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Young Scientists Summer Program

Green transition pathways for the maritime industry – modeling interactions of behavioral and socioeconomic aspects of demand with alternative fueling options

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Approved by:

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This report represents the work completed by the author during the IIASA Young Scientists Summer Program (YSSP) with approval from the YSSP mentor.

It was finished by Sebastian Franz and has not been altered or revised since.

Mentor signature:

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Abstract

Reducing greenhouse gas (GHG) emissions from the maritime sector will be a crucial component of climate mitigation toward meeting the Paris Agreement targets. Therefore it is essential to identify decarbonization pathways for the maritime industry that are feasible, efficient, and avoid carbon-intensive lock-in, while still supporting the movement of goods needed for human well-being. To study how these pathways may interact with broader socio-economic conditions, we developed an open-source maritime gravity demand model that incorporates a wide range of SSP-differentiated measures for an interdisciplinary set of phenomena, that enables maritime activity projections to vary in a complex manner with socio-economic and -cultural futures. We begin with a large historical dataset on shipped goods and combine it with several SSP-specific projectionsdrawn from interdisciplinary sources. The combined dataset allows us to draw a holistic picture differentiated across shipping market segments like oil, container, and bulk dry. Based on regression coefficients of historical data for the respective parameters, we extrapolate trade flows by multiplying them with future projections—drawn from recent literature—of the respective parameters. This process yields trade flows in monetary units, which we then translate into cargo tonnage by mapping them with geo-spatial data of actual port calls in a base year. The final product is projected maritime demand for different ship types and SSPs. While rich in their own right, these projections will also be used (beyond the YSSP) to parametrize an improved version of the shipping representation in the MESSAGEix-GLOBIOM/MESSAGEix-Transport global integrated assessment model. The added detail in this model will allow it to cover demand/activity for maritime shipping of all commodities.

The gravity model results *per se*show vast differences in future maritime demand projection across both SSPs and countries. We project that some countries will significantly increase maritime activity while that of industrialized countries will eventually saturate. The level of maritime activity in the future heavily depends on the chosen parameters for the respective ship segment and its future projections. Overall, the work demonstrates a successful combination of interdisciplinary datasets into one analysis yielding improved maritime demand projections and improved representation of SSP narratives, reflective of socio-economic factors that are usually omitted from sector-focused analyses.

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Introduction

Reducing greenhouse gas (GHG) emissions from the maritime sector will be a crucial component of climate mitigation toward meeting the Paris Agreement targets. As of today, the maritime sector is responsible for circa 2.5% of global greenhousegas(GHG)emissions, with this share expected to rise in the future (IMO, 2021)(IMO, 2021) (IMO, 2021). Therefore, it is essential to identify decarbonization pathways for the maritime industry that are feasible, efficient, and avoid carbon-intensive lock-in, while still supporting the movement of goods needed for human well-being. Reliable projections of this need—that is, the level of expected future demand,in different socioeconomic scenarios,formaritime services per ship type,are thus crucial.

The exploration of global climate mitigation pathways makes use of increasingly detailed subsectoral modeling (Sharmina et al., 2021)(Sharmina et al., 2021) (Sharmina et al., 2021) and thus will require detailed assumptions about maritime demand futures. Given the prominence of the framework of shared socioeconomic pathways (SSPs) for global modeling studies, the lack of a readily usable, transparent, and documented set of maritime demand pathways along SSPs is a significant gap. Previous studies that looked into SSP variations of maritime demand (IMO, 2021) have only used single elements of SSPs (such as gross domestic product (GDP)) and thus fail to capture the full complexity of the different SSP narratives.

There are many different approaches to the current research on maritime demand projections. Among others (Sardain et al., 2019) and (IMO, 2021) both use a gravity-type model of trade to derive maritime demands on an origin and destination (O&D) level. The gravity type model of trade in its original form relates bilateral trade flows to GDP and distance and is the most used theoretical framework when deriving maritime demand flows (Anderson A & Wincoop, 2003; Anderson, 1979; Kepaptsoglou et al., 2010)(Anderson A & Wincoop, 2003; Anderson, 1979; Kepaptsoglou et al., 2010) (Anderson A & Wincoop, 2003; Anderson, 1979; Kepaptsoglou et al., 2010). While there exist a growing number of papers related to the application of gravity-type models for different trade flows and then deriving demand from the trade flows(Sardain et al., 2019; Verschuur et al., 2022; Xu et al., 2020), none yet combines a gravity model formulation with a set of socioeconomic variables in order to achieve a richer representation of SSPs framework(Riahi et al., 2017). Thus in this study, we go beyond the classical formulation of a gravity-type model of trade by introducing SSP-specific socioeconomic parameters in the model formulation to explore the dynamics and extremes of future maritime demand induced by human behavior. We aim the fill two methodological gaps in the literature. One relates to achieving a richer representation of the SSP narrative beyond single elements of SSP quantifications, namely GDP. The second relates to extending the gravity type model of trade formulation beyond its classical formulation by exploring the dynamics and impacts of including a set of application-specific (in this study, maritime industry) independent variables.

