

Trade and trade-offs: Shipping in changing climates

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ABSTRACT

This paper addresses the evolution of maritime transport demand in response to global climate change mitigation and adaptation efforts. The complexity of the global shipping system makes predicting volumes and patterns of long-term future international maritime trade a challenging task which is best explored by building scenarios rather than 'precise' forecasts. We present four contrasting scenarios of international maritime trade out to 2050, available in high resolution in terms of the dimensions studied (regions, countries, commodities, decades), which are consistent with high and low levels of global CO₂ mitigation and associated climate impacts. The scenarios project trade increasing to between two and four times the 2010 value by 2050. Scenarios characterised by low temperature increases and material intensity lead to the lower bound trade increase with high trade growth in bioenergy commodities. Unfettered production growth across countries, high temperature increases and material intensity lead to a quadrupling of trade across energy, containerised, dry and wet commodities. The estimated range is lower than those in existing scenarios and forecasts in which globalisation is assumed to continue apace. The scenarios which project the highest growth presupposes both limited decarbonisation (in contrast to the Paris Agreement) and continued growth in expanding markets. The scenarios therefore become a valuable policy and decision-making tool to address technological and operational change required of the shipping sector, if it is to deliver mitigation in line with the Paris Agreement.

1. Introduction

The Paris Agreement sets the goal of limiting global warming to well below 2 °C, and ideally to below 1.5 °C and “[i]n order to achieve the long-term temperature goal [...] Parties aim to reach global peaking of greenhouse gas emissions as soon as possible”, followed by “rapid reductions thereafter” [1]. While the Agreement was unanimously adopted by the parties to the United Nations Framework on Climate Change Convention, the main emitters not explicitly included in the agreement are not countries, but the international aviation and shipping sectors. In article 2.2 of the Kyoto Protocol, the International Maritime Organisation (IMO) is charged with regulating greenhouse gas emissions from international shipping, but no legally binding targets on sectoral emissions have been agreed [2]. In October 2016, at the 72nd meeting of its Marine Environment Protection Committee (MEPC), the IMO produced a draft roadmap towards the adoption of an “IMO Strategy on reduction of GHG emissions from ships” [3]. This roadmap was further built upon in 2018 at MEPC 72 wherein it sets a GHG emission reduction pathway of “at least” 50% on 2008 levels by 2050 with a clear aspiration on full decarbonisation by 100% by 2050 if possible (MEPC, [49]).

Both agreements *inter alia* make reference to the maritime industry's need to reduce levels of emissions and develop abatement opportunities that contribute to meeting long-term temperature goals. In order to do so, public and private stakeholders engaged in setting marine policy or scoping future investment decisions in adopting green maritime technology need to incorporate expectations about the future demand for maritime transport. Specifically, how might the demand for maritime transport evolve until 2050 when efforts to mitigate and adapt to climate change are endogenised within national production industries? In such a context how might varying socio-economic framings such as population change, material intensity, technological advances and economic growth further influence the demand for maritime transport?

This paper addresses the aforementioned challenges by presenting four scenarios of global maritime trade until 2050, each exploring a contrasting climate change figure consistent with high and low levels of global CO₂ mitigation and associated climate impacts. The outcome is a matrix of goods quantities transported by sea for each future decade between 16 regions of the world according to a particular scenario, which can be further broken down at the region, country, commodity or

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decade levels for in depth examination of future trade flows. This novel tool improves our understanding of the plausible evolution of shipping by removing some of the uncertainty associated with predictions of maritime trade flows which is replaced by informed impacts attributed to the scenario narratives. Concurrently it could i) enhance policy efforts concerning the maritime sector's actions to mitigate GHG emissions; ii) augment shipowners' and shipmanagers' investment decisions, be it current or future, binding or not, for greener ships and technologies.

The paper is structured as follows: The remainder of Section 1 surveys the literature concerning projections of maritime trade, and defines our aims, scope and methodological context. Section 2 summarises the scenario narratives and presents our methodology. Section 3 presents and discusses the derived trade scenarios. Conclusions are drawn in Section 4.

1.1. International trade and the demand for sea transport, present and future

Over 80% of global trade by volume and more than 70% of global trade by value is transported by sea [4]. These are carried by approximately 94% of the world fleet of ships¹, while the remainder is occupied with the transport of passengers and other functions [5].

From the 1950s until the mid-2000s, international trade has grown at a rate of 5.9% p. a. and trade relative to economic output more than tripled [6,7]. During this period total shipping emissions rose to around 950 million tonnes of CO₂ and of CO₂e of GHGs in 2012 [8], emissions of the same order as those of Germany [9], or the aviation sector [10].

