuels in the analysis. From the study mentioned above, data on upstream emissions of all sources used in the analysis were derived, taking care to convert them from $\frac{gCO_2}{kWh}$ to $\frac{gCO_2}{g_{fuel}}$ dividing the initial value by the SFC of each source, previously calculated.

3.4.2 Estimate of emissions marginal abatement costs

The marginal abatement cost (MAC) of GHGs represents the relationship between the reduction of greenhouse gases emitted and the cost of individual abatement technologies. In general, for each additional unit of GHG removed the cost of abatement technology increases, and for many technologies the Marginal Abatement Cost Curves have been developed to model this relationship. This method accurately captures the effect that when very high abatement rates are achieved the cost of removing an additional unit is higher than the cost of removing a low percentage.

Another indicator that lends itself to this analysis is the Cost of Avoided CO_2 (CAC) that applies to all GHGs and instead of considering the cost per additional unit as in the previous case, uses a posteriori approach. The total avoided emissions are compared to the total costs incurred for this purpose. This method, therefore, unlike the previous one, places the amount of GHGs removed and removal costs in a linear relationship, but it is very useful in the comparison of different technologies or in the aggregate analysis of more solutions.

Below are the main drivers that contribute to the differentiation of costs of alternative technologies compared to the use of heavy fuel oil.

- The fuel cost is the main driver of cost-efficiency difference between two abatement technologies and especially in the initial phase where no learning curve is applied can be very different from each other.
- The extra investment cost on engines and storage equipment; some technologies may require different types of engines than ICE (e.g. a fuel cell), which brings with it higher or lower capital costs.
- The cost of revenue lost due to the difference in volumetric energy density, which leads to oversizing the fuel storage tank to the detriment of the loading capacity.

Estimating the investment and operating costs of using one fuel rather than another is extremely difficult and inherently uncertain. Just think that some technologies such as fuel cells, considered the most efficient way to use hydrogen, are still under development in the naval context. Consequently, there is a lot of uncertainty about which technology is winning in the use of ammonia and hydrogen (Fuel Cell (18), dual fuel engine, ICE) and learning curves that represent their cost reduction potential. For the purpose of this analysis therefore it was considered to consider only the effect of fuel costs and not the marginal capex.

The fuel costs used in this study refer to the literature, such as IMaeEST (2011), Frontier Economics (2019), IMO, and ECOFYS (2019), and are shown in the table below.

Table 4: Conventional and low carbon fuel cost for the period 2015-2050 (4).

Fuel type	Mean fuel cost
HFO (VLSHFO)	375
LNG	590
Methanol	400
Hydrogen	3300
Ammonia	660
Biomass methanol	800
Unit: USD/ton	

3.4.3 Projection of CO2 emissions from maritime sector

In this section we will illustrate the model for the estimation of annual CO_{2eq} emissions from maritime transport, which consists of a dynamic linear least-cost optimization problem. The tool used is message-ix, a dynamic system optimization model, an open framework for the integrated analysis of energy, climate, environment and sustainable development policies. Its mathematical formulation is based on a model developed by (68), the MESSAGE Integrated Assessment model, then re-integrated and extended as message-ix package. It was originally formulated for strategic energy planning and integrated assessment of energy-engineering-economy-environment systems (E4). The framework can be used to operate different models of energy systems, which can range from very simple to very detailed ones such as the MESSAGE-GLOBIOM global model (17). The framework can be applied to analyze scenarios of transformation of the energy system under technical-engineering constraints and socio-economic considerations, also includes the possibility of integration with the MACRO model of general economy, to incorporate the effect of price changes on the demand for energy goods and services (18).

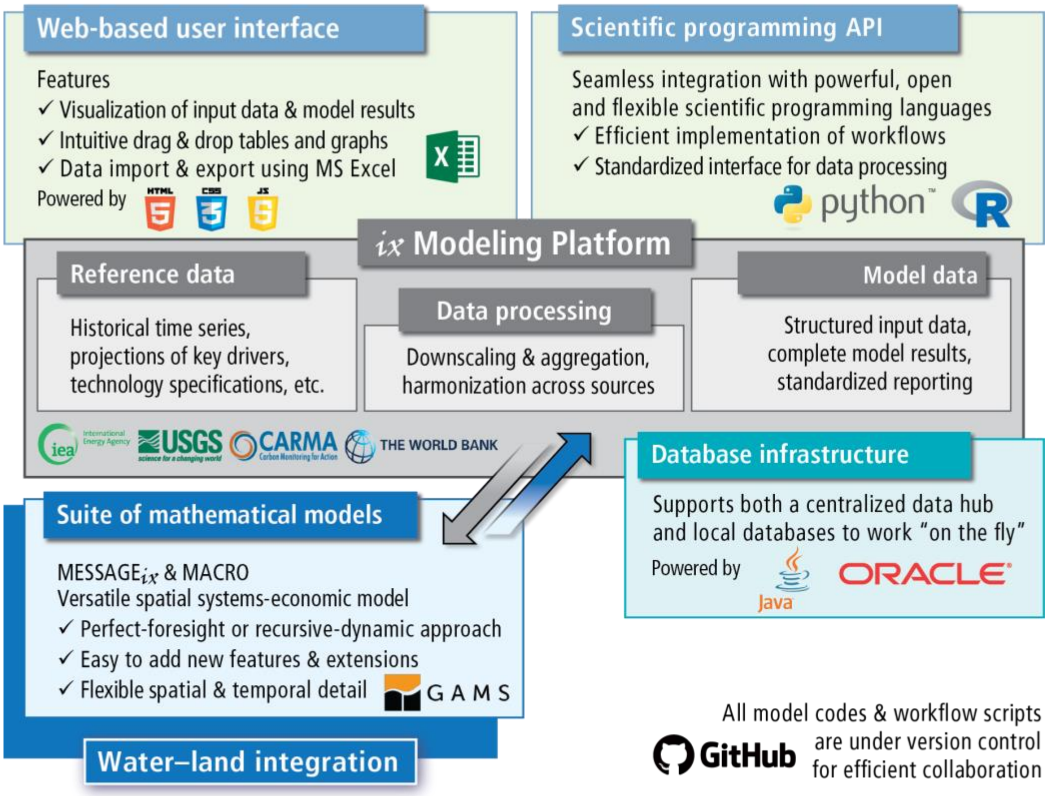


Figure 11: Input/output Message-ix framework.

The codes in the message-ix package are written in the *GAMS* mathematical programming language, which is also used to calculate the numerical solution of a model instance.

The framework is also structured around the *ix* modeling platform (*ixmp*), a powerful database infrastructure to support scenario and workflow management. Its versatile and modular structure easily interfaces with the most used programming languages and allows to use this framework as a data warehouse for balance, simulation or optimization models.

As clarified above the model is developed primarily for the analysis of energy systems, and the evolution of the system with respect to the demand for goods and services related to it (18). However, just for the versatility of the platform *ixmp*, the model message-ix lends itself well for the sectorial analysis of the demand of a good or a service not strictly energetic, like for example the demand of job of transport or the demand of production of an alimentary kind. In the following paragraphs we illustrate the main features of the model and the most important parts of its mathematical formulation. The complete documentation is available at Message-ix Framework website (69).

Set definition

Some of the indexes that will be present in the following formulas are shown in Table 5.

Table 5: List of Message-ix sets.

Node	n	Region, countries
Mode	m	Modes of operation for specific technologies
Emission	e	Greenhouse gasses, pollutants ecc.
Year	y	Model horizon
Technology	t	Technologies that use input commodities to produce outputs

Purpose of the model

The model aims to satisfy the demand value of a given commodity in a node (i.e. a region, country, or globally) at the lowest total cost. The objective function aggregates all costs incurred in the various modules that will be described below, which include both investment and operating costs of the individual technologies, but also any costs of extraction, land consumption or transport, taxes and other expenses (18) (68). The model then determines the optimal configuration of the energy system (or the particular sector considered) according to a logic of cost minimization, taking into account the various technical-economic, physical or engineering constraints.

$$\min_x OBJ = \sum_{y \in Y} OBJ_x(x_y) \tag{16}$$

$$OBJ = \sum_{n,y \in Y} COST\_NODAL_{n,y} \tag{17}$$

The formulas present the standard model resolution version, which considers all *y* years of the horizon and resolves the entire model in the target variable *OBJ(x)*, as a minimization of *COST NODAL* costs.

Technologies

The mathematical formulation of message-ix is based on technologies that produce different commodities. These commodities can be modeled at different levels, but ultimately all of them contribute to satisfy the demand for one or more goods/services placed in the "useful" level. Overall the levels are primary-secondary-final-useful and refer to a basic energy system in which we move from primary resources to useful products. Around the technologies rotate all the instance of the model, they represent the steps of the supply chain for a given energy system/sector. Each of them has certain technical-engineering parameters, such as limits on activity or production capacity, useful life, operating and investment costs. It is possible to represent in detail the capacity already installed for each technology, in order to make changes in the installation time such as decreasing efficiency or increasing costs towards the end of the useful life. In addition, the model determines endogenously the optimal moment to withdraw a plant, based on the evaluation of production costs, and this allows to distinguish between "technical lifetime" (engineering parameter) and "economical lifetime" that depends on the market response. Finally, dynamic constraints such as the expansion of capacity or activity level in a given period can represent the inertia of a system or economic-engineering limitations to the diffusion of a technology beyond a certain threshold. All these aspects are modeled with some key equations below:

$$\sum_{m} ACT_{n,t,,m,y} \leq capacity_{factor_{n,y,t}} * CAP_{n,t,y} \quad \forall t \in T \tag{18}$$

Equation on activity constraint, the actual activity of a technology cannot exceed the physical limits due to the available capacity, considering the capacity factor.

$$\sum_{m} ACT_{n,t,,m,y} \leq max\_utilization_{factor_{n,y,t}} * capacity_{factor_{n,y,t}} * CAP_{n,t,y} \quad \forall t \in T \tag{19}$$

This constraint indicates the upper limit of the exploitable capacity in a year, to represent the scheduled availability of a technology.

$$\sum_{m} ACT_{n,t,,m,y} \geq min\_utilization_{factor_{n,y,t}} * CAP_{n,t,y} \quad \forall t \in T \tag{20}$$

In the same way this constraint provides a lover bound to the utilization of the capacity over a year.

The ACT variable is the key element for the message-ix code developed in this thesis. As said above, the framework includes standard variables and equation, which the developer sets up when creating its own model. In the code developed for this research, ACT is the energy shaft output in kWh derived from the exploitation of any of the fuels included in the analysis. The equations in the next page represent upper and lower bounds on activity rate which are particularly relevant when running this program. In fact, absolute bounds on the activity of technologies and on activity growth rates are used to model the penetration rate (or level off) of conventional and low-carbon fuels.

.

$$\sum_{y,m} ACT_{n,t,m,y} \geq \sum_{y-1,m} ACT_{n,t,m,y-1} * \left(1 + growth_{activty-lo_{n,t,y}}\right)^{y} \quad (21)$$

$$\sum_{y,m} ACT_{n,t,m,y} \leq \sum_{y-1,m} ACT_{n,t,m,y-1} * \left(1 + growth_{activty-up_{n,t,y}}\right)^{y} \quad (22)$$

$$\sum_{y,m} ACT_{n,t,m,y} \leq bound\_activity\_up_{n,t,y} \quad (23)$$

$$\sum_{y,m} ACT_{n,t,m,y} \geq bound\_activity\_lo_{n,t,y} \quad (24)$$

Emissions and pollutants

Commonly the model is used to study the implications of the application of targets on the maximum levels of emissions or their trend resulting from market choices. The implementation therefore includes dedicated formulas for the upper limits of GHG and local pollutants. The formulation is also flexible and allows to disaggregate emissions from different types of pollutant or from a specific category of technologies, or to bind global average emissions only in a given period of the horizon.

$$EMISS_{n,e,y,t} = \sum_{y,m} ACT_{n,t,m,y} * emission\_factor_{t,y,e,m} \quad (25)$$

$$(EMISS_{n,t,e,y} + \sum_{m} historical\_emission_{n,t,m,y}) \leq bound\_emission_{n,t,y} \quad (26)$$

The equation defines the general constraint on the average annual emissions level by including the current year's emissions and those from previous years.

4 Data Analysis

The next section presents the logical and chronological steps for the construction of the maritime emissions model. In particular, the analysis focuses on three cores that constitute the research nuclei within this study: demand side, supply side, emissions side. Each one is the result of the application of statistical models illustrated in the previous chapter and of data analysis; among them there is a hierarchy that places them by increasing dependence.

Methodology

The steps for the estimation of CO_{2eq} emissions from shipping are listed below and represented in the form of a flow chart in Figure 12. Here, the code languages used in different computational phases are shown as well, in the form of boxes.

1. Prediction of the value of bilateral trade between the selected countries in the 2015-2050 horizon and calibration of the results.
2. Forecast the demand for transport of energy and non-energy products for four categories of ships in all their size bins.
3. Detailed forecast of the evolution of the fleet compared to base year 2015.
4. Estimated energy consumption per transport unit (kWh/ton-nm) in the 2015-2050 horizon.
5. Assessment of the fuel mix evolution scenarios, hence the penetration rate of zero emissions fuels.
6. Combination of data derived from points 3,4,5 and emissions derivation in the period 2015-2050.

In this chapter, the first section collects data and results from the "demand side" models, the second from the analysis on fleet evolution and the third explains the values used for emissions characterization. To facilitate the reading of databases with large quantities of values only a portion of the intermediate results will be shown.

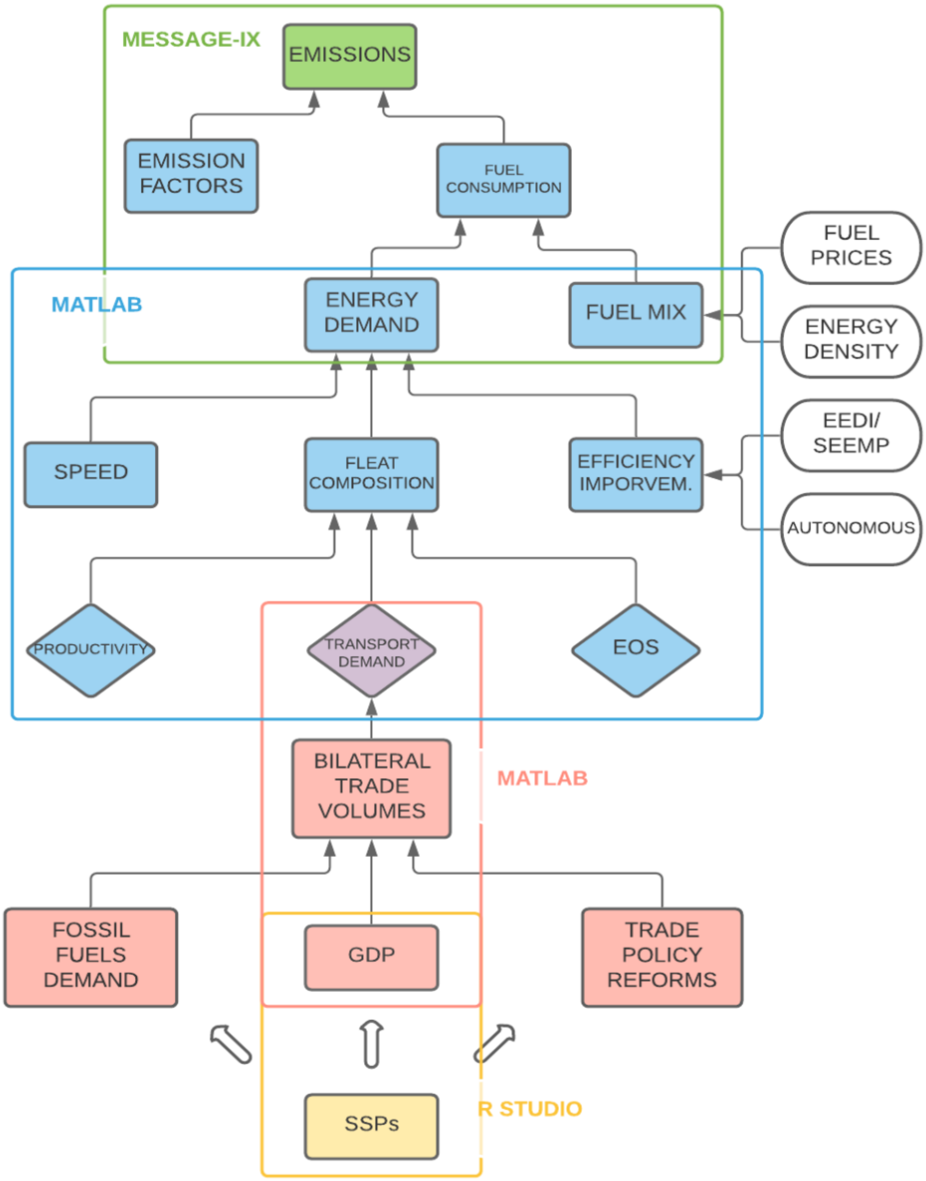


Figure 12: flowchart for overall CO2-eq projection model

4.1 International trade data

4.1.1 Gravity model coefficients calculation

The first step in the application of the gravity model is to derive the multiplicative coefficients of GDP and distance (see Equation 1), starting from historical data. In this regard, a linear regression has been made using R+, starting from data from CEPII (11), the leading French center for research on the world economy. It was necessary to merge two different databases:

- '*gravity data*' for distance values between countries.
- '*BACI_HS*' for the 2015 trade volume values.

The logic for the analysis of this data is illustrated in Figure 13. The codes written in R+ have the purpose first of all to establish what kind of correlation there is between distance, GDP and commercial volume values, and then to derive the gravity model coefficients via Ordinary Least Squares (OLS) regression.

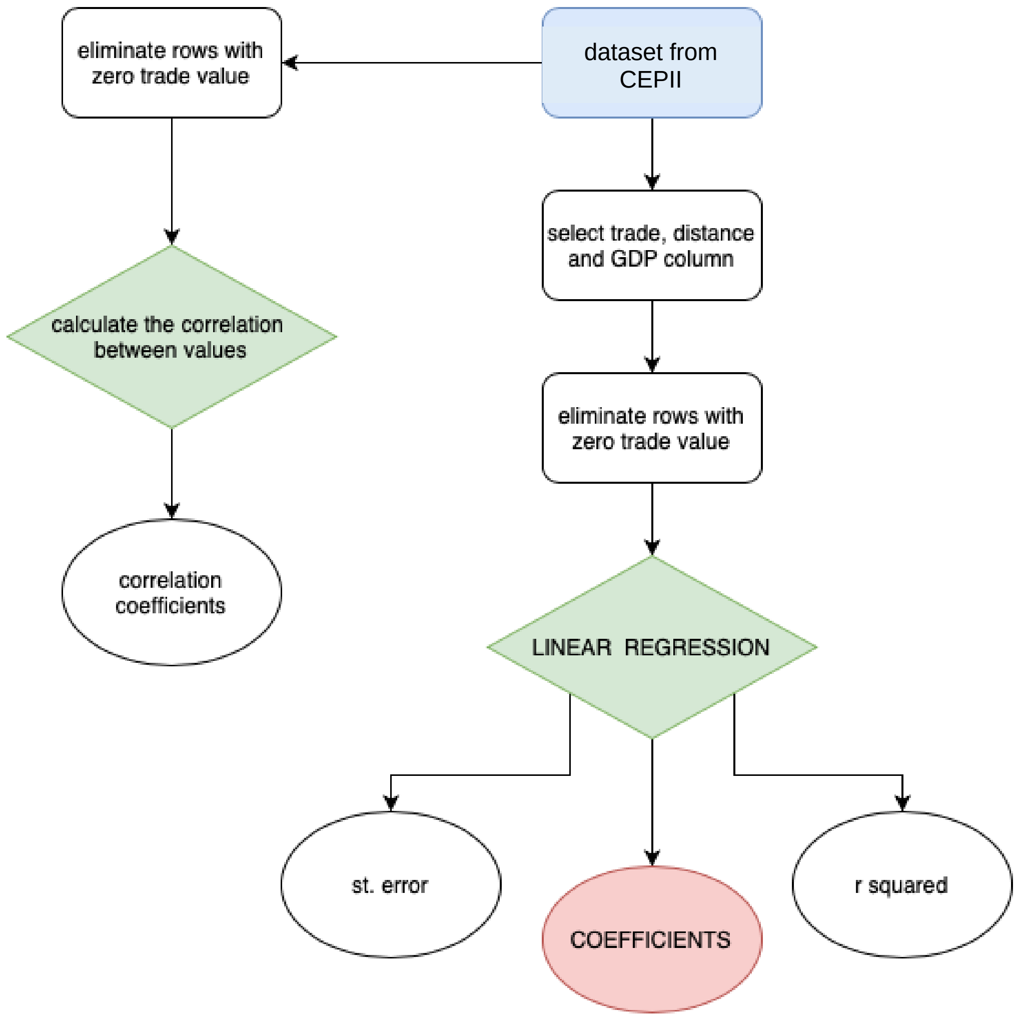


Figure 13: Regression process logic and correlation

In Table 6 a portion of the database resulting from the merging of the two described above is shown, where *Iso3_o* and *Iso3_d* are the exporter and importer codes. In the merging procedure performed with a MATLAB code, data pairs not present in one of the two sources have been excluded.