This work builds upon the(Kramel, 2023) gravity type model of maritime demand for different SSPs, in order to tackle the main research question: How do climate mitigation pathways for the maritime industry interact with broader socio-economic conditions? We developed an open-source maritime gravity demand model(S. Franz, 2022) that incorporates a wide range of SSP-differentiated measures for an interdisciplinary set of phenomena that enables maritime activity projections to vary in a complex manner with socio-economic and -cultural futures.

Methods

We use a model with trade as its dependent variable, and dimensions of sector, origin and destination country, time (annual), and ship type. This model is formulated as a gravity model of trade(Anderson, 1979) to derive maritime trade flows between a respective country pair. We go beyond the classical formulation of the gravity model of trade by including maritime-specific socioeconomic parameters in the modeling formulation to achieve a richer representation of the underlying SSP narrative. We model multiple ship segments separately as they behave differently in many ways, given segment-specific demand drivers or geospatial location of major hubs. The seven modeled ship segments are Dry Bulk, Container, Chemical, Refrigerated, Oil, Liquefied Gas, and Roll-on-Roll-off (RoRo).

Understanding Shared Socioeconomic Pathways

The SSP-specific projections in this work are subject to the underlying narratives. In Table 1, we present a comparison based on key differentiating aspects of the underlying SSP narrative. This comparison shows that differentiation beyond GDP is key for consistently representing the narratives in a holistic manner, especially with regard to lifestyle patterns and consumption behavior—both key drivers of activity for individual shipping segments and across the maritime industry.

Table 1: Comparison of SSP1, SSP2, SSP3, SSP4 and SSP5 by certain categories. Adapted from (O'Neill et al., 2017) Elements that motivate differentiation of behavioral parameters for maritime demand are highlighted in bold italics

Indicator	SSP1	SSP2	SSP3	SSP4	SSP5
Demographics					
Population growth	Low	Medium	High	High	Low
Migration	Medium	Medium	High	High	High
Economy & Lifestyle					
GDP growth	High	Medium, uneven	Slow	Low in LICs, medium in other countries	High
Inequality	Reduced	Uneven, reduced moderately	High, especially across countries	High, especially within countries	Strongly reduced
Globalization	***Connected markets***	***Semi-open global economy***	***De-globalizing, regional security***	***Globally connected elite***	***Strong***
International Trade	Moderate	Moderate	Strongly constrained	Moderate	High

Consumption	Low material consumption	Material intensive	Material-intensive consumption	Elites: high consumption lifestyles; Rest: low consumption, low mobility	Materialism, Status consumption, High mobility
Diet	***Low meat diets***	***Medium meat consumption***	***N/A***	***N/A***	***Meat-rich diets***
Technology					
Development	Rapid	Medium, uneven	Slow	Rapid in high-tech economies and sectors; slow in other	Rapid
Energy technology change	***Directed away from fossil fuels toward efficiency, renewables***	***Some investment in renewables, 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***
Environment & 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***
Land-use	***Strong regulations to avoid environmental trade-offs***	***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 agriculture productivity; rapid diffusion of best practices***	***Medium pace of tech change in agriculture sector; entry barriers to agriculture 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***
Policies & instruments					
International cooperation	***Effective***	***Relatively weak***	***Weak, uneven***	***Effective for globally connected economy, not for vulnerable populations***	***Effective for development, limited for environment***

Environmental policy	***Improved management of local and global issues; tighter regulation of pollutants***	***Concern for local pollutants but only moderate success in implementation***	***Low priority for environmental issues***	***Focus on local environment in MICs, HICs; little attention to vulnerable areas or global issue***	***Focus on local environment, little concern with global problems***

Gravity Model Formulation

The gravity model equation is "one of the most empirically successful in economics"(Anderson A & Wincoop, 2003) and is used to relate bilateral trade flows between a country pair also called origin and destination (O&D). The gravity model equation does not have a theoretical foundation. The existing theory(Anderson, 1979) only tells us that distance between an O&D has a negative correlation with the respective trade flow while controlling for GDP. On the other hand, GDP has a positive correlation with the respective trade flow of a respective O&D while controlling for distance. The missing theoretical foundation has significant implications on the results that needs to be considered in order to understand the results. One significant implication is that the estimation results are biased due to omitted variables(Anderson A & Wincoop, 2003). For this reason and for the fact that we want to improve the representation of the SSP-specific narratives, we developed a gravity model that goes beyond the common gravity model formulation of using primarily GDP and distance of the O&Ds as independent variables. Here we introduce an updated version of the empirically gravity model equation, which includes a set of independent variables specifically chosen for the respective ship segment.