The evolution of shipping demand is inexorably linked to the growth of world trade, and it is inherently difficult to predict in the long term due to diverse influencing factors and their interlinkages [11]. As shipping is a derived demand, the demand for shipping services depends on transportation drivers in addition to economic growth and the pattern of trade. Production and demand for individual commodities evolve, leading to the emergence of new commodities and centres of production, while others disappear. In such a context, technological advances in the maritime sector alter the costs of transport, and their relative importance vis-a-vis other trade barriers is also subject to uncertain change. Because of such complexity and inherent uncertainty regarding the evolution of future maritime transport demand, predicting long-term sectoral CO₂ emissions is arguably infeasible. However, to facilitate the decision-making process of the policy debate concerning the decarbonisation of the shipping sector, scenarios of future shipping trade are a useful tool. This paper presents the outcomes of four such scenarios with the intention to scope the range, extent, and timing of technological and operational change required for decarbonisation.

A common approach for exploring the future under conditions of complexity and uncertainty is by developing a set of contrasting, plausible scenarios. Scenario studies provide a structured approach for comparing hypothetical futures and have been used across many areas. For instance, Hubert et al. [12]; and Alexandratos and Bruinsma [13] produced global food scenarios up to the year 2050, exploring the impact of population, GDP, changing diets, and yields on consumption and production of agricultural commodities.

Dinwoodie et al. [14] ran a Delphi study with maritime specialists to gauge expectations of future oil trade, haul lengths, and demand for oil tankers. The results suggest that dramatic policies (such as reductions in oil imports) will be needed if emission reduction commitments are to be met. As the concentration of CO₂ in the atmosphere is a key driver for climate change impacts, carbon budgets are used in Anderson and Bows [50] to establish decadal emission reduction targets for the sector, demonstrating the need for significant (> 85%) decarbonisation by 2050

if shipping is to make a proportional contribution limiting global mean temperature increase to 2 °C. Skeie et al. [15] employed a more common approach, producing transport scenarios based on indicator variables from existing suites of scenarios, in their case the SRES scenarios [16], with the aim of quantifying the future temperature response due to emissions from shipping (and other transport sectors).

Fontagné and Fouré [17] project trade until 2035 using a model of the global economy where in the first instance observed elasticities of trade to income are reproduced. Scenarios are projected based on modifications to the underlying drivers such as national level economic growth, demographics, and trade policies. Whilst there is no explicit carbon budget used to consider the impact of climate change, changes in energy intensity of GDP and other efficiency gains are included. Global trade in goods is projected to grow 1.3–4.3 times by 2035. In a related study, Château et al. [18] adopt a similar method focusing on a longer-term perspective out to 2060, with scenarios reflecting different degrees of trade liberalisation, i.e. regionalisation vs. multilateralism, which are manifested in respective annual increases of 3.6% and 3.8% in global exports, resulting in trade quadrupling by 2050. Sharmina et al. [19] converted future energy demand in global decarbonisation scenarios from the IPCC AR5 database [20] to shipped trade, concluding that fossil fuel trade would decline significantly in a 2 °C world by 2050, and that the decline would unlikely be compensated by an increase in the bioenergy trade.

Building on the work of Fontagné and Fouré [17]; Martinez et al. [21] initially project the value of trade based on identifying future centres of production and consumption, after which commodity specific estimates of value-to-weight ratios, modal share, and estimates of trade route distance are used to express scenarios in terms of global transport work. Seaborne transport work does not vary significantly between scenarios, increasing approximately fivefold by 2050. Included in the scenarios is an estimate of the carbon intensity of transport with emissions associated with seaborne trade anticipated to increase 3–3.75 times the value for 2010 by 2050.

Beyond the academic literature, Lloyd's Register [22] present three contrasting scenarios for 2030 based on the impact of key variables (population, economy, natural resources) on trade. Results are expressed for four main ship types: dry bulk, crude, other wet bulk, and containers. By 2030, trade is anticipated to increase to around 1.15–2.8 times the baseline (2010) value depending on ship type and scenario (cf. Table E.8 of the Appendix). The 3rd IMO GHG study [8] contains scenarios of maritime transport. It uses GDP as an indicator variable for unitised and non-coal dry bulk transport work; and coal and oil consumption as indicator variables for coal and oil transport work, respectively. Fitting a curve to historical data and taking projections of GDP from the shared socio-economic pathways (SSP), and coal and oil consumption from scenarios associated with the representative concentration pathways (RCP), transport work in the four categories is projected out to 2050. Using the same method, updated projections are given in Lee [39], adding cargo categories gas and chemicals, and splitting unitised cargo into containers, and other unitised. Finally, some industry market outlooks provide projections of future sea trade, e.g. Ref. [23]. Table D.7 of the Appendices provides a summary overview of the main references discussed here. Section 3.5 presents a quantitative comparison with the scenarios of study.