Table 6: Snapshot of input data for R+ analysis. Here 14 rows of 18578, 6 variables.

Iso3_o	**Iso3_d**	**Distance** (km)	**Gdp Origin** (billions US$)	**Gdp Destination** (billions US$)	**Trade value** (billions US$)
4	32	1,534	19,331	583,169	41,796
4	51	2,171	19,331	10,529	1,415
4	36	1,108	19,331	1339,141	413,629
4	40	4,567	19,331	376,953	172,145
4	58	5,331	19,331	455,086	55,252
4	100	3,819	19,331	50,199	16,104
4	70	4,374	19,331	16,191	2,002
4	112	3,766	19,331	54,608	286,549
4	68	1,510	19,331	32,997	49,659
4	76	1,322	19,331	1774,721	51,033
4	96	5,823	19,331	12,930	2,882
4	124	1,051	19,331	1550,540	1074,890
4	757	5,136	19,331	670,791	11,927
4	152	1,626	19,331	240,796	3,344

Estimating correlation between data

The first step to examine the intuition behind the gravity model is to determine the correlations among the variables. First of all, it is necessary to put the data in the correct format. The selection of the variables for which there’s an interest in calculating the correlation have already been selected in the table-merging process, here service products has been chosen and the “trade quantity” column has been discarded. Each country pair include four variables as: trade, distance, GDP of export country and GDP of import country. Afterwards the code makes sure that zero and missing values are discarded from calculations. The resulting correlation coefficients can be seen in Table 7.

Table 7: Correlation coefficients

	Trade	Dist	Gdp_exp	Gdp_imp
Trade	1	-0.2647	0.3643	0.3730
Dist	-0.2647	1	0.0517	0.0430
Gdp_exp	0.3643	0.0517	1	-0.3103
Gdp_imp	0.3730	0.0430	-0.3103	1

The correlations coefficients of interest are found in the non-unitary elements of the matrix. Here we can see that trade and GDP are strongly positively correlated, and also that the value is approximately the same with respect exporter and importer GDP. This finding is in line with the basic intuition that bigger (richer) countries are more likely to trade. On the contrary, there is a negative correlation between trade and distance: this support the idea that for country pairs that are far apart from each other trading is more difficult. Again, this result is in line with the intuition presented in the precedent chapter.

Estimate of the intuitive gravity model

At this point, procedures for the actual estimation of the gravity model coefficients can be performed. The preliminary operations of filtering null or missing data are performed as in the previous case, then through the *lm-robust* function the program performs an OLS regression of the input arrays: trade, distance, GDP. Below in Figure 14 are shown the code used and the results, which are named after as variable *reg1*.

```
# make sure you have the data loaded and transformed as in Box 1
# drop missing values for dist, gdp_imp and gdp_exp
SERdataLR <- SERdata[complete.cases(SERdata[ ,c("dist","gdp_exp","gdp_imp")]),]
# do not include zero values for trade
SERdataLR <- SERdataLR[SERdataLR$trade != 0, ]
# install.packages("estimatr") # uncomment in order to install package
library(estimatr)
reg1 <- lm_robust(log(trade) ~ log(dist) + log(gdp_imp) + log(gdp_exp), cluster = dist,
                  data = SERdataLR, se_type = "stata")
```

```
> reg1
                Estimate Std. Error   t value      Pr(>|t|)    CI Lower    CI Upper   DF
(Intercept)  -21.6849841 0.70905075 -30.58312 7.149395e-171 -23.0754804 -20.2944877 2151
log(dist)     -0.7485666 0.03313976 -22.58817 1.488641e-101  -0.8135559  -0.6835773 2151
log(gdp_imp)   0.6149072 0.01458271  42.16686 1.015656e-283   0.5863095   0.6435048 2151
log(gdp_exp)   0.6006349 0.01360663  44.14281 1.410982e-303   0.5739514   0.6273185 2151
> 
```

Figure 14: OLS estimates of the intuitive gravity model.

In the Estimate column of the *reg1* matrix there are the coefficients of our interest, where the items Intercept, *log(gdp_exp), log(gdp_imp), log(dist)* refer respectively to the coefficients *a, b, c* and *d* of equation (1).

It can be seen that the coefficients fit the data seemingly well: it returns an R^2 equal to 0.54, which means that the observed variation in trade values depend on the selected variables for over 50% of the data. This result would improve as there were more data available feed the regression.

4.1.2 Bilateral trade projections

The next step after calibration is to obtain the actual trade volume projections. To do this, input data from the International Institute for Applied Systems Analysis (IIASA) (12) have been used. In particular, estimates of GDP trends in all countries are available, obtained for each SSP through the OECD Env-Growth model. SSPs are usually coupled with some RCP scenarios (see Introduction), but for this study only the SSPs coupled with the baseline RCP scenario have been downloaded.

In contrast to the previous phase where up to 55 countries were considered in the analysis and all possible matches, in this section and in all the following ones 25 countries will be referred to, for a total of 625 couples in bilateral trade relations. The countries have been chosen to cover all five continents, and within each continent the criteria are the current or potential level of development by 2050, the presence of particular markets affecting the activity of certain categories of ships (e.g. cereals for dry bulk or fossil fuels for oil tankers), and finally the presence of important port hubs (such as Rotterdam in the Netherlands). The selected countries and other information are reported in Table 8.

The data in SSP Database are provided with two types of resolution: 32-regions and country level. It was chosen to use the 32-r database and eventually fill in the missing data with the strings from the other table. In Table 9 a portion of the database is given for clarity.

At this point it was necessary to decide which reference to take for the calculation of distances: the options are port-to-port distance or distance between the most populous cities in a couple of countries. In some cases, these distances may differ greatly, so a test has been conducted to understand how much this variation affects the final trade value. As the difference between the results was 1%, the error is considered negligible and the distances between the most populous cities, already available, were used (see previous section).

Table 8: Countries selected for the emissions projection model

Continent	Country	Country acronim	Country Iso code
ASIA	Saudi Arabia	'SAU'	682
	China	'CHN'	156
	Indonesia	'IDN'	360
	India	'IND'	699
	Japane	'JPN'	392
	North Korea	'KOR'	410
	Pakistan	'PAK'	586
	Russia	'RUS'	643
AFRICA	Turkey	'TUR'	792
	Egypt	'EGY'	818
		'ZAF'	711
AMERICA	Brasil	'BRA'	76
	Canada	'CAN'	124
	Mexico	'MEX'	484
	United States	'USA'	842
	Argentina	'ARG'	32
EUROPE	Belgium	'BEL'	58
	Spain	'ESP'	724
	Italy	'ITA'	381
	Great Britain	'GBR'	826
	Moroco	'MAR'	504
	Germany	'DEU'	276
	Netherland	'NLD'	528
	Norway	'NOR'	579
OCEANIA	Australia	'AUS'	36

Table 9: Portion of IIASA 32-regions resolution. Database include SSP1-5 and projection up to 2100.

Model	Scenario	Region	Variable	Unit	2010	2015	2020	2025	2030	2035
OECD Env-Growth	SSP1	R32AUNZ	GDP|PPP	billion US$2005/yr	906,474	1067,055	1254,862	1451,334	1667,778	1911,723
OECD Env-Growth	SSP2	R32AUNZ	GDP|PPP	billion US$2005/yr	906,474	1066,007	1250,084	1429,700	1605,520	1784,256
OECD Env-Growth	SSP3	R32AUNZ	GDP|PPP	billion US$2005/yr	906,474	1054,004	1210,977	1344,592	1454,396	1547,168
OECD Env-Growth	SSP4	R32AUNZ	GDP|PPP	billion US$2005/yr	906,474	1063,313	1243,386	1432,148	1639,066	1870,744
OECD Env-Growth	SSP5	R32AUNZ	GDP|PPP	billion US$2005/yr	906,474	1078,184	1292,234	1546,627	1865,465	2255,742
OECD Env-Growth	SSP1	R32BRA	GDP|PPP	billion US$2005/yr	1967,541	2303,632	2796,631	3352,735	3996,137	4746,484
OECD Env-Growth	SSP2	R32BRA	GDP|PPP	billion US$2005/yr	1967,541	2313,373	2814,726	3308,152	3776,172	4225,471
OECD Env-Growth	SSP3	R32BRA	GDP|PPP	billion US$2005/yr	1967,541	2322,977	2833,335	3275,810	3616,064	3857,539
OECD Env-Growth	SSP4	R32BRA	GDP|PPP	billion US$2005/yr	1967,541	2307,059	2790,695	3250,369	3693,666	4118,368
OECD Env-Growth	SSP5	R32BRA	GDP|PPP	billion US$2005/yr	1967,541	2302,620	2800,474	3425,068	4238,996	5262,758
OECD Env-Growth	SSP1	R32CAN	GDP|PPP	billion US$2005/yr	1201,888	1355,371	1537,669	1689,670	1845,407	2031,119
OECD Env-Growth	SSP2	R32CAN	GDP|PPP	billion US$2005/yr	1201,888	1353,751	1531,718	1694,124	1861,567	2046,673
OECD Env-Growth	SSP3	R32CAN	GDP|PPP	billion US$2005/yr	1201,888	1340,315	1488,502	1602,145	1715,258	1851,025
OECD Env-Growth	SSP4	R32CAN	GDP|PPP	billion US$2005/yr	1201,888	1350,294	1521,654	1675,346	1845,615	2048,810
OECD Env-Growth	SSP5	R32CAN	GDP|PPP	billion US$2005/yr	1201,888	1366,986	1576,148	1807,107	2114,057	2526,656
OECD Env-Growth	SSP1	R32CAS	GDP|PPP	billion US$2005/yr	434,613	570,892	748,998	983,756	1250,007	1540,132
OECD Env-Growth	SSP2	R32CAS	GDP|PPP	billion US$2005/yr	434,613	573,928	752,744	974,909	1198,528	1420,335
OECD Env-Growth	SSP3	R32CAS	GDP|PPP	billion US$2005/yr	434,613	576,291	759,111	976,284	1187,370	1389,561
OECD Env-Growth	SSP4	R32CAS	GDP|PPP	billion US$2005/yr	434,613	570,812	743,384	960,303	1192,551	1437,460
OECD Env-Growth	SSP5	R32CAS	GDP|PPP	billion US$2005/yr	434,613	569,992	747,690	1008,381	1335,851	1722,921

At this point it was necessary to reorganize the data for better handling. This arrangement was done using a MATLAB code with the following tasks:

- Filtering data for the 25 previously selected countries.
- Cut data sets at year 2050.
- Create the 625 pairs of trade partners.
- For each year, pair the transposed GDP data belonging to each country of the couple.
- Merges the table thus obtained with the distance values of each country pair.

Table 10 presents the updated and filtered layout of the IIASA database. An assumption has been made regarding intra-state trade for which it is null and void, which may in some cases be unrealistic, but it was evaluated that the error is negligible compared to the analysis.

Table 10: New database after data manipulation. Data in trillions of US$.

Country pairs			**2015**		**2020**	
Export	**Import**	**Dist**	**Gdp_o**	**Gdp_d**	**Gdp_o**	**Gdp_d**
682	682	0	0	0	0	0
682	156	7.093	0,667	16,631	0,712	24,590
682	360	7.736	0,667	1,412	0,712	2,094
682	699	3.509	0,667	6,500	0,712	10,511
682	392	8.854	0,667	4,071	0,712	4,130
682	410	7.965	0,667	1,317	0,712	1,354
682	586	0	0,667	0,503	0,712	0,614
682	643	3.833	0,667	2,574	0,712	2,96
682	792	2.118	0,667	0,854	0,712	1,016
682	818	1.456	0,667	0,511	0,712	0,636
682	711	6.169	0,667	0,458	0,712	0,553
682	76	10.659	0,667	2,189	0,712	2,605
682	124	10.634	0,667	1,370	0,712	1,559
682	484	13.616	0,667	1,521	0,712	1,805
682	842	11.716	0,667	13,829	0,712	15,121
682	32	12.675	0,667	0,604	0,712	0,743
682	58	4.508	0,667	0,4242	0,712	0,509
682	724	4.680	0,667	1,466	0,712	1,711

We can then move on to the actual estimate of bilateral trade values for all pairs of countries considered. Two simultaneous processes have been applied at this stage:

- Application of Equation (1).
- Calibration of the coefficients obtained from the R+ code Figure 14. In particular, the intercept value (coefficient a) has been varied from year to year in order to standardize the results with respect to the expected GDP values. From the revision of the sources, in fact, it is estimated that, depending on the scenario, the global Gross Domestic Product is destined to grow by an annual percentage between 2% and 5%. Figure 15 shows the global GDP growth rates for the period 2005-2017 presented in the Fourth IMO Report (4), which have been used as a reference for the calibration of the gravity model coefficients. As can be seen the actual trend (in the OECD orange line) shows an important deviation from forecasts, but this behavior is justified by the fact that a global economic crisis was being experienced in the same period. In previous and subsequent periods, the trend was in the range spanned by the five scenarios. As far as the volume of world trade (the sum of bilateral trade between all the countries of the world) is concerned, the same increase was therefore considered, since in the intuitive gravity model GDP it is considered the only driver of the trend. It is therefore estimated that bilateral trade will grow 2.2 to 3 times in 2050 compared to 2015. Using uniquely the intercept value of -21.68 this constraint is not respected and

the global trade forecasts for 2050 would be up to 30 times the 2015 values. The intercept has been shrimped year by year by executing a goal seek in Excel and imposing a maximum annual increase in trading volumes equal to the characteristic percentages of each SSP. The final intercept values have decreased from the initial value up to -41.13/-41.78.

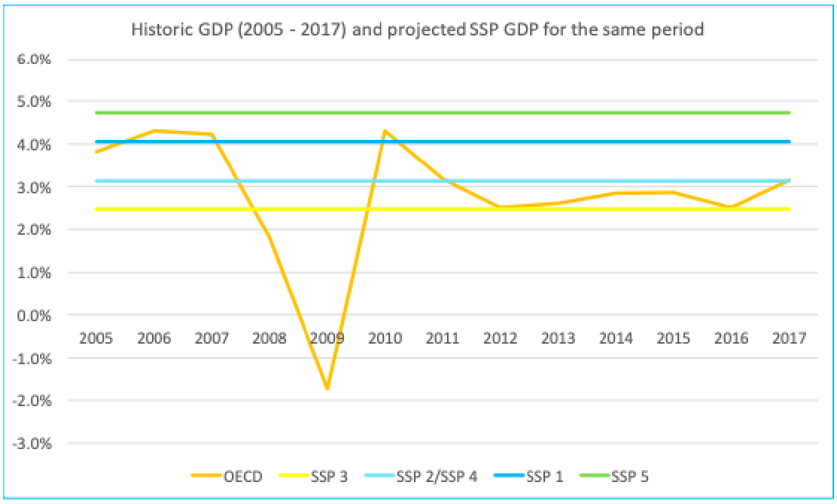


Figure 15: Reference trend for GDP growth projection. Source: Fourth IMO Report (4).

Below is a portion of the resulting database including only the first four vintages and 19 country pairs (Table 11).

Table 11: Bilateral trade results for SSP1, lines 19 of 625, 4 of 8 columns. Data are in trillions of US$.

Export	Import	Trade 2015	Trade 2020	Trade 2025	Trade 2030
682	682	0	0	0	0
682	156	39,533	47,606	50,106	53,626
682	360	0,542	0,656	0,779	0,950
682	699	28,509	39,887	52,084	67,447
682	392	2,520	1,614	1,133	0,955
682	410	0,458	0,300	0,204	0,169
682	586	0	0	0	0
682	643	5,158	4,074	3,198	2,820
682	792	2,323	1,945	1,740	1,772
682	818	1,910	1,726	1,610	1,780
682	711	0,122	0,105	0,099	0,111
682	76	0,641	0,536	0,453	0,437
682	124	0,293	0,227	0,193	0,190
682	484	0,225	0,187	0,169	0,173
682	842	11,91	8,652	6,899	6,472
682	32	0,054	0,048	0,041	0,040
682	58	0,188	0,160	0,148	0,155
682	724	1,409	1,140	0,996	1,001
682	381	3,333	2,763	2,569	2,705

For a better view of the results, heat maps are shown in Figure 16 and Figure 17. Each pixel represents a certain level of bilateral trade between two of the 25 countries, indexed to 2015 values. To facilitate understanding, black lines have been inserted to delimit groups of countries belonging to the same continent. The rows represent the exporting countries while the columns represent the importers. This graphic tool is useful to capture the different evolution of some markets compared to others.

It can be seen from Figure 16 for example that for the SSP1 in the year 2050 some trade routes will increase in monetary value up to 20 times compared to 2015, as can be noticed in the top left corner which represents the import-export in Asia. This effect is mitigated by a very modest or nearly zero increase in other regions, for example in the Eurozone visible in the bottom right corner, so that overall world trade grows between 2 and 3 times.

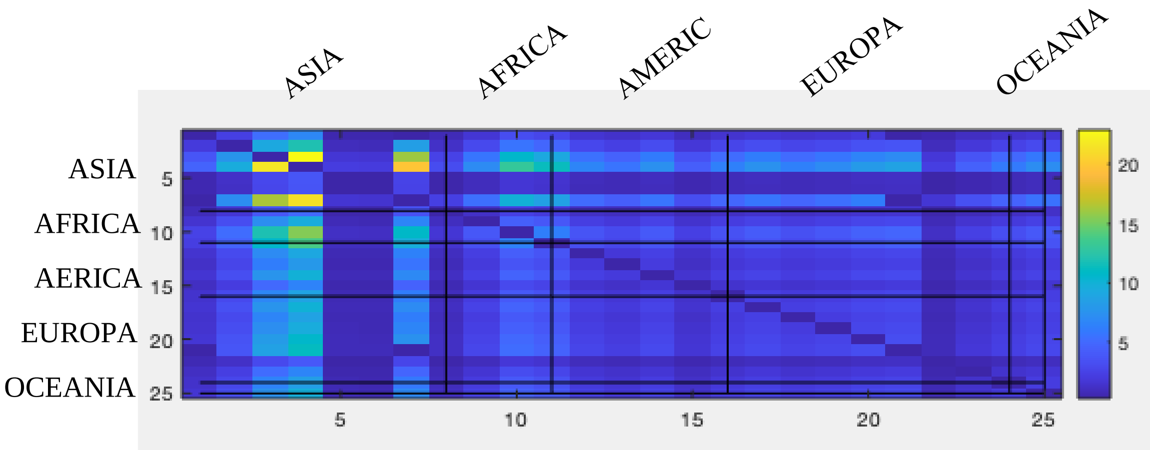


Figure 16: Heat map for trade volumes projections considering GDP data from SSP1, year 2050. Values are indexed with respect to 2015 level of trade (not-indexed data in billion USD).