$$T_{s,o,d,y,z} = \beta_0 + \sum_{i \in I} \beta_{s,i} * \left(logX_{o,d,i,y,z}\right) \qquad \text{(I)}$$

with:
s = ship segment (bulk-dry, oil, ro-ro, chemical, refrigerated, LNG, container)
i = independent variable (GDP, Pop, Gravity, Fossil Fuel usage…..)
β = historical coefficient of independent variable
β_0 = constant
X = future projection of independent variable
y = year
o = origin country
d = destination country
z = SSP scenario
T = Trade Flow

In equation I we show the derived gravity model equation. The objective is to derive a O&D trade flow for each ship segment, year and SSP scenario ($T_{s,o,d,y,z}$). In doing so we sum over the product of the historical ship segment and independent variable specific coefficient ($\beta_{s,i}$), which has been derived by OLS regression beforehand (see table 2 for exact value and standard errors), multiplied by the respective years logarithmic SSP specific future projections of the independent variable for each O&D ($logX_{o,d,i,y,z}$). We show the used independent variable in the Data section of this article. The number of potential independent variables in this regard is limitless but due to data availability restrictions and requirements we included only a few. The data specific requirements for the independent variables are availability of both historical data and future projections that are SSP-specific, and resolution of individual countries (as opposed to, for instance, world regions).

Data

We begin with a large historical dataset on shipped goods and combine it with several interdisciplinary SSP-specific projections. The combined dataset allows us to draw a holistic picture differentiated across shipping market segments like oil, container, and bulk dry. Based on regression coefficients of historical data for the respective parameters, we extrapolate trade flows by multiplying them with future projections—drawn from recent literature—of the respective parameter. The used parameters are chosen carefully for the respective ship segment to improve the extrapolation (e.g., historical animal product demand and projections for the same are linked to trade flows on refrigerated vessels, but not others). This process yields trade flows in monetary units, which we then translate into cargo tonnage by mapping them with geo-spatial data of actual port calls in a base year. This method yields projected maritime demand for different ship types and SSPs
The different data sources used can be seen in Table 2. As mentioned all of the historical data and future SSP-specific projections. This is a requirement else, the respective data can not be used in the gravity model formulation. The used data sources in the present set are not to be seen as a final set, but rather as illustrative of our approach to reach a holistic, interdisciplinary view on SSP narratives. We carefully collected data up until August 2022 from the literature that fulfills the requirements regarding data availability and SSP representation. Thus this analysis can be improved in the future by adding new SSP-specific projections. The underlying code for the gravity model has been written in a way that enables easy and fast integration of new data sources. This piece of work paves the way for how to integrate interdisciplinary datasets to achieve a richer, more heterogenous, and holistic representation of SSP narratives in future demand projections.

The most classical gravity model independent variables are Gross-domestic-product (GDP) and Population. We use data from the CEPII gravity database and the SSP database, which contains lots of data for gravity modeling purposes such as distance, common colonizer, common language, connection via land, regional trade agreement, and membership in the World Trade Organization (WTO).

The other major set of new data input is related to SSP specific data. These data sources have been carefully selected based on the relevance and data requirements. The following list is by no means a finalized list, it rather reflects the current status on availability of SSP specific projections for socioeconomic and behavioral parameters.

Table 2: Used Data Sources to achieve a richer representation of the underlying SSP narrative

Parameter	Source	Availability	Description	Historical Data Source
Population	(Riahi et al., 2017)	Open-Source	Population projections for SSP on a country-level	CEEPII
GDP	(Riahi et al., 2017)	Open-Source	GDP projections for SSPs on a country-level	CEEPII
Animal Product Demand	(Bodirsky et al., 2020)	Open-Source	Animal Product (e.g. diary-products, meat) Demand projections for SSPs on a country level	*FAO*
Gini Coefficient	(Rao et al., 2019)	Open-Source	Gini Coefficient SSP projections on a country-level	World Bank
Governance Index	(Andrijevic et al., 2020)	Open-Source	Governance Index for SSP on a country-level	(Andrijevic et al., 2020)
Timber Production	(Bodirsky et al., 2020)	Upon Request	Timber Production SSP projections on a 0.5° resolution	FAO
Staples Demand	(Bodirsky et al., 2020)	Open-Source	Staples (e.g., corn, wheat, rice) food demand SSP projection on a country-level	FAO