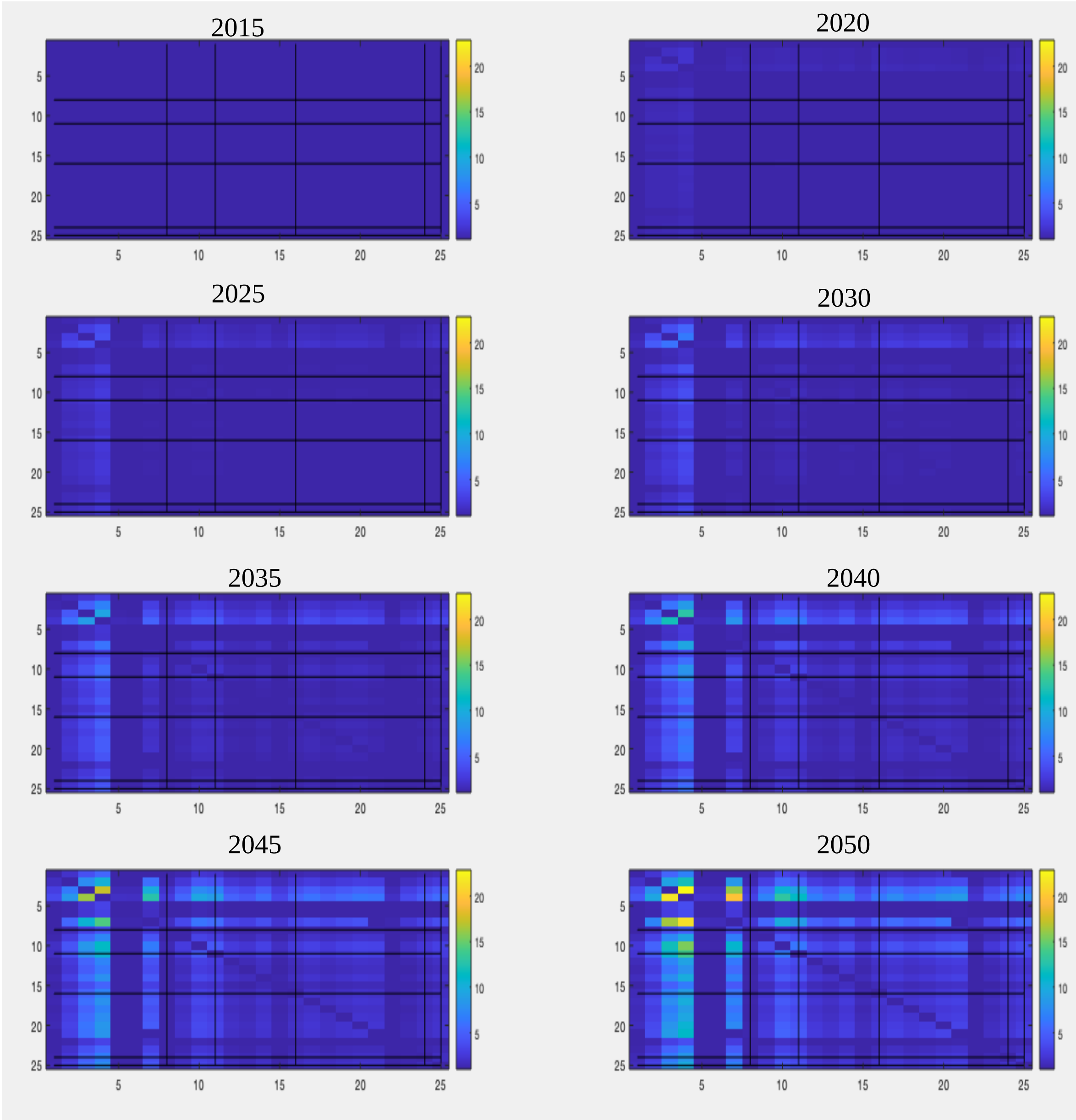


Figure 17: Heat map series for SSP1, years 2015-2050. Values are indexed with respect to 2015 level of trade (not indexed data in billion USD).

Together with the heat maps, I propose a representation of the global GDP values, useful to highlight the differences resulting from the application of the different scenarios (Figure 18). An important consideration to make is that the smallest world's domestic product value in 2050, corresponding to SSP4, is 30% lower than the highest, corresponding to SSP5. This will be important for the validation of the results on transport demand.

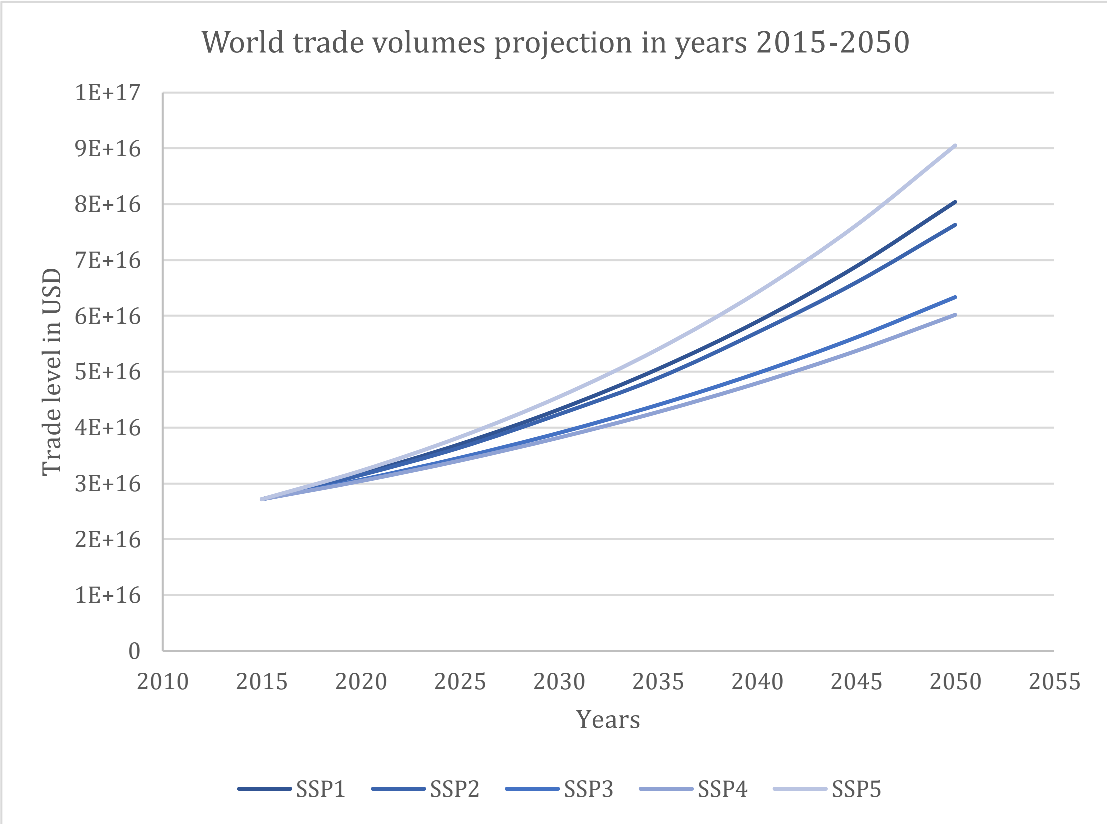


Figure 18: Estimate of world trade volumes evolution for the five SSPs.

It should also be noted that unlike Figure 15, where SSP3 is expected to grow less globally than SSP4, this relationship appears to be reversed in the results of the analysis. This may be due to the uncertainty introduced in the calibration process, so that the initial R-square value of 0.54 returned from the correlation estimation dropped to around 0.40 after the intercept re-scaling.

4.1.3 Transport demand results

To convert the data obtained in the previous point into tons of transported goods, whose method described on page 59, here split into four steps.

STEP 1: group UNCTAD sector codes into Ship categories

Starting from the Standard International Trade Classification (SITC) available on UNCTAD website (United Nations Conference on Trade And Development) (70), each category of cargo has been associated and the category of ship with which trade generally takes place. For example, fuel oils have been associated with Oil Tankers ships and finished industrial products with Containerships, as shown below in Figure 19.

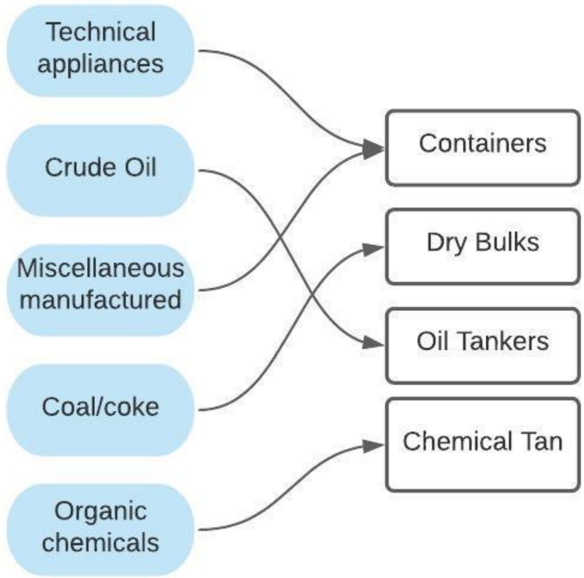


Figure 19: Classification process by ship category of each type of freight.

STEP 2: split value of trade between regions into ship categories

Now that the types of goods have been classified, the value of bilateral trade has to be partialized with respect to the various types of ships. It should be noted that for this analysis continental data aggregation is used for better data management. From the conceptual point of view the method is very simple, reported in Figure 20.

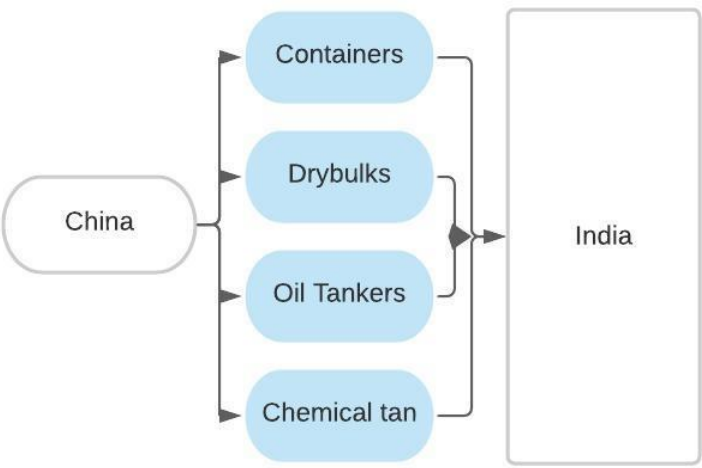


Figure 20: Partition of bilateral trade values by ship category. Logic approach.

However, processing the data in practice was not the same way linear and required the following steps:

- Download from the UNCTAD website of the bilateral trade values between the 25 selected countries, with characterization of the type of goods, for the year 2015 (71). Please note that these values do not coincide with the data used for the regression of the gravity model as they only include the value of goods traded by ships between countries.
- Aggregation of values at continental level.
- Aggregation of goods belonging to the same ship category, according to the classification of the previous section.
- Ratio of the value of goods shipped for each ship category to the total traded.

The result from the process is visible in Table 12 here a portion of data is proposed in which only the trading partner Asia appears, but the same result has been applied for exports to Africa, America, Europe and Oceania.

Table 12: Freight value share for each ship type for every country exporting to Asia. Reference year 2015.

Importer			ASIA	
Exporters	CONTAINER	DRYBULK	OIL TANK	CHEMICAL TANK
ASIA	65.51%	9.59%	16.62%	8.26%
AFRICA	44.57%	48.42%	5.36%	1.63%
AMERICA	56.58%	26.87%	9.62%	6.91%
EUROPA	87.08%	5.24%	4.01%	3.66%
AUSTRALIA	26.40%	71.48%	1.65%	0.45%

The coefficients thus obtained make it possible to break down each monetary value of trade between continents into four sub-values that correspond to the categories of vessels. For some countries exporting to Asia, the highest value of goods is transported by Container, a category generally used for the transport of manufactured finished products. For others, such as Africa and Oceania, the largest share is held by Dry Bulks, usually used for trade in raw materials.

STEP 3: Ratio between freight value and tonnage

We now proceed to determine the relationship between the value and the weight of the cargo carried by each type of ship. To do this, UNCTAD has found for the year 2015 the tonnage values of goods exported from the five continents by ship type. The importer in this case was unique (i.e. the World) and it was not possible to select a specific partner. The data for 2015 are shown in Table 13.

Table13: Tonnage of freight shipped from each continent by ship category.

2015		
Economy	**Cargo type**	**Freight loaded** (million tons)
Asia	Container	1037,971
	Dry bulk	1556,957
	Oil Tank	948,011
	Chemical Tank	530,910
Africa	Container	161,175
	Dry bulk	241,762
	Oil Tank	293,676
	Chemical Tank	58,576
America	Container	680,123
	Dry bulk	1020,184
	Oil Tank	274,531
	Chemical Tank	230,836
Europe	Container	475,984
	Dry bulk	713,976
	Oil Tank	229,458
	Chemical Tank	311,062
Oceania	Container	481,200
	Dry bulk	721,801
	Oil Tank	15,0740
	Chemical Tank	39,634

Since the tonnage data are in this form, also the values obtained in the previous step have been aggregated by global importer, obtaining an array of the same dimensions as Table. At this point each monetary value by continent and type of ship has been compared to the corresponding weight value, as indicated in the Equation (7).

STEP 4: Transport demand calculation

The remaining step at this point is the calculation of the transport work required in the 2015-2050 horizon for all ship categories, for each scenario under analysis. To do this, the formula in equation (8) to the aggregate values of continental import-export. The result can be seen in the table below for exports to Asia and Africa. The same reasoning also applied for exports to America, Europe and Oceania.

Table 14: Tonnage of freight shipped to Africa and Asia per each ship category, and exporter, in million tons.

2015	ASIA				AFRICA			
	Containers	DryBulks	OilTankers	Chemical	Containers	DryBulks	OilTankers	Chemical
ASIA	875,478	1467,678	890,886	505,428	3,848	9,644	3,153	1,649
AFRICA	68,365	185,793	182,103	30,311	6,097	5,614	15,137	3,024
AMERICA	221,468	666,267	94,354	120,531	2,261	9,073	0,563	1,153
EUROPA	99,885	97,736	23,388	32,418	4,967	9,518	1,695	2,038
OCEANIA	267,645	682,507	14,626	31,963	2,454	1,572	0,002	0,030

In addition, the same matrix of results was derived for years 2020, 2025 up to 2050 and for all SSPs scenarios considered.

Each 5x4 sub-matrix of Table 14 has been multiplied by the average distance values between continents stored in Table 15, to obtain the actual demand for transport in tons-nautical miles. For the purposes of fleet evolution analysis (see next section), data in disaggregated form are not required. Therefore, columns under the same vessel have been added up to obtain only one tonnage data for Containers, Dry Bulks, Oil Tankers and Chemical Tankers for each year. By way of example the aggregated results for SSP1 are shown in Table 16.

Table 15: Average distance between harbors in each continent in nautical-miles.

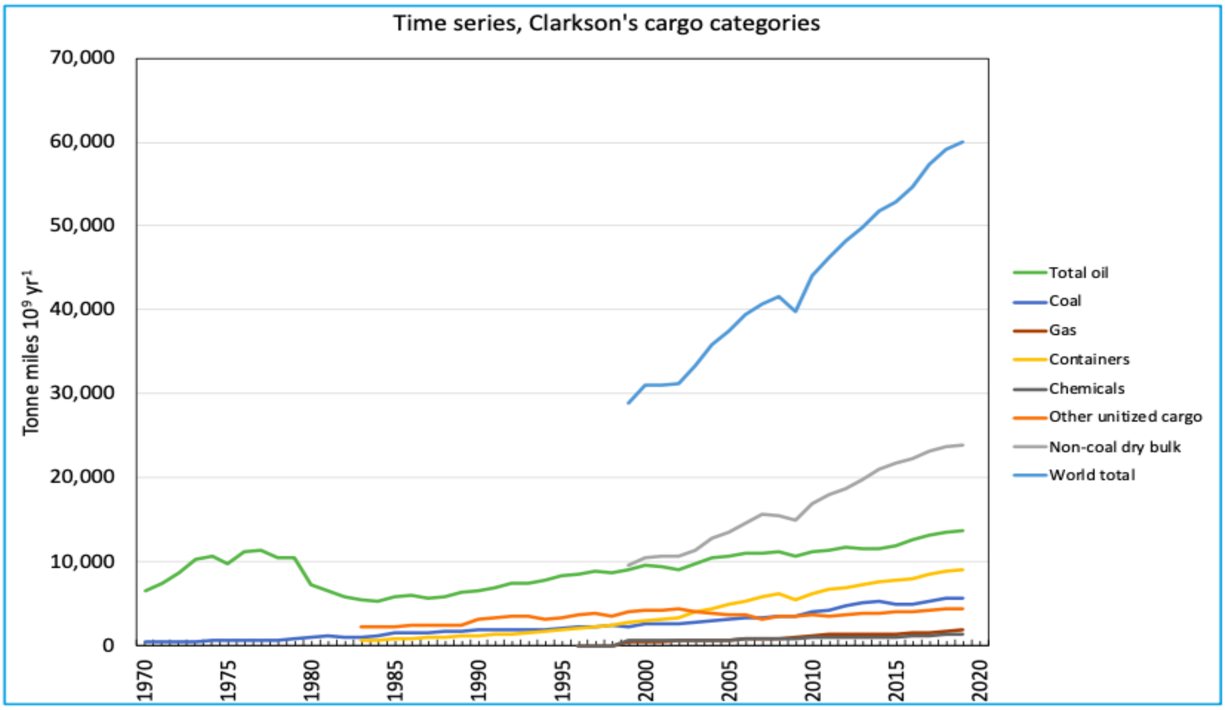
	ASIA	AFRICA	AMERICA	EUROPA	OCEANIA
ASIA	3588	6520	6458	13812	3251
AFRICA	6520	5199	8974	3454	8111
AMERICA	6458	8974	6960	13110	6779
EUROPA	13812	3454	13110	2936	11560
OCEANIA	3251	8111	6779	11560	1786

Table 16: Transport-work demand for each ship category for SSP1, values in trillion tons-nm.

	SSP1			
Years	Containers	DryBulks	OilTankers	ChemicalTankers
2015	15,858	17,675	8,708	5,705
2020	16,767	21,319	9,958	6,277
2025	18,379	25,083	11,521	7,066
2030	20,690	29,255	13,457	8,082
2035	23,872	34,209	15,877	9,379
2040	28,006	40,170	18,865	10,990
2045	33,091	47,256	22,456	12,931
2050	39,273	55,728	26,860	15,263

Results analysis

For the analysis and validation of the results, reference is made to the analyses found on Seaborne Trade Monitor (Figure 22) which shows the demand for transport broken down by type of vessel. In order to interpret the results, the reader must consider how the questions 'Coal' and 'Non-coal dry bulk' and 'Containers' and 'Other unitized cargo' are grouped together. Below are the graphs of the results for all the scenarios. Each graph refers to the transport work of one type of ship.



Source: Clarksons Research, 2020, Seaborne Trade Monitor, Volume 7 no. 2

Figure 22: Transport-work for all grouped categories of cargo provided in billion tonne-miles per year.

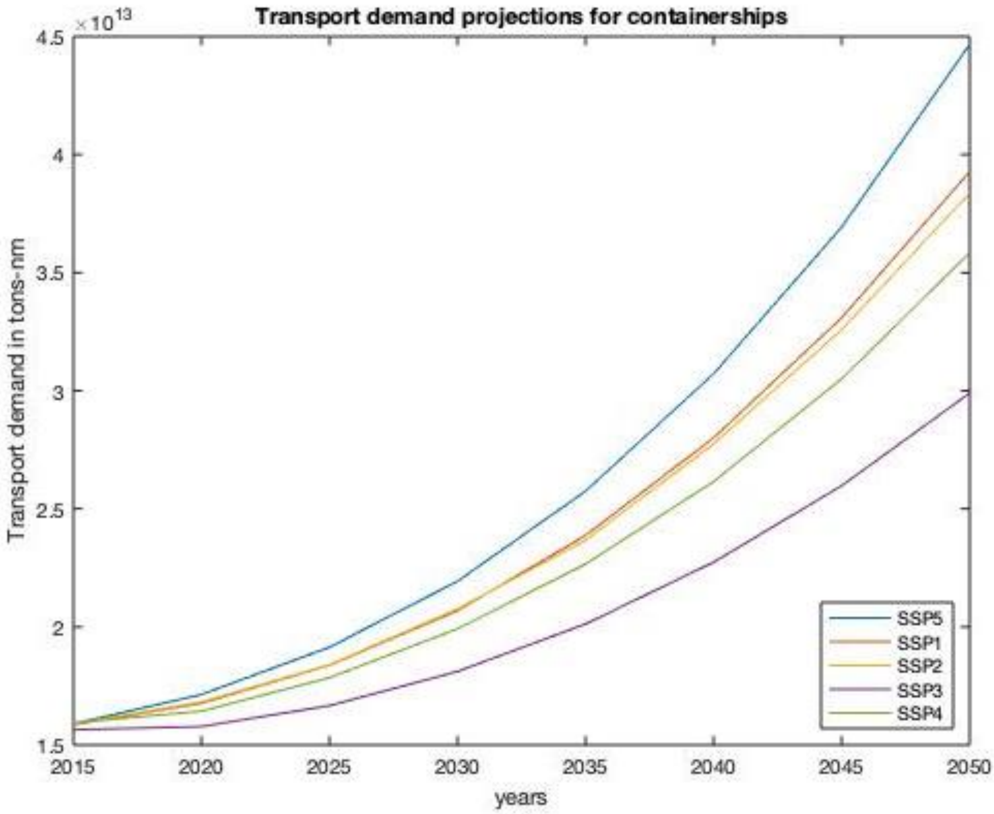


Figure 21: Transport demand projections for containerships in tonne-miles.

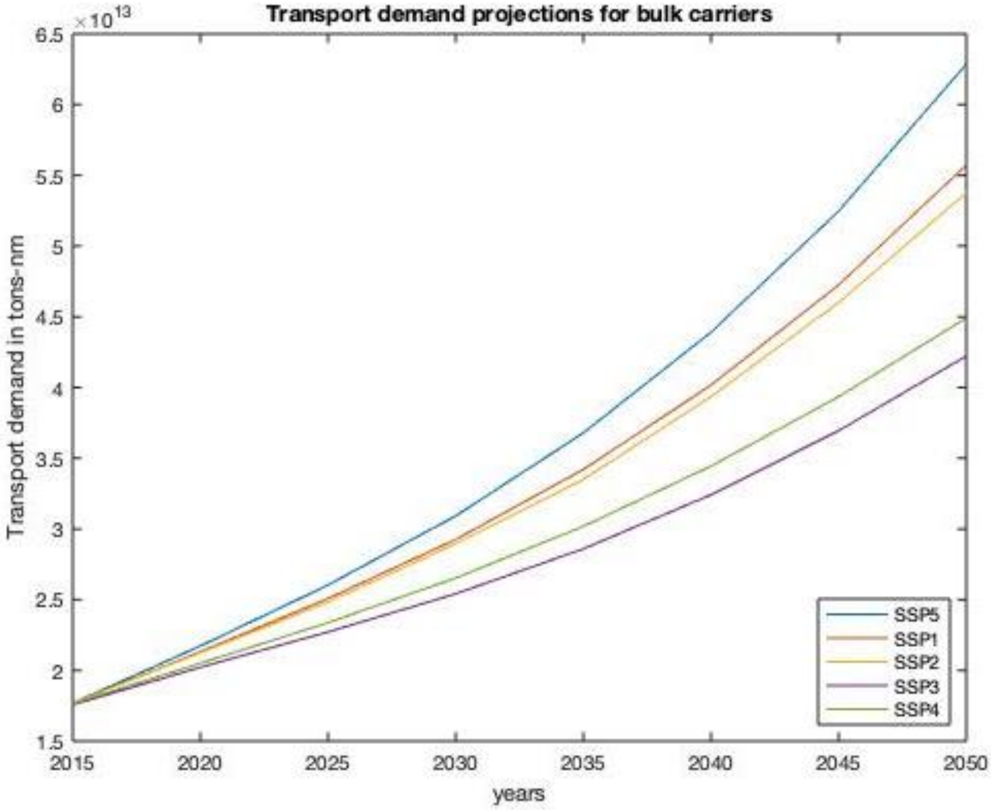


Figure 24: Transport demand projections for bulk carriers in tonne-miles.

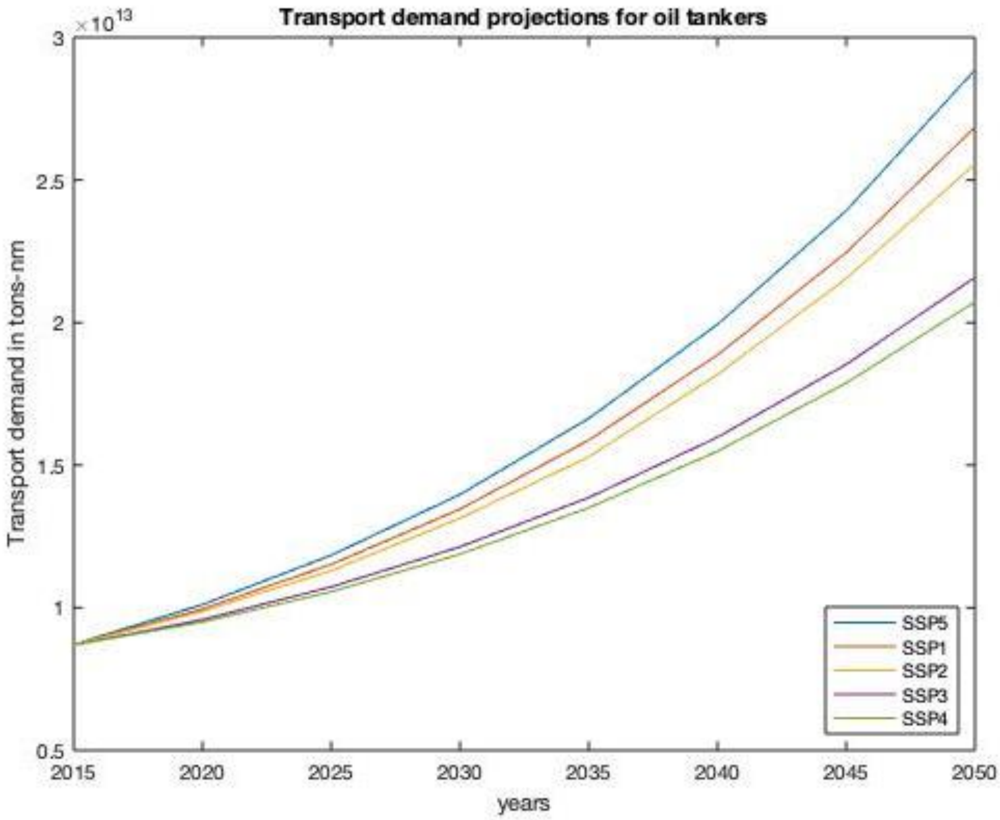


Figure 23: Transport demand projections for oil tankers in tonne-miles.

The most important considerations related to this series of graphs are the following:

- The difference between the higher and lower value of estimated demand in 2050 compared to the various scenarios is in a range between 26% and 33% depending on the vessel category. This result is in line with the variability recorded for international trade volumes discussed in the previous section.
- The average increase in transport demand for all vessels is in a range between 190-240%, as it is in line with the behaviour of the sector over the last 40 years, which has seen maritime transport grow by 250%.
- The values for the five-year period 2015-2020 are in line with the trends presented in Figure 22 in a rather approximate way. For example, chemical transporters see from the results of this study a transport demand of around 6 billion ton-nm, while Clarkson Research reports a value of 1 billion. Likewise, the demand for containers is higher in the results of the analysis, around 16 billion ton-nm in 2015 compared to 12 billion in the reference. This deviation can be attributed to the categorization of goods in the various types of ships or, more likely, to an overestimation of trade volumes for the year 2015 compared to real values.

4.1.4 Fleet evolution and fuel consumption

Data of future ships productivity and size distribution

In order to find the fuel consumption estimates on the horizon, it is important to reconstruct the evolution of the fleet for the types of vessels considered. As already discussed in the chapter Method and Data the main drivers of this transition are the adoption of EOS economies of scale, the introduction of energy efficiency indicators such as EEDI or EEOI, and the demand for transport labor. The data used in these projections are all directly or indirectly related to the above-mentioned effects. In particular, the dataset used include:

- The transport demand for each type of ship in 2050, derived from the estimates made in the previous section.
- The productivity of the fleet in the year 2050, understood as the transport work per dwt of vessel capacity [ton-nm/dwt].
- The distribution of vessels for each category in terms of size in the year 2050.

In Figure 25 the model already exposed in algebraic form from equations (2) to (6) is sketched. The input data for the year 2050 will therefore be used to estimate the final number of vessels for each size category and in turn this result will enter the logistic function used to calculate the fleet in all the intermediate years.

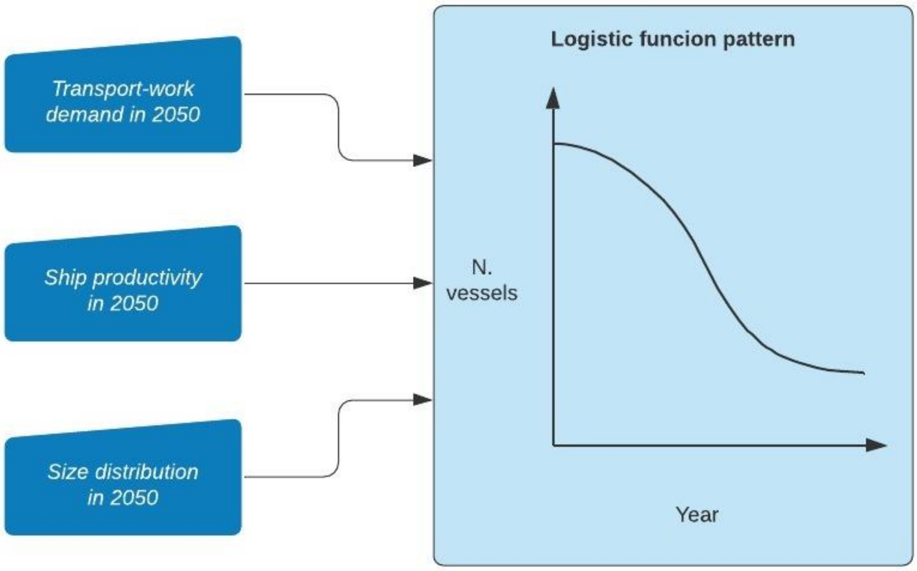


Figure 25: Input-output representation of fleet development logic.

Below the data used in the calculations will be presented in quantitative terms, which I remember have been performed with a MATLAB code. In Table 17 the values relative to the vintage capacity in the year 2015 used as data of the logistic function, the average capacity of the vessels that for the hypotheses of this study will remain unchanged throughout the horizon, and the initial value of productivity appear.

Table 17: Historical data about number of vessels, average capacity and productivity in 2015 for every ship category and size bin. (Source: Smith et. al. 2014 (13))

Ship Type	Bin size (dwt)	Number of ships 2015	Avg.dwt 2015	Productivity 2015 (tonne-nm/dwt)
Containers	TEU 0-999	1126	8634	39000
	TEU 1000-1999	1306	20436	39000
	TEU 2000-2999	715	36735	39000
	TEU 3000-4999	968	54160	39000
	TEU 5000-7999	575	75036	39000
	TEU 8000-11999	331	108650	39000
	TEU 12000-14500	103	176783	39000
	TEU 14500 +	8	158038	39000
Chemical tanker	dwt 0 - 4999	1502	2158	24000
	dwt 5000 - 9999	922	7497	24000
	dwt 10000 - 19999	1039	15278	24000
	dwt 20000 +	1472	42605	24000
Dry Bulk	dwt 0 - 9999	1216	3341	23000
	dwt 10000 - 34999	2317	27669	23000
	dwt 35000 - 59999	3065	52222	23000
	dwt 60000 - 99999	2259	81876	23000
	dwt 100000 - 199999	1246	176506	23000
	dwt 200000 +	294	271391	23000
Oil tanker	dwt 0 - 4999	3500	1985	24000
	dwt 5000 - 9999	664	6777	24000
	dwt 10000 - 19999	190	15129	24000
	dwt 20000 - 59999	659	43763	24000
	dwt 60000 - 79999	391	72901	24000
	dwt 80000 - 119999	917	109259	24000
	dwt 120000 - 199999	473	162348	24000
	dwt 200000 +	601	313396	24000

Table 18: Changes in fleet productivity indexed with respect to 2012.

Source: Third IMO Report

Ship type	Productivity		
	2012	2015	2022-2050
Liquid bulk vessels	100	113	125
Dry Bulk vessels	100	102	104
Container ships	100	109	118
General cargo vessels	100	109	118
Liquefied gas carriers	100	106	113
All other vessels	100	100	100

Table 19: Changes in ships distribution between size bins in terms of number.

Source: Fourth IMO Report

Ship size development			
Ship type:	Bin Size (dwt)	Distribution in terms of numbers	
		2012	2050
Container vessels	0 - 999 TEU	22%	13%
	1 000 - 1 999 TEU	25%	20%
	2 000 - 2 999 TEU	14%	1%
	3 000 - 4 999 TEU	19%	11%
	5 000 - 7 999 TEU	11%	11%
	8 000 - 11 999 TEU	7%	20%
	12 000 - 14 500 TEU	2%	9%
	14 500+ TEU	0,20%	6%
Chemical tankers	0-4999	30%	30%
	5000-9999	19%	19%
	10000-19999	21%	21%
	20000+	30%	30%
Oil tankers	0 - 4 999	1%	1%
	5 000 - 9 999	1%	1%
	10 000 - 19 999	1%	1%
	20 000 - 59 999	7%	7%
	60 000 - 79 999	7%	7%
	80 000 - 119 999	23%	23%
	120 000 - 199 999	17%	17%
	200 000+	43%	43%
Dry bulk carriers	0 - 9 999	1%	4%
	10 000 - 34 999	9%	13%
	35 000 - 59 999	22%	32%
	60 000 - 99 999	26%	33%
	100 000 - 199 999	31%	12%
	200000 +	11%	6%

In Table 18 and Table 19 other data about parameters changes are reported. In particular, productivity changes indexed with respect to 2012 values are used to retrieve new values of productivity starting from 2015 values. On the other hand, data on new ships distribution in terms of numbers for every bin size are necessary to split the total vessel number into each category. Here the reader can notice that just bulk carriers and containerships undergoes any variation in percentages, whereas for oil and chemical tankers Economy of Scale will not affect the fleet evolution trend, so for these types of ships it will be just driven by cargo demand and evolution in productivity.

Resulting number of ships per type and bin size

In the following are proposed the results concerning the evolution of the fleet in the 2015-2050 horizon for the various types of ships, derived from a MATLAB model that implements the model described in page 61. The results are presented as follows: for each transport category the first image shows the trend of the number of ships for each size bin, taking as reference the SSP2 transport demand. The trend, within the various categories, is the same also considering the other SSPs (even if with the axis of the originates heated according to the demand) therefore for simplicity only the trend of SSP2 is shown. The second graph instead illustrates the overall trend of the number of ships of a certain category across the SSPs. As explained above, it originates from the transport demand forecast for 2050, which in turn depends on the level of bilateral trade and the GDP trend. The factors of fleet productivity and the phenomenon of economies of scale also come into play, which have the effect of increasing the transportable cargo from the category and slightly dampening the strongly increasing trend in trade volume.

Containers

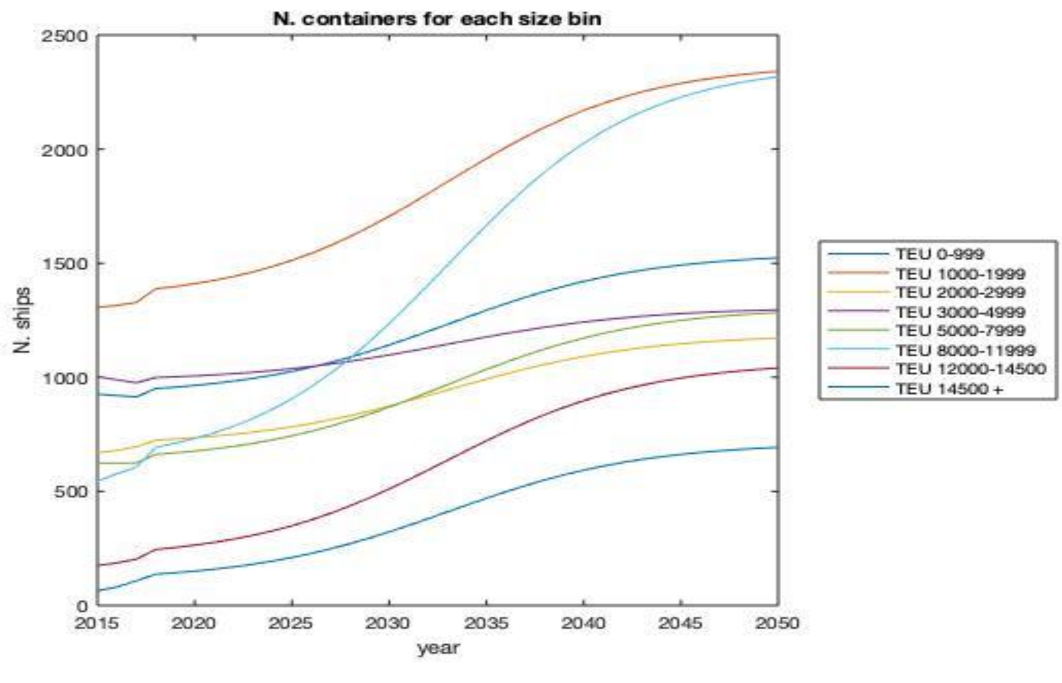


Figure 26: Number of containers every year for each size bin, considering SSP2 as reference scenario.

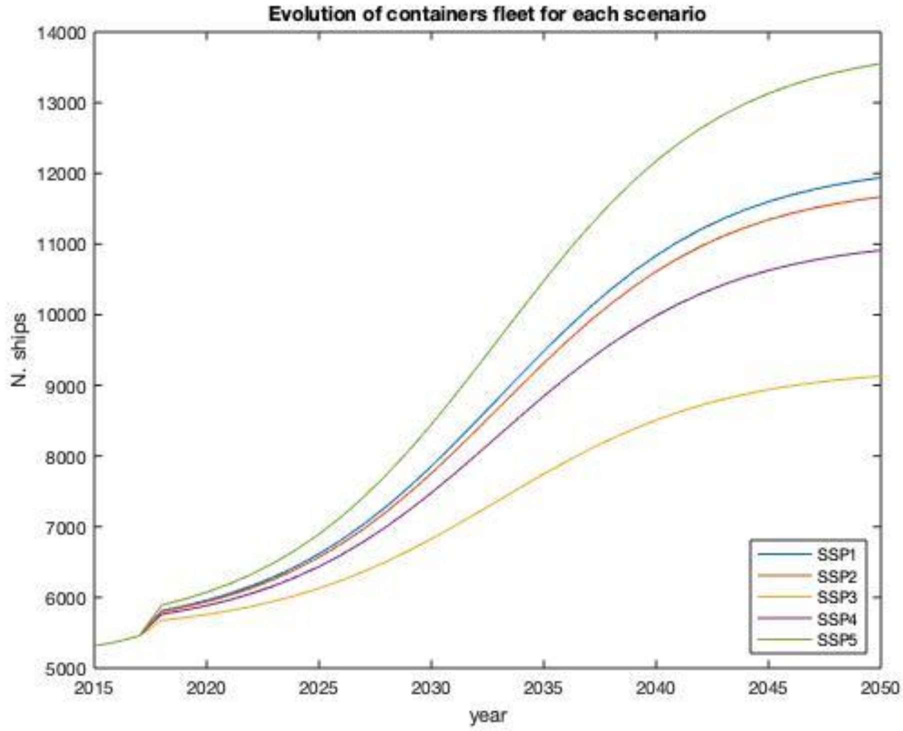


Figure 28: Different evolution in containers number per each SSP.