The historical data is being used to perform a standard OLS regression with the trade flow for the respective ship segment and O&D as a dependent variable and the many SSP specific and gravity type parameters. The respective coefficients of the OLS regression are being used in the gravity equation (see equation 1 - $\beta_{s,i}$). The overarching goal of this approach is the a) remove the impact of omitted variable bias in the gravity equation, which is a major shortcoming(Anderson A & Wincoop, 2003) and b) to improve the representation of SSP narratives beyond single element of the narrative like GDP or Population. Unfortunately, the data availability for this kind of analysis is limited to published work in the area of SSP projections. Even though in the past the has been a growing number of publications especially with focus on behavioral narratives in the SSP framework, the available data is still very scare. Most surprising to us, and perhaps also for the reader, is that there is no available data (again, including projections) on fossil fuel shares of final energy usage for SSPs at country resolution. This data would have advanced this analysis massively, as one could use this kind of data as a proxy for the economy-wide fuel transition away from centralized production of fossil fuels towards decentralized production of green fuels. The fact that around 50% of global shipped cargo can be connected to fossil fuel (e.g., coal in bulk dry, oil and LNG) indicates the potential of including this data. As this study mainly focuses on how to implement interdisciplinary datasets in an holistic gravity type model of trade, we hope to have this kind of data available once the focus will be more on the results rather than the methodology. The used historical coefficients can be seen in table 3 including the respective standard errors for each independent variable.

Table 3: Historical coefficients and standard errors (in brackets) for respective ship segments calculate with an standard OLS regression

Independent Variables	Bulk Dry	Refrig-erated	RoRo	Oil	Container	Chemical
distw_log *(distance)*	**-0.5949** (0.029)	**-0.7077** (0.0328)	**-0.4524** (0.0247)	**-1.0597** (0.0374)	**-0.8405** (0.022)	**-0.9465** (0.0227)
Contig *(connection via land)*	**0.7** (0.0684)	**0.7404** (0.0626)	**0.9641** (0.0569)	**0.4684** (0.0918)	**0.4425** (0.0406)	**0.5443** (0.0468)
comlang_off *(common language)*	**0.1369** (0.0549)	**0.0065** (0.0563)	**-0.1289** (0.0415)	**0.4725** (0.0682)	**0.3665** (0.0327)	**0.5256** (0.0345)
Comcol *(common colonizer)*	**-1.4717** (0.2875)	**-2.906** (0.3717)	**-4.0215** (0.2609)	**-3.1375** (0.2521)	**-3.0253** (0.1178)	**-1.4882** (0.1753)
Rta *(region trade agreement)*	**0.0283** (0.0809)	**0.0404** (0.0634)	**0.5735** (0.0427)	**-0.1899** (0.0711)	**-0.1259** (0.0384)	**-0.3328** (0.0473)
pop_o_log *(population origin)*	**-3.5213** (0.2024)	**-1.8029** (0.1539)	**-0.0782** (0.111)	**-2.4851** (0.1894)	**0.5406** (0.0884)	**-0.8571** (0.1005)
pop_d_log *(population destination)*	**2.2417** (0.1689)	**-0.3191** (0.1334)	**-1.8594** (0.1108)	**-0.1695** (0.1869)	**-1.4385** (0.1074)	**-0.5591** (0.0918)
gdp_ppp_d_log *(gdp destination)*	**1.4467** (0.0601)	**1.9594** (0.0533)	**0.9627** (0.0366)	**1.032** (0.0625)	**0.8457** (0.0372)	**0.6538** (0.035)
gdp_ppp_o_log *(gdp origin)*	**0.1887** (0.056)	**-0.12** (0.064)	**0.979** (0.0476)	**1.7898** (0.0531)	**0.6542** (0.0372)	**1.2908** (0.0445)
animal_product_demand_o_log *(animal product demand origin)*	**-0.4926** (0.1066)	**1.0155** (0.0856)	**-0.6843** (0.06)	**-0.6087** (0.1396)	**0.3292** (0.0556)	**-0.5488** (0.0571)
animal_product_demand_d_log *(animal product demand destination)*	**-0.018** (0.0782)	**-0.7476** (0.0787)	**-0.1306** (0.0569)	**-0.768** (0.0995)	**-0.3056** (0.0492)	**-0.1183** (0.052)
gini_d *(gini coefficient destination)*	**-0.027** (0.0026)	**-0.0232** (0.004)	**0.0509** (0.0022)	**0.0357** (0.0026)	**0.0347** (0.0018)	**0.0313** (0.0018)
gini_o *(gini coefficient origin)*	**0.089** (0.0024)	**0.0728** (0.0031)	**0.0077** (0.0028)	**0.0222** (0.0038)	**0.0091** (0.0019)	**0.0205** (0.0021)
governance_d *(governance index destination)*	**0.0004** (0.0032)	**-0.0018** (0.0029)	**0.0184** (0.0019)	**0.0407** (0.0028)	**0.0211** (0.0012)	**0.0184** (0.0014)
governance_o *(governance index origin)*	**0.0225** (0.0014)	**0.0306** (0.0022)	**0.0605** (0.0024)	**-0.0379** (0.0021)	**0.0196** (0.0018)	**0.0084** (0.0018)
timber_production_d_log *(timber production destination)*	**0.3563** (0.0284)	**0.0842** (0.0147)	**-0.1218** (0.0082)	**0.1809** (0.0272)	**-0.028** (0.0077)	**0.1583** (0.0126)
timber_production_o_log *(timber production destination)*	**-0.3213** (0.0101)	**-0.1548** (0.0103)	**0.125** (0.0164)	**-0.3038** (0.0158)	**0.2** (0.0224)	**0.1583** (0.0133)
staples_demand_o_log *(staples demand origin)*	**2.9014** (0.1738)	**0.7861** (0.1248)	**-1.8042** (0.0985)	**0.1151** (0.1812)	**-1.4771** (0.0942)	**-0.6545** (0.0831)
staples_demand_d_log *(staples demand destination)*	**-3.9807** (0.1976)	**-2.4216** (0.1343)	**0.0461** (0.1002)	**-1.0649** (0.1595)	**0.2746** (0.0687)	**-0.2539** (0.0775)

As can be seen in table 3 the standard errors of the coefficients for independent variables are relatively high compared to the actual coefficient value. This may indicate that the respective independent variable is not well suited to be included in the gravity model equation for the respective ship segment. However, to not make the choice arbitrary about which independent variable to include and which not we decided to include the same independent variables for all shipping segments. For further research, we are working on a method to let the model decide which independent variable is suitable for the respective ship segment and which one is not. This decision process will be based on a threshold approach regarding the ratio between the coefficient and the respective standard error. Furthermore, we are currently advancing the gravity equation toward a multidimensional gravity equation using hierarchical and k-means clustering (Bernard Chen et al., 2005)(Bernard Chen et al., 2005) (Bernard Chen et al., 2005) of similar O&Ds. This improves the overall statistical power of the model and thus helps us to remove the omitted variables bias and improve the representation of the underlying SSP narratives.

Monetary Trade Flows to Transport Volume

Once the trade flows on a O&D level are being derived one needs to transform the monetary trade flows into actual deadweight tonnage, as the objective of this modelling approach is to derive the demand for maritime ships in the future to narrow down the challenges towards climate mitigation of this "hard-to-abate" sector(Ueckerdt et al., 2021). The actual deadweight tonnage demand can than be used as a driving assumption of sectoral least-cost optimization models(S. M. Franz et al., 2022), that feature a lifecycle perspective on green fuels emissions and costs, upscaling of electrolysis capacity (Odenweller et al., 2022) and ship-stock modeling, to analyse the requirements for a green transition of the maritime sector. For the transformation process, we use two geospatial data sets containing port calls and satellite data. The port calls dataset is from IHS Markit including data on time and date of arrival and departure for each ship type and port. As the data for some regions were not sufficient to draw a sophisticated picture of the shipping activities in a base year (here 2017), we combined the port-call data set with satellite data (0.1° latitude−longitude resolution) using a combination of Dijkstra's algorithm(Dijkstra, 1959) and the A* path-search algorithm(Hart et al., 1968). For more details see (Kramel et al., 2021).