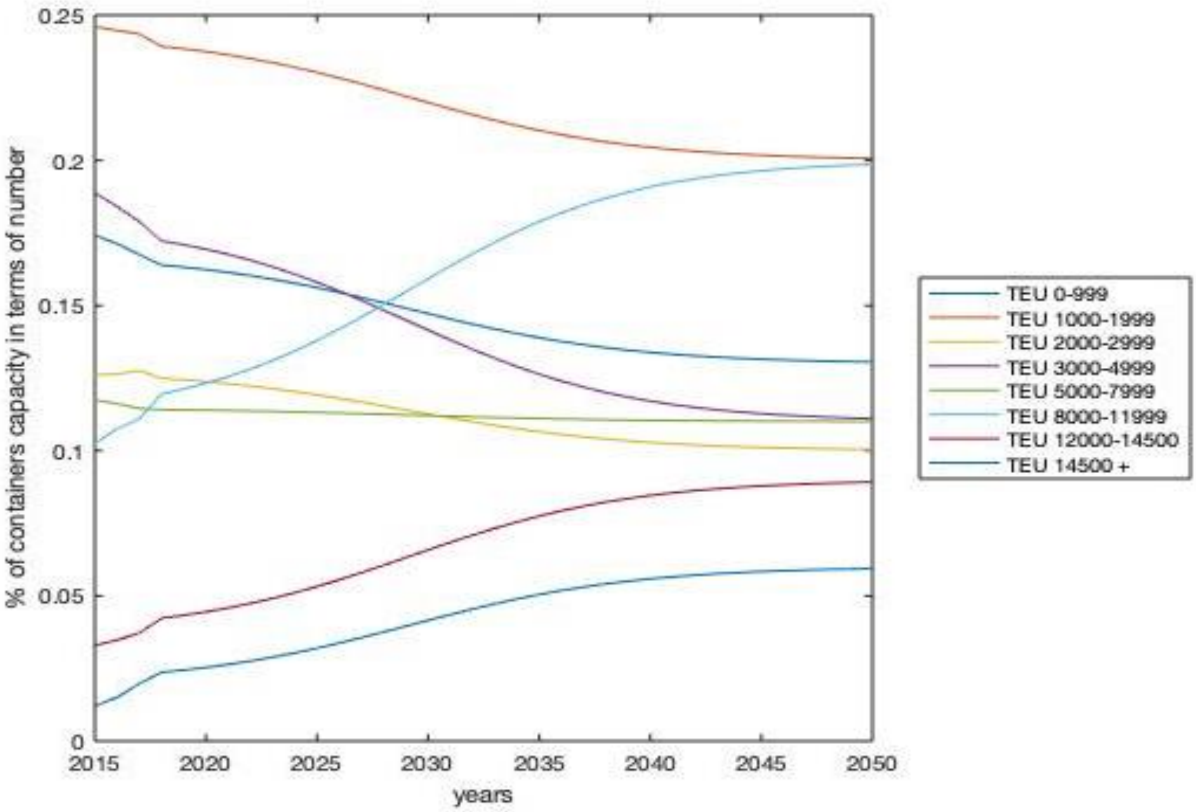


Figure 27: Expected variation in the distribution of containerships in terms of numbers over size categories within the horizon. Reference scenario for this graph is SSP2.

Dry Bulks

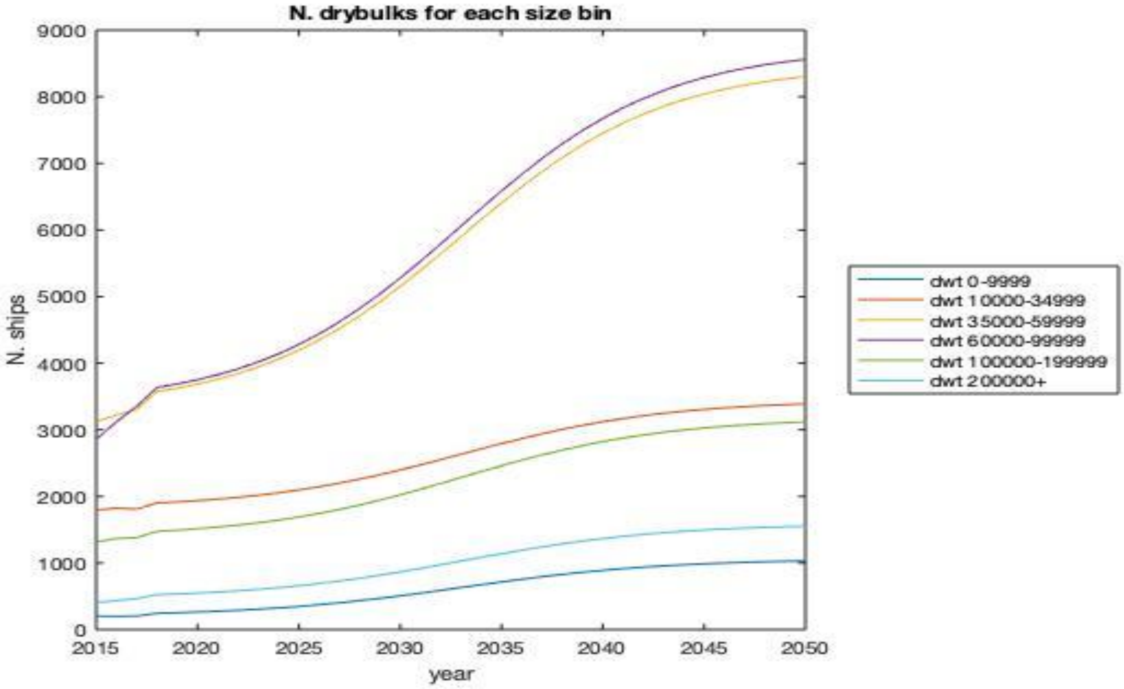


Figure 30: Number of dry bulks every year for each size bin. Reference scenario is SSP2.

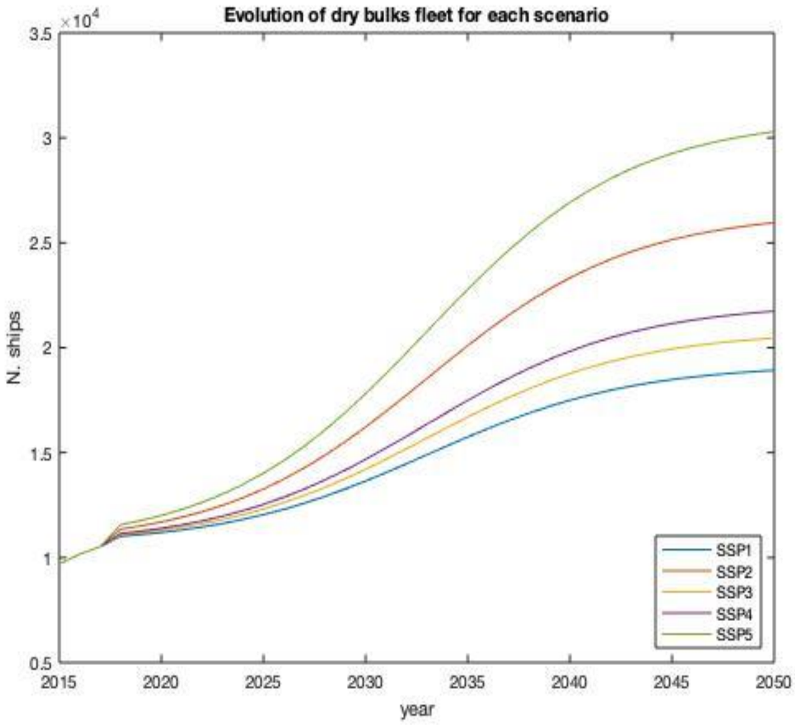


Figure 29: Different evolution in dry bulks number per each SSP.

Chemical Tankers

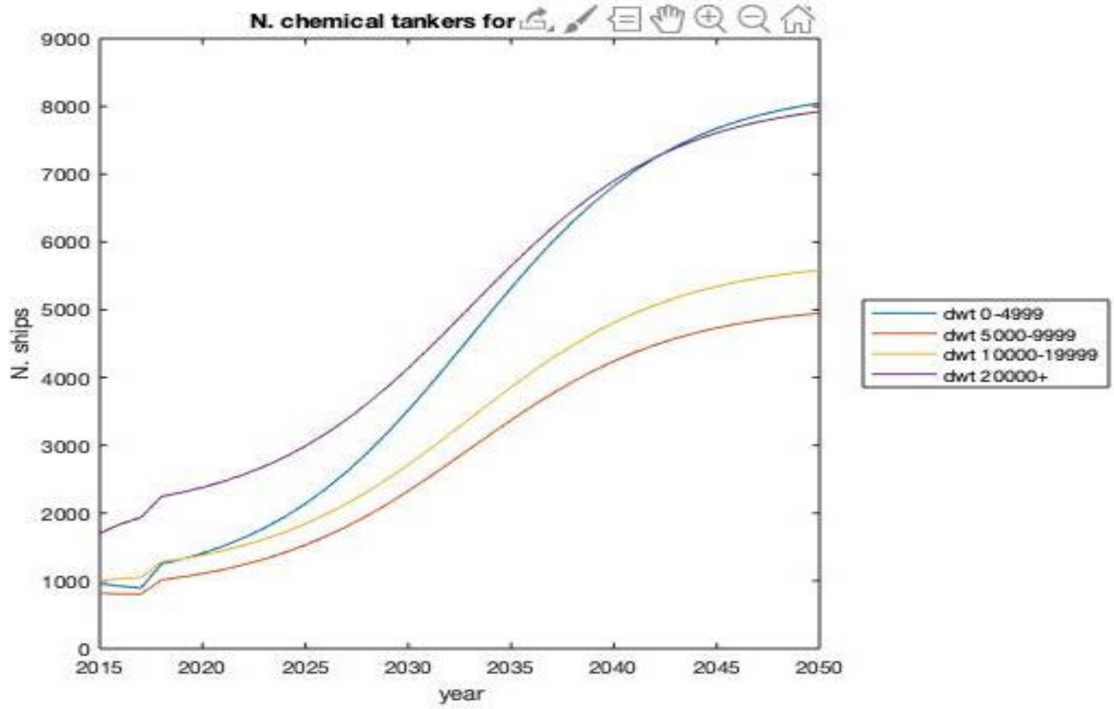


Figure 31: Number of chemical tankers every year for each size bin. Reference scenario is SSP2.

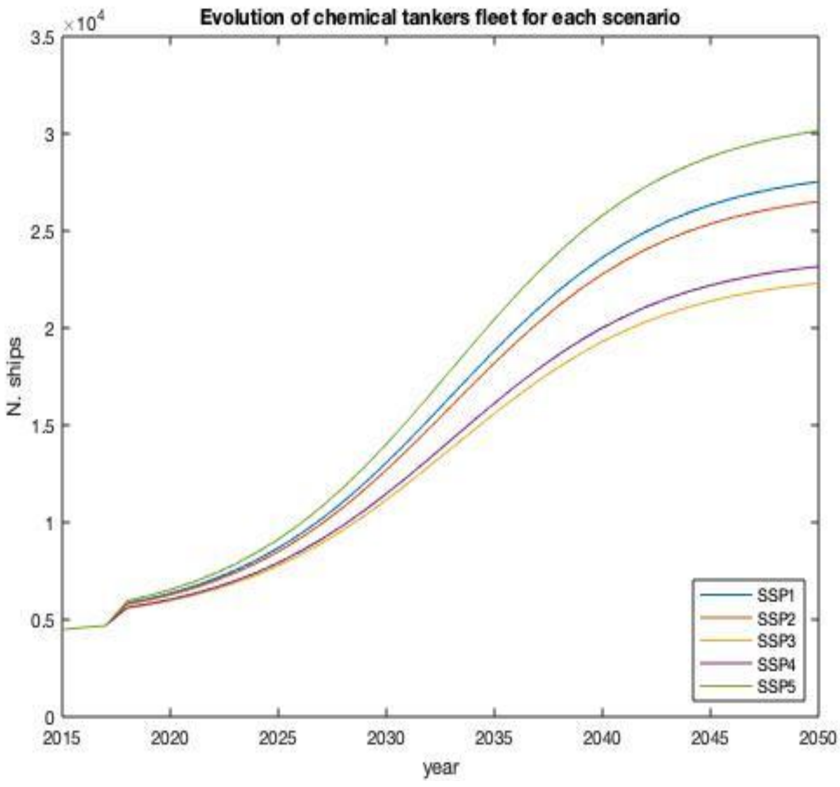


Figure 32: Different evolution in chemical tankers number per each SSP.

Oil Tankers

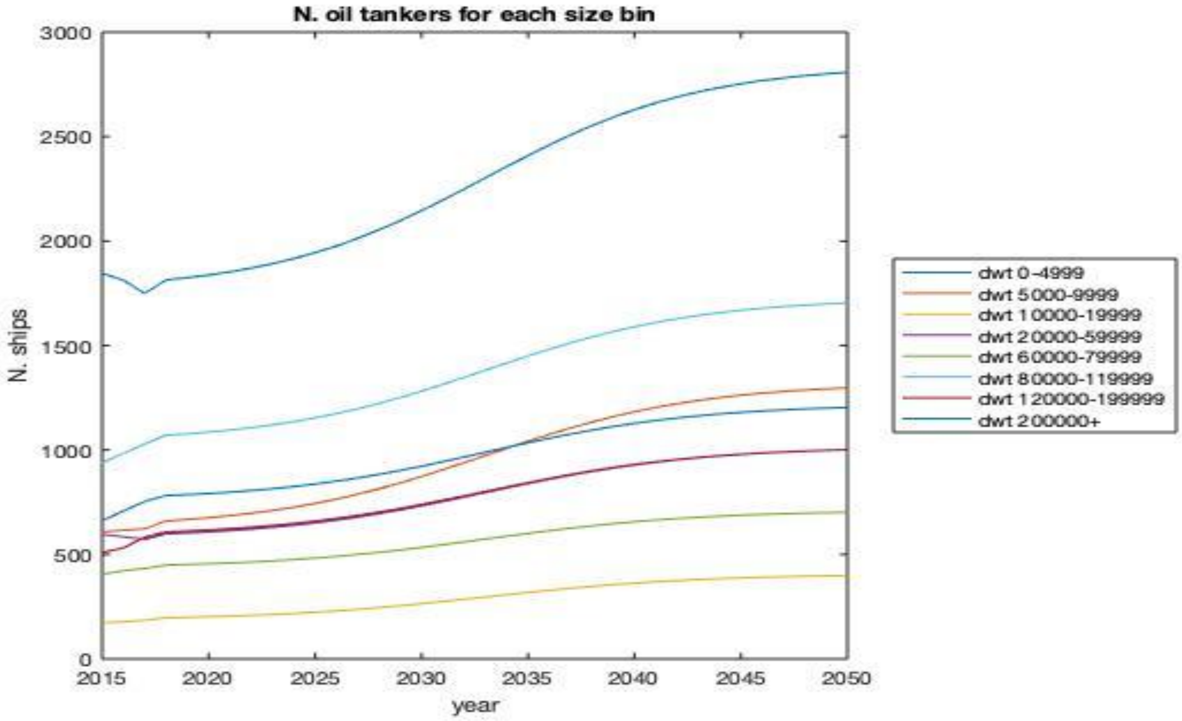


Figure 33: Number of oil tankers every year for each size bin. Reference scenario is SSP2.

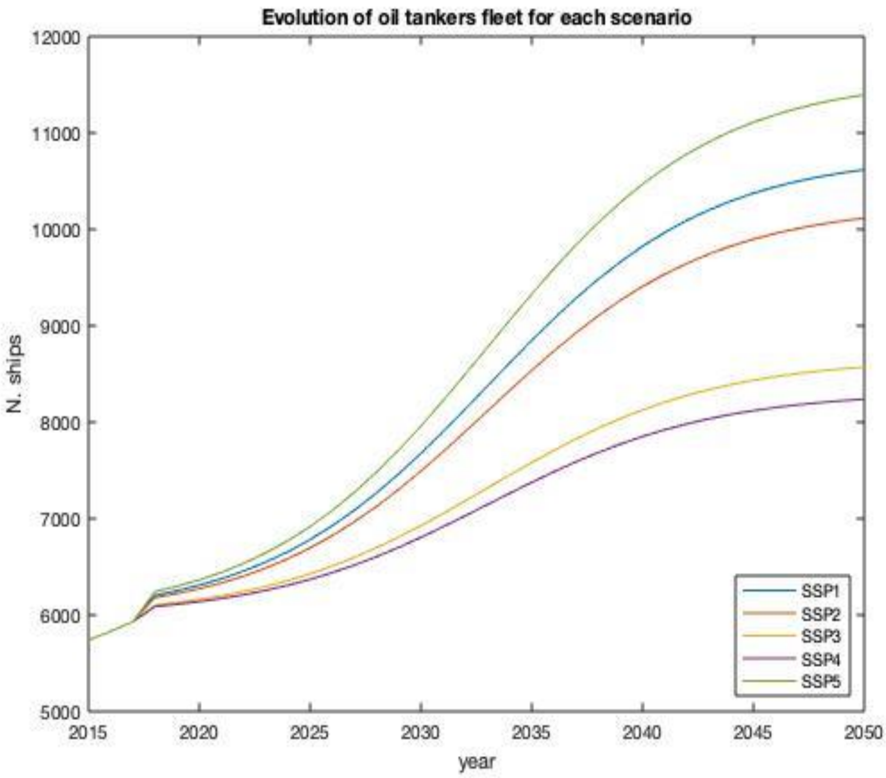


Figure 34: Different evolution in oil tankers number per each SSP.

4.2 Emissions data

4.2.1 Emission factors for existing and new fuels

As can be seen from the charts presented in the previous section, the number of ships tends to increase in each category, in order to meet market demands. As a direct consequence, fuel consumption will also increase, although mitigated by improvements in engine energy efficiency. The aim of this project is to identify winning fuel mix solutions to decouple the dizzying growth in emissions from the marine sector from the amount of fuel consumed. This through the use of low or zero emission fuels. Below are the data concerning GHGs emissions in the operational and production phases, for all the fuels analyzed. In the fourth column instead the resulting values of CO2 equivalent using the coefficients in Table 21.

Table 20: Operation and Upstream emissions per each GHG of alternative and conventional fuels.

Sources: BioMEOH: Lisboa et. al. 2011 (15).
Conventional fuels: Smith et. al. 2014 (13).
All others: Gilbert et. al. 2018 (16).

Fuel type	**Emission specie**							
	CO_2(g/gfuel)		CH_4(g/gfuel)		N_2O (g/gfuel)		CO_{2eq}(g/gfuel)	
	Upstream	Operation	Upstream	Operation	Upstream	Operation	Upstream	Operation
HFO/LSHFO	0,338	3,114	0,0032	0,00006	0	0,00016	0,4276	3,158
MDO	0	3,206	0,0032	0,00006	0	0,00015	0,0896	3,247
LNG	0,511	2,75	0	0,051	0	0,00011	0,511	4,212
BioMeOH	2,034	0	0	0	0	0	2,034	0
LH2 ren.	1,798	0	0	0	0	0	1,037	0
LH2 fossil	14,38	0	0	0	0	0	10,375	0
NH3 elec.	0,231	0	0	0	0,00001	0	0,233	0

Table 21: CO2-eq. coefficient for each GHG. (Source: Fifth IPCC Report)

Emission specie	**Coefficient**
CO_2	1
CH_4	28
N_2O	265

4.2.2 Message-ix model calibration data

Capacity factors

To calibrate the model in message-ix the data regarding the *capacity factors* of each fuel are needed, which in the context of this study are defined as the energy that can be extracted by burning one kg of fuel. As far as conventional fuels are concerned, these data are the reciprocal of the Specific Fuel Oil Consumption and have been taken from the Third and Fourth IMO Report (13) (4). The values are shown in Table 22.

Table 22: SFOC and capacity factors for conventional fuels.

Fuel type	SFOC Main [g/kWh]	Capacity factor [kWh/kg]
HFO	185	5,405
MDO	175	5,714
LNG	156	6,410
BioMeOH	379	2,638

As far as low carbon fuels are concerned, these data have been obtained from the heating value of each fuel, multiplied by the efficiency of a conventional engine, as shown below in Table 23.

Table 23: Capacity factors for non-conventional fuels. Source: Energy density: P. Gilbert et al. 2018 (16), Engine efficiency: Comer B. 2019 (72)

Fuel type	Engine efficiency	Heating Value [Wh/g]	Capacity factor [kWh/kg]
Hydrogen	0,54	33,3	17,98
Ammonia	0,54	5,16	2,78

Fuel costs, which are also necessary to run the model, have already been presented in the 'Method' section.

First year activity levels

For the year 2015, referring to the Fourth IMO Report, it was considered that 79% of the total energy required was guaranteed with the use of Residual Fuels, i.e. HFO or LSHFO, 20% from distillates (MDO) and the remaining 1% with LNG. Methanol and all other alternative fuels have a zero-activity level in the first five years as they have only been adopted experimentally by a negligible number of vessels.