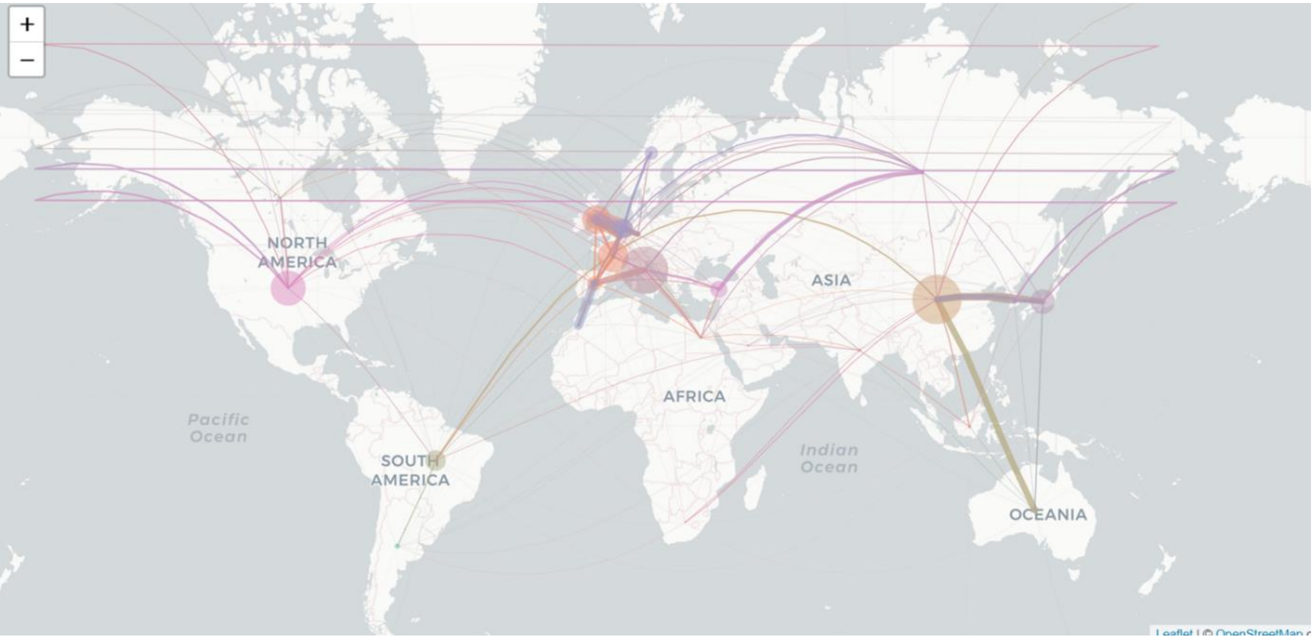

Figure 1: Actual Cargo Flows in the base-year 2017 used the calibrate the transformation from monetary trade flows into deadweight-tonnage cargo value.

In Figure 1 we show the combined economy-wide cargo flows for the base year 2017. With this data we calculate the ratio between monetary value and deadweight tonnage on the respective ship type for each product category. We assume that these values stay constant over time. This assumptions has a major impact on the final results, thus we are planning to improve this modeling approach by adding more detail to this assumptions with regards to the rolling time-horizon.

Results

We find there is a diversity of possible future maritime demand scenarios based on the respective SSPs. In Figure 2 we show the global SSP specific trade flows cumulated for all ship-segments. We find that demand is projected to grow fastest in SSP5 by a large amount, and leads to high maritime demand across ship-segments and thus high challenges towards climate mitigation. SSP1 ends up with higher trade volumes than SSP2 which is at first sight counterintuitive to the underlying narrative. However, the data in Figure 2 is global—thus, heterogeneity across regions is not captured in this figure. In Figure 5 we show an example of the heterogeneity across SSPs for one specific country and thus also a richer representation of the underlying SSP narrative. SSP3 and SSP4, both scenarios that are related to challenges towards adaptation rather than mitigation, yield the lowest trade volume and thus maritime demand. However, even these scenarios are show significant growth in demand over the coming years and thus still pose a challenge to decarbonize this hard-to-abate industry effectively.