Bounds on new technologies penetration

The penetration rate is a key parameter in projecting the final emissions level. It is defined as the share of the ships on the total fleet which will adopt a certain technology. The reduction of equivalent $CO_2$is largely influenced by the penetration rate of abatement measures. In fact, CO_2 reduction potential of each alternative fuel is related to the expected rate of penetration in 2030 and 2050 with respect to today levels, which are mainly equal to zero.

For this parameter the only available reference is the Fourth IMO Report, which used the values to estimate the Marginal Abatement Cost (MAC) of new technologies. For measures which have seen a spread to the market already in 2018, IMO assumed 100% penetration rate by 2030. On the contrary, to estimate the penetration rates of technologies that involve the adoption of alternative fuels, IMO set two different scenarios assuming different levels of spread for 2030 and 2050, as shown in Table 24. This because high cost occurring nowadays along with technical immaturity makes quite difficult to estimate penetration rates for these novel technologies, which are rather or not at all spread by 2018.

As a basis, the sum of CO_2emission reduction is maximized in principle in Scenario 1. After 2019, any abatement technology is expected to be completely implemented by all newly constructed ships. As a result, regardless of its penetration in 2018, 54 percent of the total number of ships in 2030 (45 % for scrap and constructed and 9 % for expanded fleet) and 100 % of the total number of ships in 2050 is assumed to account for the number of ships embracing the technology after 2019. First of all, the use of LNG in Internal Combustion Engine ICE is being introduced and spread, and then alternative fuels with carbon can be turned altogether into zero-carbon fuels.

It is expected that Scenario 2 has relatively high barriers to adoption, so lower penetration rates have been believed than those in Scenario 1. From now on Scenario 1 is named as S1 and Scenario 2 like S2 for simplicity.

Table 24: Penetration rates for alternative technologies. Source: Fourth IMO Report.

Technology		**Penetration rates (% of ships applying a technology)**				
			Scenario 1		**Scenario 2**	
		2018	*2030*	*2050*	*2030*	*2050*
Alternative fuels with carbon	LNG + ICE	1.0%	55.0%	0.0%	1.5%	20.0%
	LNG + FC, Methanol + ICE	0.0%	54.0%		0.05%	
Alternative fuels without carbon	Hydrogen, Ammonia ecc.	0.0%	0.1%	100%	0.05%	20.0%

The two scenarios presented above are a starting point for setting bounces within message-ix, but they do not exhaust the range of analysis possibilities. Below are the scenarios that will be studied within the *ixmp* platform:

1. Business as Usual (BAU). The objective is to have a reference scenario against which to evaluate the potential of the measures modelled by the following scenarios.
2. SSP1, SSP2, SSP3, SSP4, SSP5 - S1. It is analyzed how the different transport work demand, peculiar of each SSP affects the installation of alternative technologies, given the assumption of high penetration rate.
3. SSP1, SSP2, SSP3, SSP4, SSP5 - S2. The focus is on the difference in emission levels compared to the results of the previous point, due to a lower penetration rate.
4. SSP1 – RES. A hypothesis has been made that hydrogen and ammonia in this case are produced from renewable sources. This is unlike all the previous points where these substances are considered produced with conventional methods (Table 20).
5. SSP2 - S1 - Sensitivity Analysis. By relaxing the bounds that impose the growth levels of zero emission technologies, the sector's response to a growth/decrease of 10% and 20% on fuel costs (HFO and MDO) is evaluated.
6. SSP2 - Emissions CAP. In this case a cap is applied to the SSP2 scenario that limits the total annual CO_2 emissions equivalent to twice the current value. No bounds have been applied about the diffusion of alternative fuels.

Another important clarification is that even with regard to zero emissions fuels, their emissions factors are positive since their upstream emissions have also been counted. Consequently, in the results, the share of CO2eq caused by zero emissions fuels is to be thought of as external to the shipping sector, although directly related.

5 Results and Discussion

5.1 Energy consumption

The graphs resulting from the energy consumption estimates of the shipping sector are presented below. In particular, in Figure 35 the values are indexed to the year 2015 and broken down into the various ship types. The graph in question refers to the SSP2 scenario but the behavior is similar for all the other scenarios considered. Figure 36 instead presents the total consumption values for each scenario.

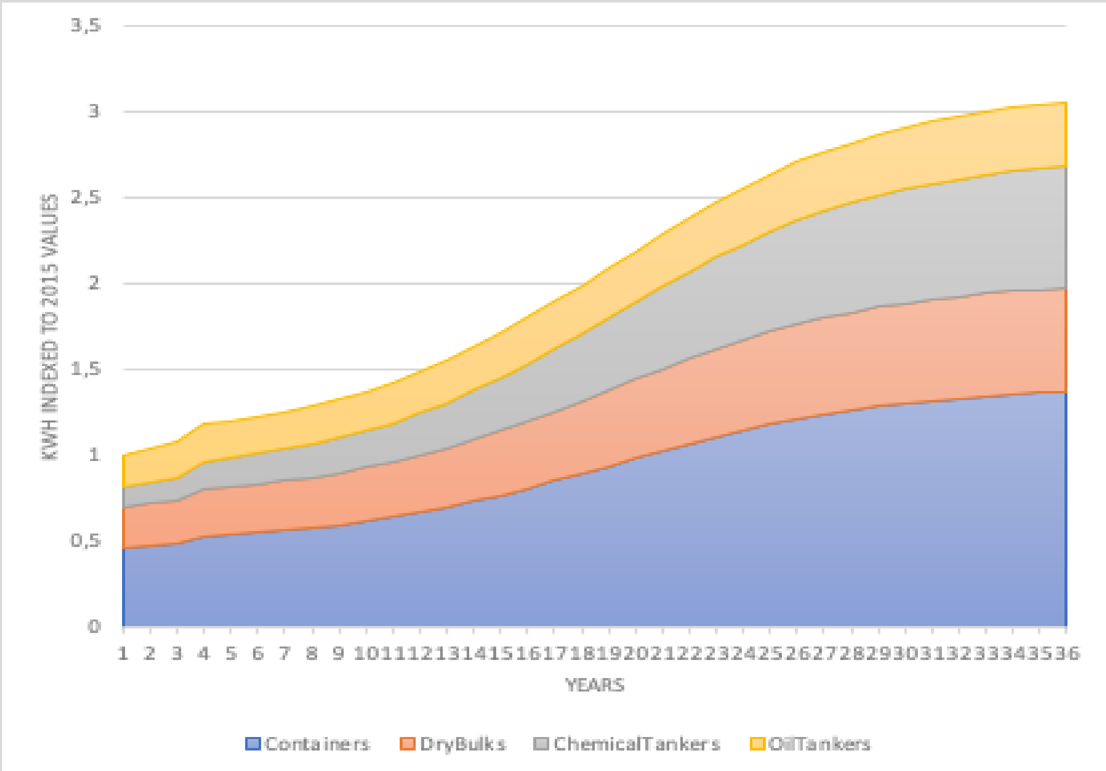


Figure 35: Energy consumption split into ship category, SSP2.

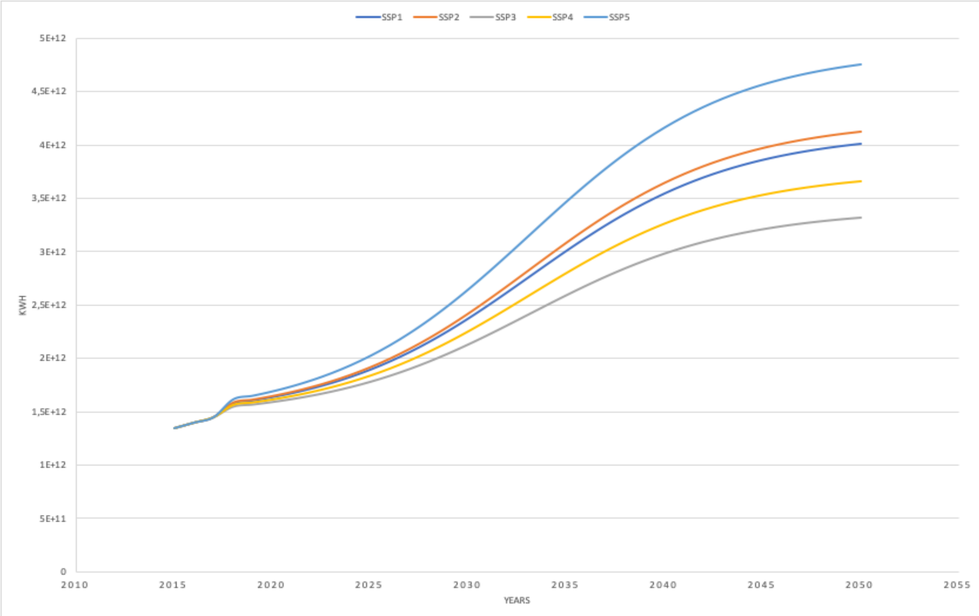


Figure 36: Total energy consumption resulting from fleet evolution model per each SSP.

It can be noted that the trend in energy consumption follows the pattern of the total number of ships in the different categories. This phenomenon is due to the fact that, for the estimation of this value, the forcing factors are the trend in the number of ships (increasing), the productivity of each ship in ton-nm/ship (weak growth) and the energy consumption factor per transport work unit kWh/ton-nm (weak degrowth). The last two parameters therefore compensate for their growth and degrowth and induce the number of ships trend to force the shape of the graph.

5.2 Emissions projections

In this section the results of the analysis conducted on the *ixmp* platform will be presented. The scenarios implemented have been listed in the previous chapter and try to cover comprehensively the range of possibilities for the future, also thanks to the combination of several scenarios at the same time. The results lend themselves to interesting reflections regarding the application of alternative technologies and their method of production.

Business as Usual Scenario

This section presents the projections of CO_2emissions of shipping up to 2050 in business-as-usual (BAU) scenarios. In the context of this study, BAU refers to the shipping sector. The definition of BAU is that no new regulation will be adopted for shipping that has an impact on emissions or energy efficiency. One way to interpret the BAU scenarios is that they show how the emissions of shipping would develop when other sectors follow a certain economic and climate pathway and shipping does not. The assumption adopted to build the BAU scenario is that conventional and alternative fuels follow the actual market share, hence 99% for Fuel Oils, 1% for LNG and zero for all the others. In this interpretation, the scenarios show the effort required to meet a certain emissions target for the shipping sector.

Figure 37 shows the activity of the different technologies in the hypothesis of an evolution according to business as usual, therefore without any forcing that pushes the diffusion of alternative or conventional fuels beyond today's growth rate. Then activity graphs for the S1 and S2 scenarios, in which different levels of technology penetration are set are shown in Figure 38 and Figure 39, and the projection of emissions resulting from the three models are compared in Figure 40.

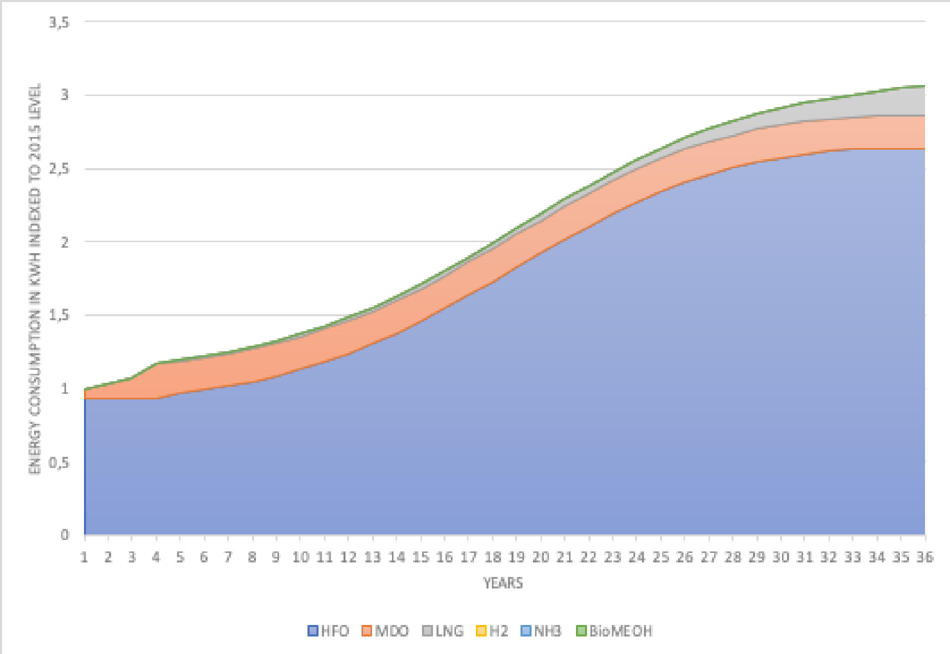


Figure 37: Activity of technologies in a Business As Usual scenario. Values in kWh indexed to 2015 levels.

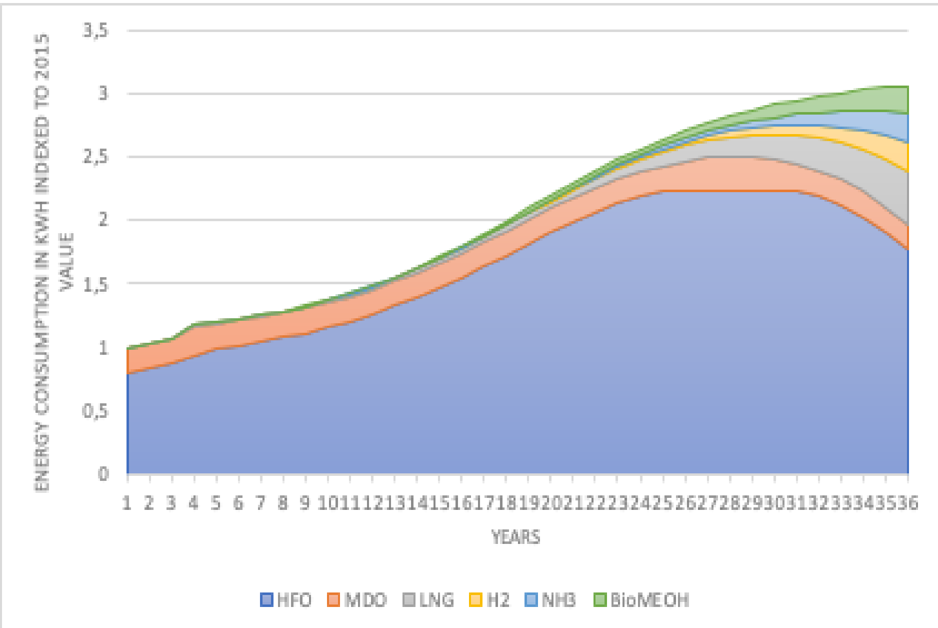


Figure 38: Activity of technologies in Scenario 2. Values in kWh indexed to 2015 levels

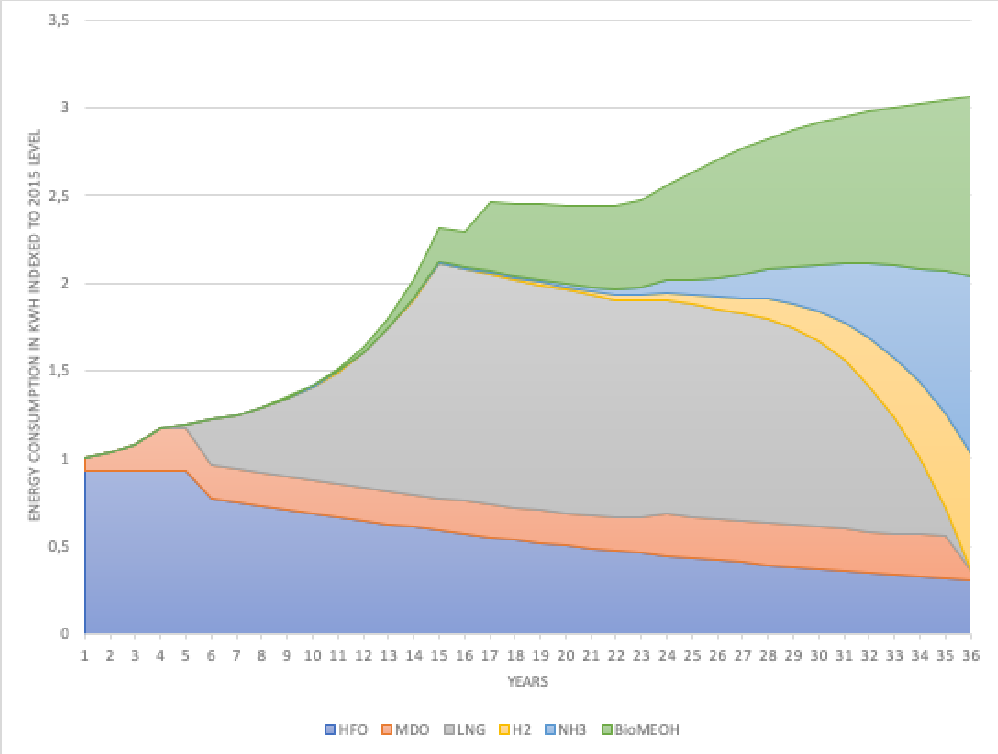


Figure 39: Activity of technologies in a Scenario 1. Values in kWh indexed to 2015 levels

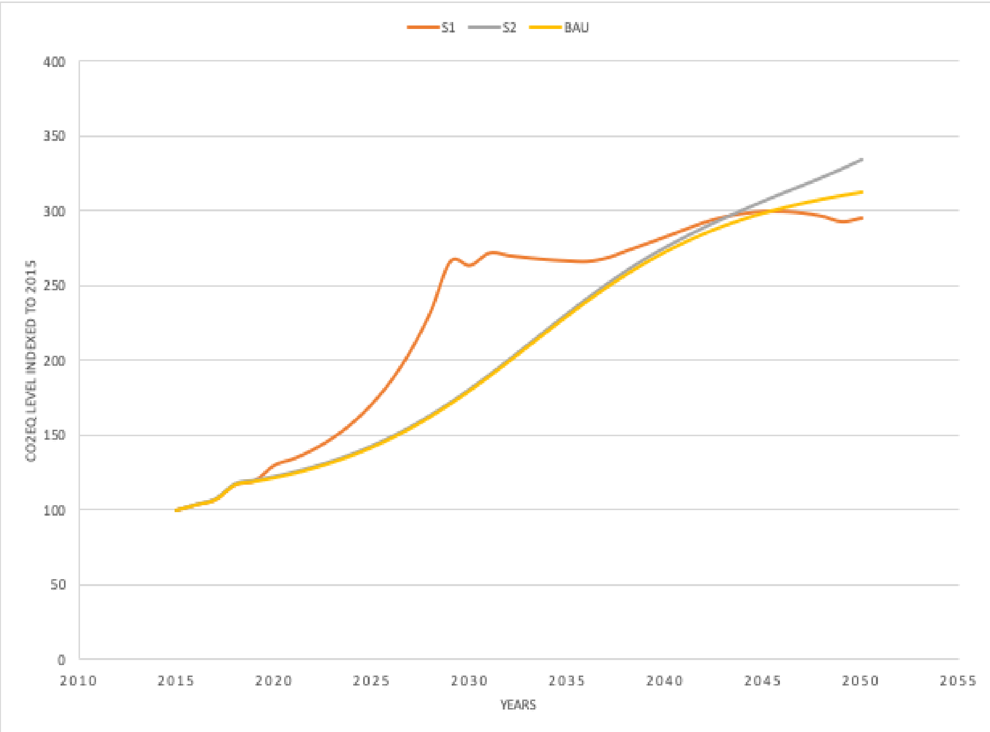


Figure 40: CO2-eq emissions for S1, S2 and BAU starting from SSP2. Values in million tons indexed to 2015 level.

The following considerations can be made from the images above:

- The BAU and S2 scenarios run parallel and, towards the end of the horizon, S2 even bypasses the BAU. The result is justified by the fact that LNG has a higher CO_{2eq}emission factor than HFO and MDO, and its greater diffusion in S2 compared to BAU scenario implies that overall emissions are also higher.
- For the same reason mentioned above, emissions increase sharply under the assumptions of S1 scenario, and then increase more moderately thanks to the diffusion of zero-emission technologies.
- Among the alternative fuels, ammonia sees a greater diffusion than hydrogen, due to the difference in cost between the two fuels that prevails over the fact that the capacity factor estimated for hydrogen is almost ten times that of ammonia.
- The use of alternative fuels, produced with conventional methods (Steam Methane Reforming), does not contribute to the decrease in emissions and indeed the value in 2050 stabilizes just below the BAU curve. This is explained by the fact that upstream CO_{2eq}emissions due to their production are of the same order of magnitude as the operational emissions of conventional fuels. Moreover, with the exception of hydrogen, capacity factors are lower than those of fuel oils and consequently higher fuel consumption is required.

S1 and S2 model per each SSP

The graphs below show the trend in annual CO_{2eq} emissions for each SSP, under the assumptions of high penetration of zero emission technologies (Scenario 1) and low penetration (Scenario 2), in Figure 42 and Figure 41 respectively. Both graphs also show the trend for the BAU Scenario as a yardstick for comparison. The expected result is that GHGs values are consistently lower for S1 and slightly higher for S2.

For SSP1 and SSP5, rapid technological development is expected, leading to an increase in energy consumption. Unlike SSP5, however, in SSP1 this is accompanied by a technological transition shifted away from fossil fuels and towards renewables, thus to a low carbon intensity. In the scenario considered here, however, the hypothesis of a rapid transition away from fossil constraint has not been implemented, as it is exhaustively treated in another scenario designed ad hoc. SSP3 and SSP4, on the other hand, envisage a slow or sectorial technological development, and a high and medium energy intensity respectively. The integration of these assumptions implies that the resulting carbon intensity is medium/low for both scenarios compared to SSP1-SSP5 and Busines as Usual.

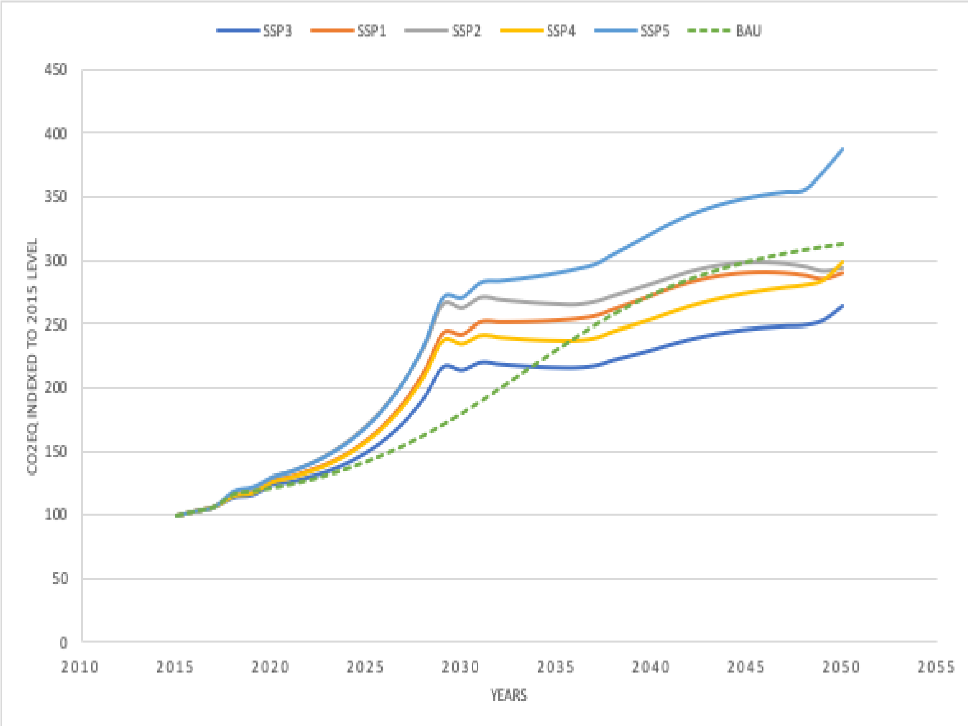


Figure 42: CO2-eq emissions for S1 for each SSP plus BAU scenario. Values in million tons indexed to 2015 level.

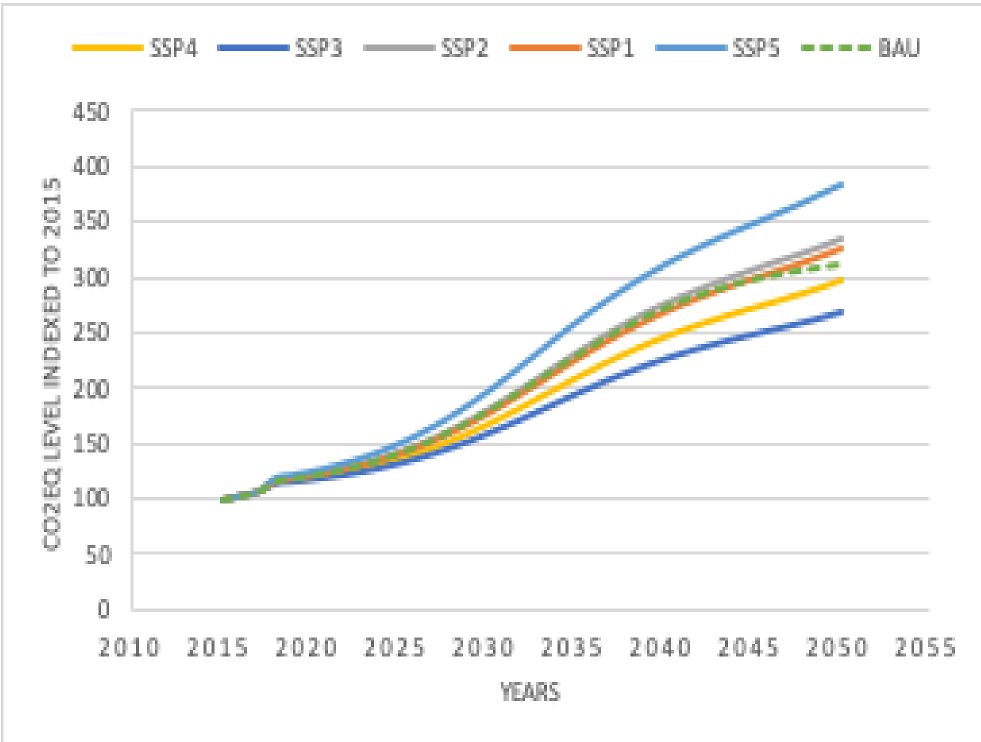


Figure 41: CO2-eq emissions for S2 for each SSP plus BAU scenario. Values in million tons indexed to 2015 level.

As can be seen from the charts above, the results are not fully in line with expectations. Despite the totally different assumptions between S1 and S2, the expected carbon intensity for 2050 is not seen to be very different between the two charts. In fact, both graphs show that in the higher-level model (SSP5) emissions tend to quadruple, while in the lower-level model (SSP3) they are about 2.5 times the 2015 level. Minor differences can also be noted with regard to SSP2, SSP3 and SSP4, which are in both cases close to the Business as Usual scenario, with a tripling of the level of emissions compared to 2015. The graphs therefore show the same dramatic increase in carbon intensity, which exactly follows the evolution of the sector's energy consumption. The only difference lies in the path by which emissions reach the 2050 level. In the case of S1 there is a first stage of rapid increase due to the strong penetration of LNG, followed by a second stage of more moderate growth due to the implementation of alternative technologies. For S2, on the other hand, due to a modest development of the same, and a more uniform LNG spread, the trend is pseudo-linearly increasing. Apparently, these results may lead to the conclusion that a transition to alternative fuels is ineffective to reduce the level of emissions, but the underlying assumption is that these fuels are still produced with conventional methods. These estimates therefore also incorporate the share of emissions generated by sectors outside the maritime-transport industry, since the CO_{2eq} produced by zero emissions fuels is only "upstream", whereas is considered null during operations. The interesting conclusion from these results is that the diffusion of alternative technologies, if produced with conventional methods, will have no other result than to shift emissions from the shipping-trade sector to the industrial production sector, without systematically abating them.

Production of ZEF from Renewable Energy Sources

It is of interest for the above considerations to study the impact of more sustainable production of alternative fuels. This hypothesis has been implemented starting from SSP1, which underlies the hypothesis of a rapid and constant detachment from fossil dependence. Below the first two graphs present the share of CO_{2eq} emissions under the hypothesis that hydrogen and ammonia are produced through Steam Methane Reforming (Figure 44) or Water Gas Shift using renewable energies in all phases of the process (Figure 43). For hydrogen, the total emission factor drops from 14.4 to 1.8 gCO_{2eq}/g, while for ammonia it goes from 0.23 to 0.17 gCO_{2eq}/g (16). On the other hand, the overall emissions trend given by the new set-up is reported, together with the scenarios already analyzed previously SSP1-S1 and S2 (Figure 45).

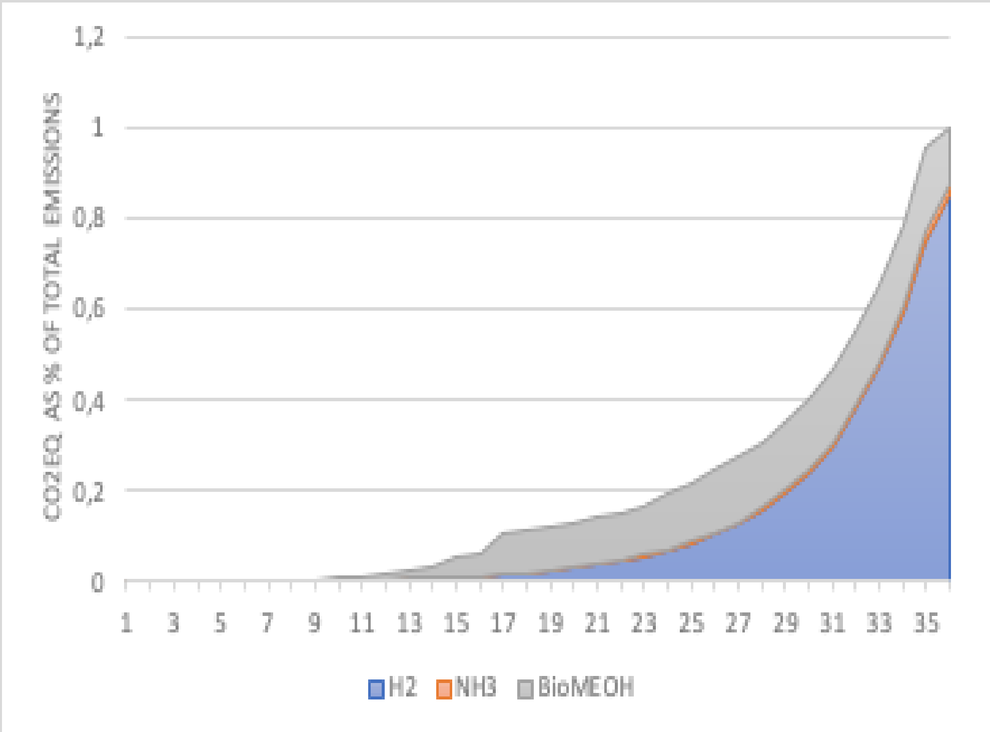


Figure 44: Impact on total amount of upstream emissions from ammonia, hydrogen and Bio-methanol in a scenario where they are produced with conventional methods. Values as a share of total CO2-eq emissions.

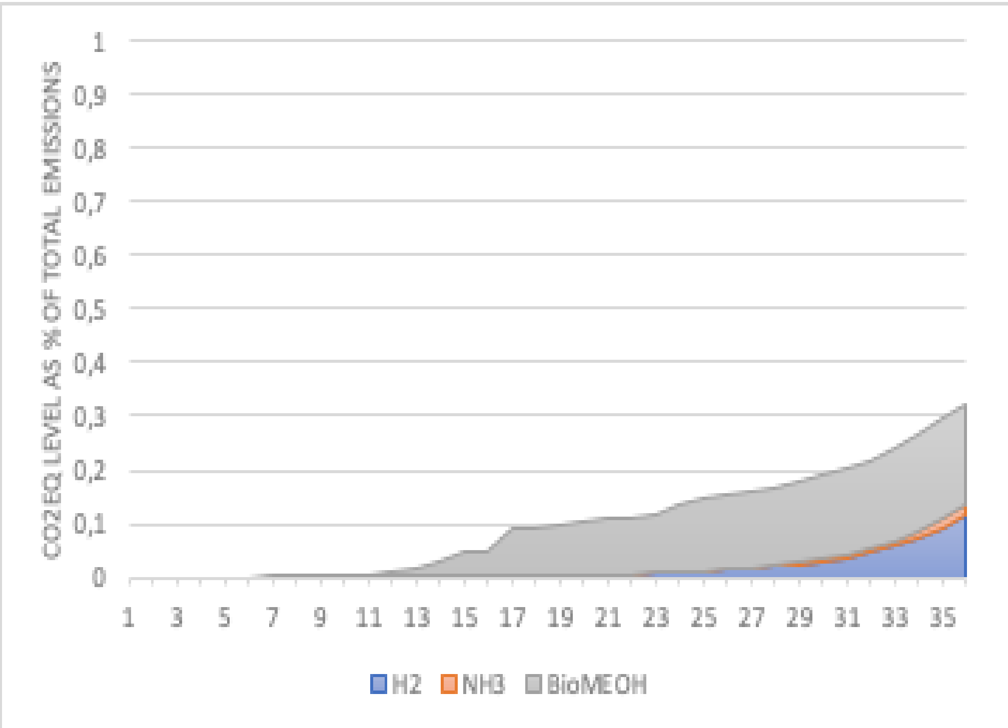


Figure 43: Impact on total amount of upstream emissions from ammonia, hydrogen and Bio-methanol in a scenario where they are produced from renewable energy sources. Values as a share of total CO2-eq emissions.

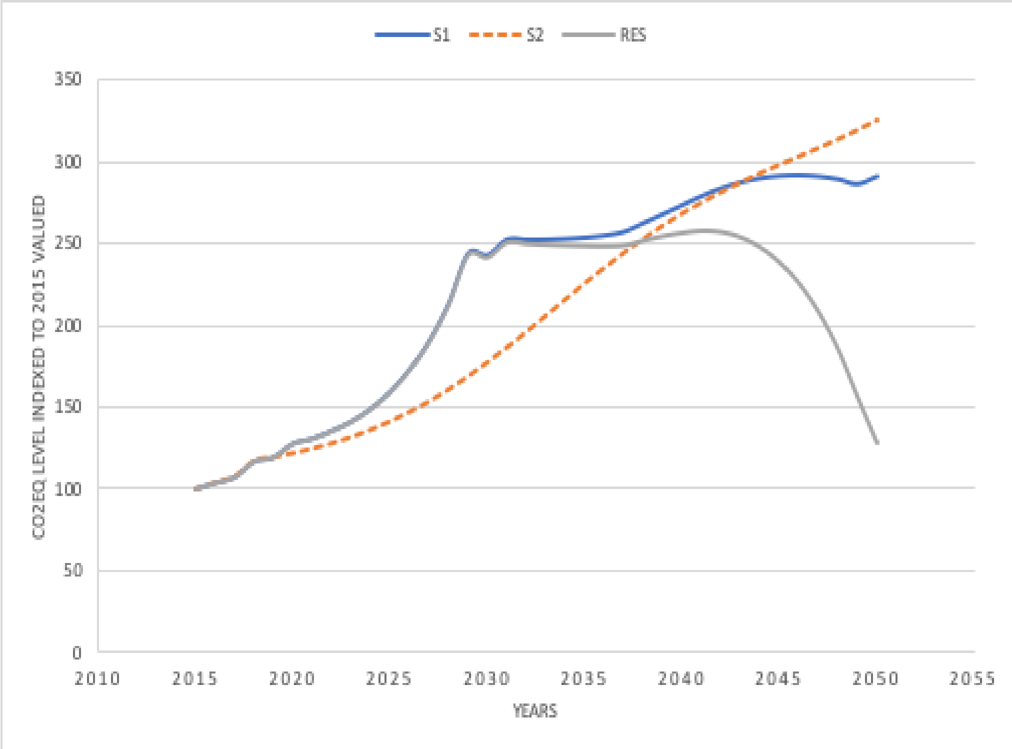


Figure 45: CO2-eq emissions for SSP1 for Zero emissions fuels production starting from RES, plus SSP1-S1/2. Values in million tons indexed to 2015 level.

A more sustainable production of hydrogen and ammonia can reduce their impact on overall shipping emissions by 70%. Particularly significant is the behavior of hydrogen, which with production methods exploiting renewable sources is able to reduce its share of estimated emissions from 82% to 11% in 2050.

As a consequence, while fuel activities remain those typical of the S1 scenario (see Figure 39), final CO_{2eq} levels are 56% lower than in S1 and 60% lower than in S2. Moreover, this means that at the end of the horizon GHGs emissions will be 25% higher than the 2015 values, instead of reaching 300% as in the other scenarios.

Sensitivity analysis on fuel cost

The following figure shows the results of the sensitivity analysis conducted on the cost of fuel oils (HFO and MDO) in order to investigate whether it is a driver for reducing emissions. The analysis was conducted considering SSP2 and varying the price of fuels by more or less 10% and 20%. In theory, a higher or lower cost of conventional fuels should accelerate or slow down the diffusion of alternative fuels, though given the results from the previous scenario it is unlikely to have an impact on the final carbon intensity level.

As can be seen in Figure 46, increasing or decreasing the cost of HFOs and MDOs generates a deviation between 8% and 15% in emission values by 2050 compared to the results of SSP2-S1. It can therefore be said that a 20% increase in the cost of fuels, together with a boost in the diffusion of abatement technologies, has the potential to reduce the level of GHGs by 15%, a value which, although interesting, is insufficient to meet the targets defined by the IMO.

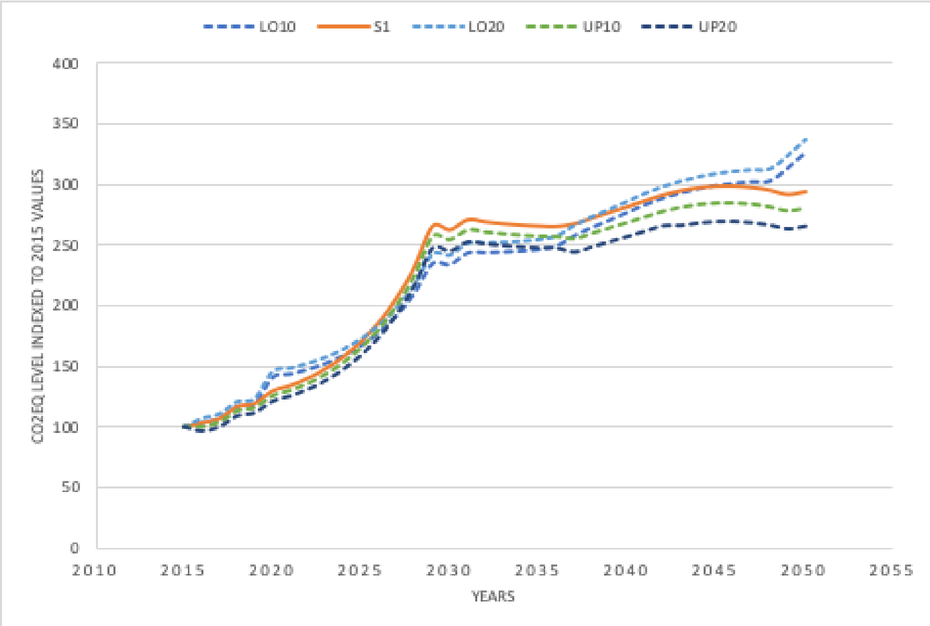


Figure 46: CO2-eq emissions for sensitivity analysis, +-10% and +-20% on HFO and MDO cost, plus SSP2-S1. Values in million tons indexed to 2015 level.

CAP on emissions scenario

In this scenario, SSP2 has been adopted for the reference fuel consumption demand, and a constraint has been imposed on the annual level of emissions, which provides that they should not exceed the level of 2 Mt CO_{2eq} (twice the level of 2018). Together with this and in order to make the solution feasible, it has been assumed that from the year zero (2015) alternative fuels will be produced only from renewable energy sources, thus with very low upstream emissions. This analysis aims to understand how the market should evolve from a theoretical point of view, in order to reach a given emission target according to a technical-economic optimization.

In Figure 47 the activity of the various technologies is shown. These trends are in some ways unrealistic because they impose traumatic growth or decrease rates over a period of time of a few years or the sudden phase out of some technologies and then reappear later. Such development rates are certainly unsustainable by the market, but the graphs lend themselves to some important considerations. Finally, in Figure 48 the trends of annual emissions in the CAP scenario are presented, as opposed to other trends previously studied like BAU, SSP2-S1 and S2.