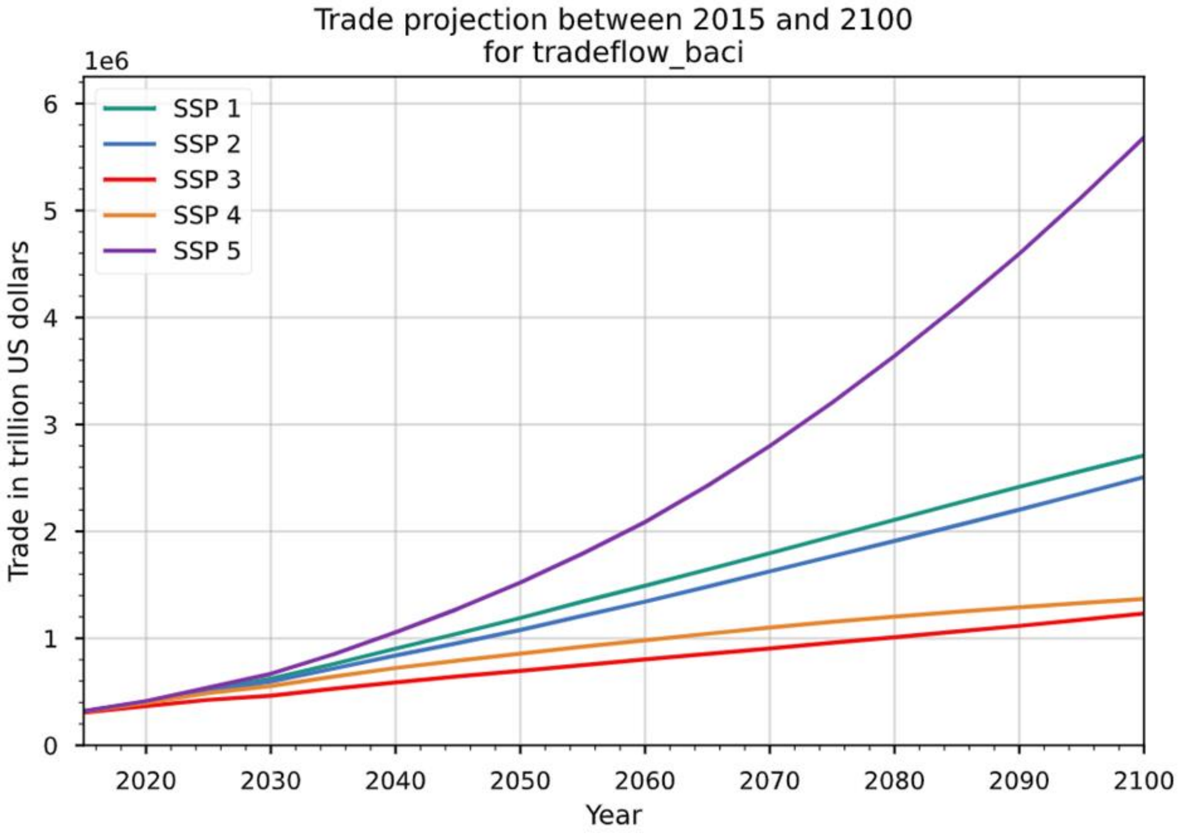

Figure 2: SSP specific trade flows for cumulated for all ship-segments

Discussion

When looking on a country level basis we can identify high heterogeneity across regions and countries leading to a richer representation of the underlying SSP narrative. In Figure 4 we show only outbound cargo for all ship-segments cumulated for the year 2050. The size of the bar plot indicates the total trade volume. As can be seen the major drivers of maritime cargo are China, the United States of America, Europe as a whole but also Australia and Brazil. The heterogeneity across SSPs for each of the countries is quite large resulting from the divers set of independent variables that enhance the representation of the underlying SSP narrative.

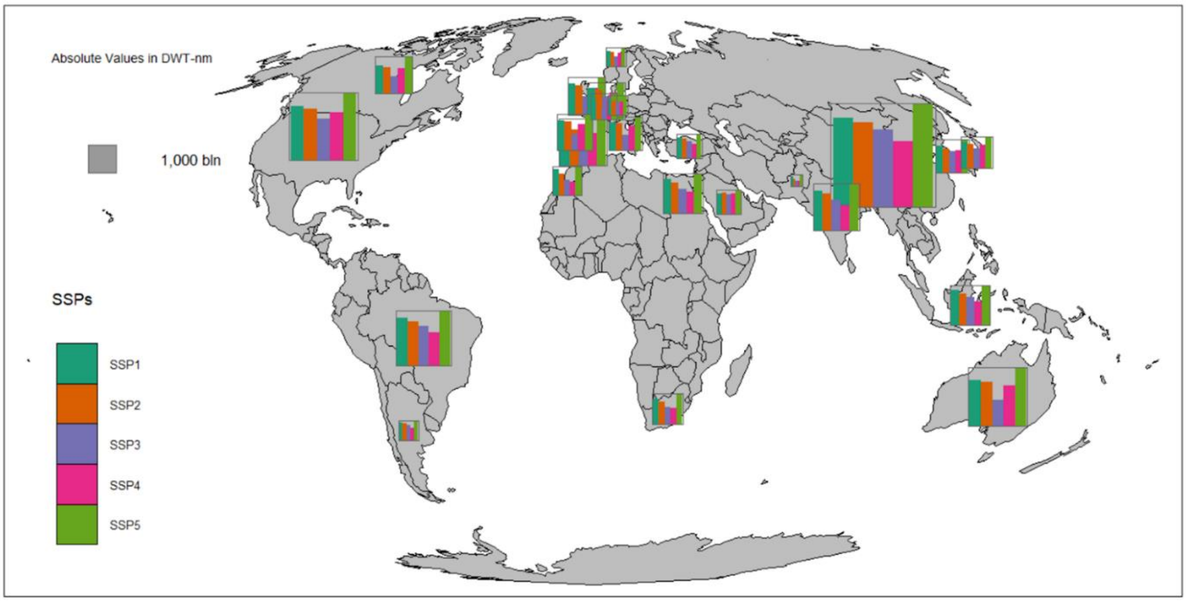

Figure 3: Maritime Cargo Outbounds for different SSPs cumulated over ship-segments for the year 2050

When looking at the growth rates of maritime demand for a specific country across SSPs one can see the impact of the new modelling framework of including interdisciplinary datasets to achieve a holistic and rich representation of SSP narrative in future maritime demand projections. In Figure 5 we show the annual growth rate of bulk dry demand for Spain across SSPs from both baseline or simple model, which represents the usage of GDP, population, and distance between countries as the only independent variables, and also the "individual" case or model, which corresponds to the above-described modeling framework of using multiple interdisciplinary independent variables in the gravity model formulation.