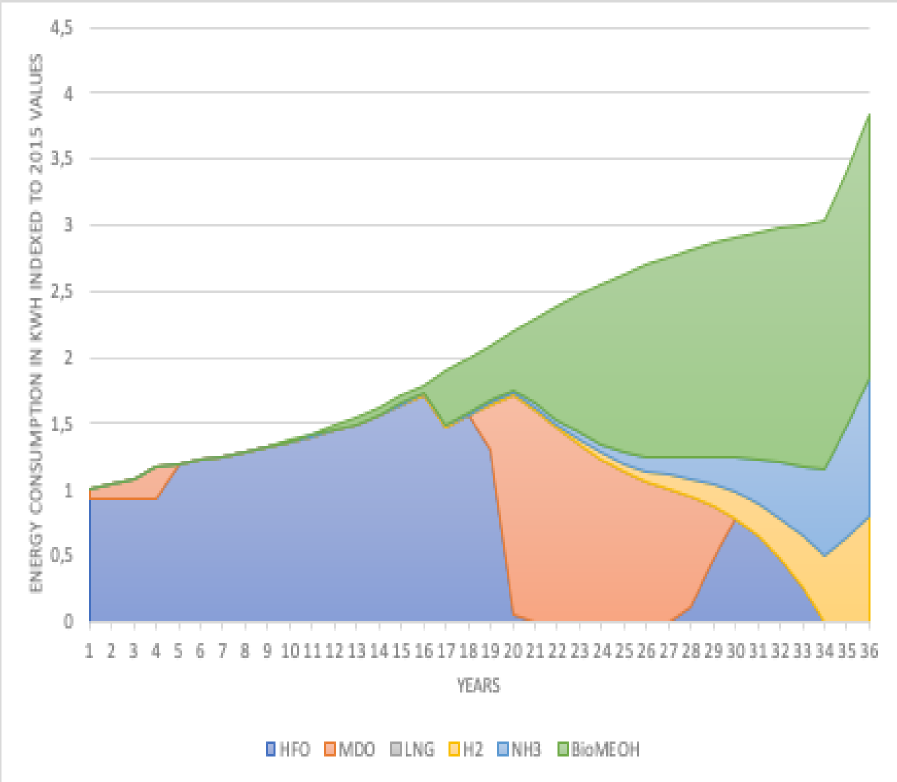


Figure 47: Activity of technologies in an emissions CAP scenario. Values in kWh indexed to 2015 levels.

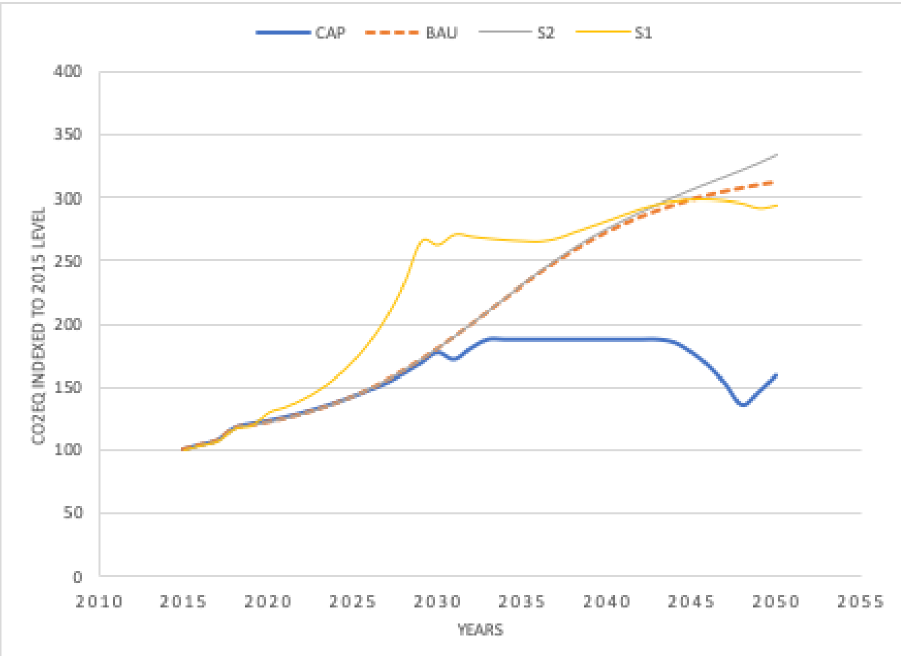


Figure 48: CO2-eq emissions for CAP on Emissions Scenario, plus BAU, SSP2-S1/2 scenarios. Values in million tons indexed to 2015 level.

As mentioned earlier, some technologies see their emergence in a sudden and unrealistic way, as in the case of the transition from HFO to MDO around 2035 and then the opposite behavior in 2045. These abrupt transitions are due to the absence of constraints on the growth/degrowth of the technologies, whose only constraint remains the technical-economic optimization. Even with these criticalities, important considerations can be made by dividing the trends into macro-categories of conventional fuels and alternative fuels:

- Traditional fuels on the whole see a rapid decrease starting from 2035 (year 20) with an average annual rate of -12% and a total phase out starting from 2048, a phenomenon that is not reflected in any of the previous scenarios.
- LNG, which sees as the only constraint the minimum level of activity between 2015 and 2020 (for consistency with real data), is eliminated from the market from 2021 onwards. This is due to the fact that although its cost is among the lowest in the fuel range (set to 590 USD/ton) its specific CO2-eq emission value is the highest of all (equal to 4.7 gCO_{2eq} per gLNG), consequently its use is cancelled by the CAP imposed on total emissions.
- Alternative fuels have seen an overall increase in their activity since 2035 (year 20), with an average annual penetration rate of 13%. Among the three, the leader of the transition is bio-methanol and the slowest in diffusion is hydrogen because of its high cost.
- The implementation of alternative fuels combined with their production from renewable sources has the potential to cut emissions by 48% compared to the value estimated for 2050 by the Business as Usual scenario.
- Another important result linked to this scenario cannot be shown graphically: an attempt has been made to link total emissions to a constant decrease until reaching the value of 50% of the 2008 level (target proposed by IMO), equal to nearly 47% reduction from 2015 levels. Considering the non-zero emission factors also in the case of alternative fuels, the ixpm platform has returned a result of infeasibility. This shows that although the fuel transition has a good abatement potential, it alone cannot cut absolute GHGs emissions by 50% compared to 2008 values. However, they can contain their growth in 2050 within 50% of 2015 levels.

6 Conclusions

In this chapter the knowledge gained and the quantitative results from my analysis are combined enabling assessment of emission reduction potential from alternative fuels adoption. The next section proposes a detailed discussion of the results and their implication with respect to the state technology of seaborne industry. Then the Possible Improvements section deals with possible caveats of my research process and gives directions for future research within the area.

6.1 Discussion of results

One of the goals of my research was to investigate whether and how the fuel transition, combined with the expected tripling of world seaborne freight, could allow emissions reductions by 2050. According to the IIASA SSPs scenario, this projected growth in sea transport is based on global GDP growth that will lead maritime trade to increase by 250-300%. With these assumptions, freight volume will increase from 41 000 billion ton-nm in 2007 to a minimum of 106 000 billion ton-nm in 2050 for SSP3 to a maximum of 153 000 billion ton-nm for SSP5, according to the results of my analysis, which is consistent with the Linstad 2013 projections (2). Idealistically, the establishment of the future market share of the various types and sizes of vessels was based on the projected transport work of the respective types of cargo to be moved in 2050, coupled with estimates of productivity improvements. On the other hand, the growth trend within the horizon was retrieved assuming a logistic function.

If this increased freight work is transported with the current fuel mix (here referred to as 2015 fuel mix) in a Business as Usual scenario, the emissions will follow the path of the freight work, thus increasing of three times 2015 levels. This despite the fact that 2050 fleet will undergo efficiency improvements, due to Economy of Scale and productivity increase. Considering modest zero emissions fuels share and rely of LNG to achieve GHG reductions proves completely inadequate, as proven in S2 which gives total sea transport cargo emissions ranging between of 2 470 and 3550 million tons of CO_2 in 2050 depending on the SSP evaluated. This equals a 250%-400% increase in emissions compared to the 1 billion ton of CO_2 emitted in 2018 (4) and for three out of five SSP the final value of CO2-eq emission goes beyond the BAU's estimate (Figure 41). It will also lead to increased emissions per freight unit transported since the growth, i.e. 170-220%, in freight work is lower than the increase in emissions, thus the final specific emissions would go from 19 gCO2/ton-nm up to minimum 25 gCO2/ton-nm. Even in a more optimistic case where high spread of clean fuels is accounted (S1), emission projections set them close to the former results. Here only SSP5 overcomes BAU 2050 emissions levels, but still the four other SSP predict an increase between 250 and 300% with respect to 2015 CO2-eq levels. This led to the main conclusion that adoption of zero emission fuels is ineffective if not coupled with greed decarbonization or and a more sustainable production system. For consistency it should be noted that none of the figures in this comparison includes emissions from vessels which are built for other purposes than freight transport, such as cruise, ferries, fishing, service or offshore vessels, equivalent to 20% of the total emissions (2). Instead of assessing the likelihood of the S1 versus the S2 scenario, both where used as a starting point to analyze the reduction potential of a cut in upstream emissions for zero emissions fuels, fluctuation in conventional fuels price and the effect of a cap on total emissions as possible policy to reduce carbon per freight unit transported by 2050 by up to 80%, as to meet Paris Agreement targets. Total sea transport emissions can also be reduced through reductions in trade and transport volumes, but assessing this option is outside the scope of this thesis.

My studies show that it is difficult to ensure reductions in greenhouse gas emissions and progress towards decarbonization. No readily available fuel option is currently available to deliver substantial savings on local pollutants and greenhouse gas emissions in conjunction. Fossil LNG, in particular, is a promising option for meeting current regulations, but the results show that it is not a low-carbon alternative. Among the other alternative fuels considered, no ready solution exists to reduce greenhouse gas emissions significantly in the near run. The two key environmental challenges for any alternative fuel, reducing local pollutants and meeting longer-term greenhouse gas emission reductions, sometimes are in contrast. Plus, it is important to consider the emissions released over the full lifecycle and not just during fuel combustion to understand the full extent of the environmental implications. Otherwise, there is a risk of misleading the industry and policy on any alternative fuels' true emission penalties. The fuel options chosen in this paper are based on literature review, but they are not necessarily exhaustive, nor are they unique or mature paths for producing these fuels. The results obtained are nonetheless considered robust. An eventual increase in fuel oil price coupled with sustainable fuels spread may have a modest benefit over the total GHG levels, contributing for just a 15% maximum reduction with respect to 2050 projections in S1 (Figure 46). A CAP on total carbon levels set to 2 Mt CO2-eq starting from 2030 can provide a reduction of 1.3 to 2 times of specific emissions per ton-nm, which is far from the required 5 to 6 times reduction suggested by Bouman et. al. (19). Low carbon fuels have the potential of reducing their upstream emissions by 70%. Coupled with a substantial shift in the fuel mix in 2050 (referring to S1), this would lower specific emissions per freight unit transported of 1.7 to 2 times from 2015 value. This means that if alternative fuels adoption is to be taken into account, they only prove effective if it comes with sustainable production processes, whose spread is not straightforward nor already happening on large scale. Complicating matters, this is not enough to deliver the necessary cut in global maritime sector emissions, thus it is fundamental to explore all others technical and operational measures not taken into account in this thesis, and any market-based or regulatory instrument to enhance their actuation. Since the urgent need to reduce greenhouse gas emissions is a more significant problem, it is also important to ensure that any short-term measure does not reduce the capacity for long-term deployment of low carbon fuels, especially when considering the long life of ships and the infrastructure for the supply of fuel.

Bio-methanol has the potential to cut CO_2 emissions significantly as shown in Figure 47 where its adoption surpasses the one of renewable hydrogen and ammonia from a cost effective point of view. The feedstock, however, is limited and, in terms of CO2e, the exploitation of its reduction potential depends on the ability to control both upstream and operational methane emissions. Methanol derived from biomass could improve life-cycle emissions, while raising issues related to other bio-derived fuels as well. For example, it is necessary to further verify the assumption that the biomass feedstock takes up atmospheric CO2 that would otherwise not have been absorbed, and the inclusion of emissions from land use change can dramatically alter the greenhouse gas balance, with results subject to great uncertainty and highly dependent on the process of production of feedstock. Some emissions may be particularly difficult to mitigate, such as those associated with the application of fertilizer, depending on soil conditions. Whether and to what extent sustainable production processes can be implemented depends on a wide range of variables, including the availability of land, competition for food-producing land use and demand from other sectors. Hydrogen does not have operating CO2-eq emissions, but the associated life-cycle emissions are significantly higher in the baseline case than for conventional fuels. Significant advantages are only realized when full life-cycle emissions are taken into account and CO2-eq emissions from its feedstock and input energy supply are reduced or eliminated. This is feasible only through the successful application of CCS and decarbonization of input electricity or through the use of renewable energy sources through electrolysis in production. Outside of the scope of this paper, there are also other obstacles and problems, such as hydrogen transport and storage. Summing up the above considerations, while some unresolved issues are more directly related to shipping technology, others are not directly related to the shipping industry or are immediately susceptible to sector regulation.

The needed take-up of innovations for energy efficiency and CO2 reduction goes way beyond what is currently being encouraged by existing regulations and market conditions such as fuel prices. There appears to be a lack of a long-term goal or objective which would affects both the legislation and the market, requiring a clear direction of certainty and incentives. Due to the lack of information disclosure, the impact of the EEDI regulations has been weak, as the data captured and reported by the IMO does not show which technologies were used to meet the reduction targets. Another issue is the weakness in the strictness of the regulation itself, which means that only incremental energy efficiency technologies will be deployed at best. While surely necessary, these are not sufficient to achieve sectoral decarbonization. In addition, Miola et. al. 2011 (54) points out that many new construction ships are achieving phase two and three (2020 and 2025) reduction targets. A ship-level use of alternative fuels with a lower carbon content will be needed to go above a certain pollution mitigation goal. As a result, efforts need to be directed at overcoming obstacles for exploitation of the low carbon potential of fuels identified, or finding alternatives that are not considered here. Significant efforts will be required for any promising option, first to prove actual applicability and then to be scaled up to industrial level.

Different forms of risks affect the implementation of such step-change technologies, posing a challenge for policymakers as it requires decision-making on threats that are unknown but require high investment, due to long time-lags between action and effect. The problem faces the risk of time-inconsistency actions due to a misunderstanding about potential gains when facing high current costs, triggering lawmakers to delay or compromise measures to offset greenhouse gases that are believed to be optimal in the long run. These factors must also be combined with the internal characteristics of the international ship transport sector, with ships continuously changing flag and being highly diverse in type, size and usage. Policy making therefore encounters intrinsic barriers such as emissions allocation, carbon leakage, permit allocation, fleet variety treatment, and transaction cost. All of these issues summarized partly explain the inability of the UNFCCC and the IMO to implement a clear policy of reducing GHG emissions. On the other hand, the global financial crisis and the high volatility of price of oil are now gaining the attention of the whole maritime community, providing the right background for the market in order to reconcile the economic and environmental objectives of fuel transition. Compared to other transport sectors, the maritime transport sector has a higher degree of inertia for significant change, but an ongoing commitment from stakeholders and the market players, although moved at first by economic purposes, may represent the catalyst that leads shipping to move towards increased sustainability. Economists typically agree that market-based tools outperform command-and-control policies in terms of cost-effectiveness for environmental regulation (73), which means that competitive conditions can pave the way for lowering emissions rather than set regulations. On the basis of the above, the complexity of the GHG strategy for seaborne trade requires policymakers to set binding and ambitious long-term emission reduction targets, economic incentives to promote agile action, information sharing of innovative mitigation practices, ease of administration, and accountability mechanisms. In addition, the IMO should set an appropriate pollution cap and settle on a sectoral market-based instrument to provide operators with sufficient incentives to minimize their emissions at the least cost. For the international maritime transport market, a global maritime carbon trading system, which is accessible to other industries and allocates permits by auctioning, is a viable choice. On the other hand, a hybrid scheme that integrates a cap with a tax, present the advantage not to entail the creation of a foreign trading system and is thus easier to administer, while also supplying the industry with incentives to minimize its emissions.

6.2 Possible improvements

Some important assumptions have been made to conduct the analysis in this thesis effectively, but without exceeding the limits of the project's interest. These assumptions involved the selection of socio-economic development scenarios to refer to, here the Shared Socioeconomic Pathways, but also the OECD scenarios would have been possible. As far as the estimation of the cargo demand for the various types of ships is concerned, a possible weakness is the unification of fossil-fuels cargoes and non-fossil-fuels cargoes, which, being subject to different market dynamics, should be differentiated for coherence. This was also the method carried out in the fourth IMO GHG study. For the assessment of the evolution of the fleet, moreover, in the present study it has been assumed that the total number of ships by 2050 would depend solely on the demand for freight transport, fleet distribution in bin sizes and productivity improvements. Other market-driven effects or political interests are not taken into account. The estimation of fuel consumption was based on emission factor data from a previous study (14), and in the analysis only consumption due to the main engine was considered, and not all the secondary and auxiliary ones. For a more accurate analysis, therefore, first-hand data on specific fuel consumption per ton-nm and a more precise estimate of the specific fuel consumption of alternative fuels would be required, in this case estimated starting from the energy density of the fuel and hypotheses on the efficiency of combustion technology.

As regards interesting developments of the existing project, one possibility is to include in the cost items the investment costs for the various propulsion technologies and any additional costs due to extra refueling or revenue lost for decreased storage capacity. In the present study, in fact, only the variable costs of fuel have been taken into consideration, but the inclusion of other cost items is interesting if the Marginal Abatement Cost Curves (MACC) are to be obtained. Secondly, in this thesis various analysis nuclei have been developed with different programming languages. A possible advancement of the model foresees to standardize the analyses in a single environment (message-ix), in particular to endogenize the bilateral trade demand and the evolution of the fleet. This can be done by plugging in the sectoral model for naval sector developed by me with the global model in message-ix, where data on GDP evolution and all the consequent variables are already present in an associated database.

Although with some limitations, the results of the analysis appeared to be in line with previous estimates provided by the literature. The results for each model applied are robust and the general method used can be replicated and extended to other transport sectors. Furthermore, before the publication of the Fourth IMO Report, this study was the only one that examined the joint action of rapidly growing transport demand and implementation of alternative fuels to cut GHGs emissions from the sector.

List of Acronyms

BAU – Business As Usual

BioMEOH – Bio Methanol

BG – Biomass Gasification

CCS – Carbon Capture and Storage

CEPII – Centre d'Études Prospectives et d'Informations Internationales

DWT – Dead Weight Tonnage

ECA – Emission Control Area

EEDI – Energy Efficiency Design Index

EOS – Economy Of Scale

GDP – Gross Domestic Product

GHG – Green House Gas

HFO – Heavy Fuel Oil

IAM – Integrated Assessment Model

ICCT – International Council for Clean Transportation

IIASA – International Institute for Applied Systems Analysis

IPCC – Intergovernmental Panel on Climate Change

IMO – International Maritime Organization

ITF – International Transport Forum

FC – Fuel Cell

LCA – Life Cycle Assessment

LH2 – Liquid Hydrogen

LNG – Liquid Natural Gas

LSHFO – Low Sulphur Heavy Fuel Oil

MDO – Marine Diesel Oil

MESSAGE – Model for Energy Supply Systems And their General Environmental impact

NM – Nautical Mile

OECD - Organization for Economic Co-operation and Development

OLS – Ordinary Least Squares

RCP – Representative Concentration Pathway

S1 – Scenario 1 (of low carbon fuels penetration rate)

S2 – Scenario 2 (of low carbon fuels penetration rate)

SEEMP – Ship Energy Efficiency Management Plan

SDS – Sustainable Development Goals

SFOC – Specific Fuel Oil Consumption

SMR – Steam Methane Reforming

SOG – Speed Over Ground

SSP – Shared Socioeconomic Pathway

UNCTAD – United Nations Conference on Trade and Development

USD – US Dollar

TEU – Twenty-foot Equivalent Unit

WE – Water Electrolysis

WGS – Water Gas Shift

WtW – Well to Wheel

ZEV – Zero Emissions Vessels

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