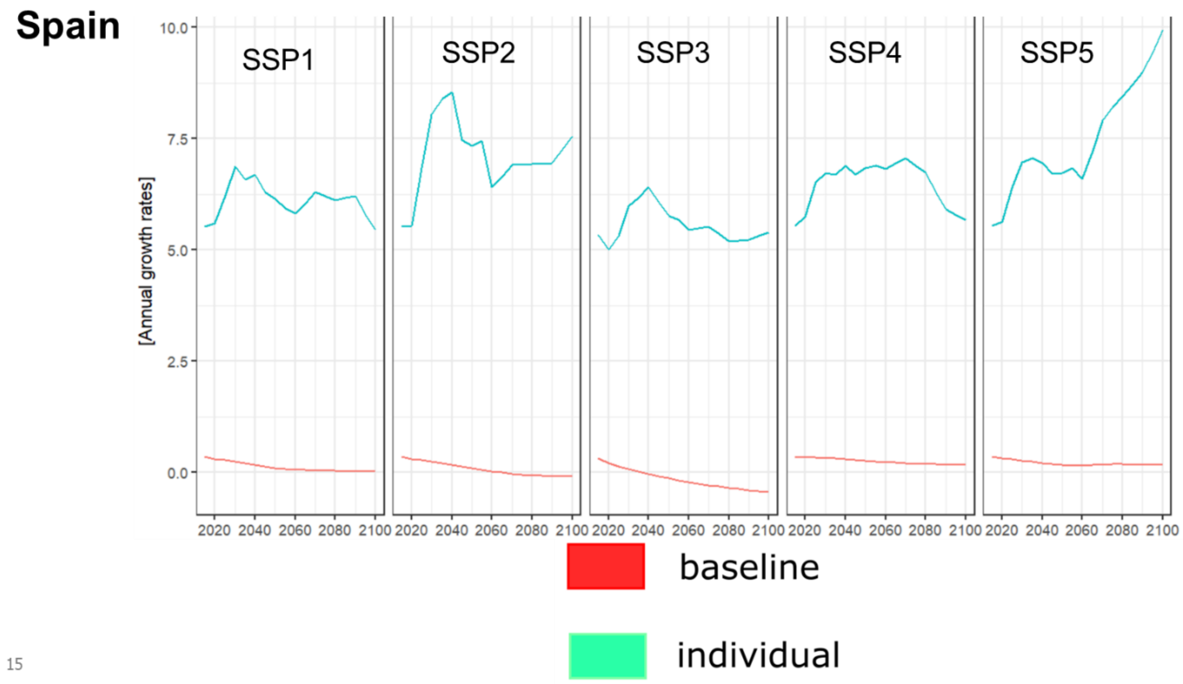

Figure 4: Comparison of annual bulk dry growth rates for a baseline setting of independent variables (GDP, Population and Distance) and the individual setting utilizing several interdisciplinary datasets to achieve a richer representation of the underlying SSP narrative.

One can see saturation in demand for the SSP1 scenario, and also a strong increase in demand for the SSP5 scenario for the individual modelling framework while the growth rates for both scenarios in the baseline modeling framework are very similar. This phenomenon underlines the importance of using multiple interdisciplinary datasets to achieve a rich representation of SSP narratives as can be seen in the case of bulk dry trade flows in and out of Spain (figure 5).

Further research will focus on adding more SSP-specific interdisciplinary datasets to improve the respective representation of the SSP narratives. Furthermore, I am planning to use the developed open-source gravity model to investigate future scenario analysis for some SSPs in which particular trade flows are strongly impacted. The main objective of this analysis is to model present disruptions like the war in Ukraine or the COVID-19 pandemic and their potential impact on trade routes and thus future maritime demand.

Conclusion

Our results show vast differences in future maritime demand projections across both SSPs and countries. We find that some countries increase maritime activity while that of industrialized countries will eventually saturate. The level of maritime activity in the future heavily depends on the chosen parameters for the respective ship segment and its future projections. Overall, the work demonstrates a successful combination of interdisciplinary datasets into one analysis yielding improved maritime demand projections and improved representation of SSP narratives, reflective of socio-economic factors usually omitted from sector-focused analyses.

The results show that some futures may be significantly easier to decarbonize is a sustainable way than others. Given the scarcity of the potential decarbonized fuel production pathways that can satisfy the growing maritime demand, a future pathway with lower overall fuel demand seems to be less challenging in terms of mitigation effort. Furthermore, not only the maritime industry but also international aviation and the petrochemical industry are considered hard-to-abate sectors(Ueckerdt et al., 2021), and so intersectoral competition for the main commodities for a green transition, such as ecologically sustainable biomass for deriving bio-based fuels (e.g. bio-e-methanol, liquified biogas or pyrolysis oil), can be expected. This implies that a policy roadmap toward a green maritime industry not only includes the supply of alternative fuels for the industry but also fuel efficiency gains and more general measures to lower fuel demand for this industry. With the improved understanding of future maritime pathways and thus mitigation challenges an early clear policy planning involving important stakeholders can be crucial to reach Paris Agreement goals for this industry and avoiding carbon-intensive lock-ins and stranded assets.

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