1.2. Scenarios of international maritime trade: aims & scope

Scenarios are used as a heuristic tool, requiring they are framed in a manner to capture the aggregated effect of processes and drivers which may act mutually or counteract given the context. While there have been some studies exploring future trade, few have aimed to integrate both qualitative and quantitative methods and regional commodity specific elements to more meaningfully address an inherently complex system, where no single investigative approach is likely to be adequate to address these issues. This is particularly relevant to trade given the

¹ Measured in deadweight units.

complexity of numerous competing agents, reinforcing that scenario results are exploratory alternative futures rather than predictions. This study developed four scenarios of future maritime trade flows over the 2020–2050 period using 2010 as the base year. Each scenario consists of a specific set of future climate change and socio-economic development hypotheses: the scenarios Green Road (GR), and Middle Road 2 °C (MR2C) are characterised by 2 °C of global warming whereas in scenarios High Road (HR), and Middle Road 4 °C (MR4C) average global surface temperature increases by 4 °C by the end of the 21st century. Using Representative Concentration Pathways (RCP) scenarios [24] RCP2.6 (GR and MR2C), and RCP8.5 (MR4C and HR), combined with Shared Socio-economic Pathways (SSP) scenarios [25], SSP1 (GR), SSP2 (MR2C and MR4C), and SSP5 (HR), we lay down the framework for examining of future socio-economic outcomes (see Table C.6 of the Appendices for more detail).

The trade scenarios cover nearly all sea-born traded commodities,² transported by three main vessel types, dry bulk, wet bulk, and containers across 16 geographical regions encompassing nearly all countries of the world (cf. Sections A and B of the Appendices).

In contrast with many existing studies, which apply a single method across most commodities, the need to capture the complexity of having different drivers for key commodities with regional specificities means that no single method or dataset was deemed sufficient in isolation. Therefore, a multidisciplinary approach is adopted for designing, simulating and deriving each future scenario. Due to the complexity of interrelations between transportation capacity, production output and coupled with technological constraints associated with each vessel type, separate methodologies to derive the quantitative elements of the scenarios are applied to three broad categories of goods. Energy commodities are projected using the TIAM UCL model; containerised goods' projections are computed using the correlation between countries' growth rates of trade, GDP and number and weight of containers containing such goods; the balance of tradeable commodities, namely non-energy, non-containerised goods are projected using elasticities obtained from econometric estimations.

This procedure allows us i) to isolate and project trade data by transport mode and commodity type and apply suitable methodologies to overcome apparent constraints, such as inconsistency in data availability and coverage across commodities, regions and time periods ii) tailor our approach to the performance of goods under specific climate change constraints. For example, scenarios requiring the substitution of consumption of crude oil by renewable energy invalidate a simple econometric approach that yields elasticities of traded quantities with respect to production output. Such an approach cannot capture shocks associated with the introduction/substitution of renewable sources of energy in either country, especially when there is no such historical record/analogue. However, a simulated approach using the TIAM-UCL model ensures that the substitution between crude oil and renewable energy consumption does feed into changes to demand for crude oil between two countries. Section 2 describes the methodologies in more detail.

Although our study shares some methodological and structural similarities with the aforementioned body of literature, its novelty is three-fold:

Firstly in the granularity in which trade is projected. Secondly in the implementation of tailor-made methods to quantify trade flows. Both climate change impacts and emission mitigation, could affect regional production potentials for commodities. Thereby, important commodity-region-specific characteristics and productive constraints are incorporated into the scenario analysis. Finally, in the explicit use of an

interdisciplinary methodological framework, including qualitative and quantitative tools of analysis, to capture the problem's inherent complexity.

The overall outcome is a matrix of traded goods for each future decade between regions. This matrix can be disaggregated to matrices at the region, country, commodity, decade levels. We analyse our findings across several of these dimensions in Section 3.

2. Method

This section presents the methodologies, summarised in Fig. 1, by which the scenarios were produced. The main outcome variable, the quantity of each commodity traded by sea, between an origin and destination pair within a year, is derived using three distinct methods applied to non-overlapping groups of commodities.³

The process for each scenario comprises a narrative that establishes a commodity/region specific assumption, which is then integrated into an estimate for global trade. There are three commodity categories each consisting of a number of distinct commodities under the ISIC classification:⁴ Energy commodities, containerised commodities and non-energy, non-containerised commodities.⁵ Energy commodity projections for each scenario are computed using the TIAM-UCL model to adhere to emission budgets and take into account substitution effects between energy carriers.

For non-energy, non-containerised goods, the elasticities of trade with respect to output are obtained from estimations of historical data of trade and regional production of the commodities and are used to future responses of trade following scenario specific adjustments to output. Lastly as historical output data in term of weight for many containerised commodities is unavailable, future container trade is projected based on observing and modifying the trends in derived elasticity of trade and GDP across key trade corridors. In the next section we present in more detail the scenario narratives and pathways, and each of the methodologies.

2.1. Scenario narratives and pathways

Each of the scenarios comprises quantitative elements, based on the underlying SSPs and RCPs, which were articulated within a qualitative narrative. We developed two scenarios consistent with limiting the global temperature increase to 2 °C by 2100 (RCP2.6) and two with a 4 °C limit (RCP8.5). The 2 °C scenarios explore a future where sustainability is important (Green Road) and a future similar to today in terms of governance (Middle Road 2C) framed by SSP1 and SSP2 respectively. Green Road (GR) in particular envisions a future where regionalisation remains a potent force. Similarly contrasting futures are explored in the 4 °C scenarios, High Road and Middle Road 4C, where High Road presents a high-tech world dominated by fossil fuels (SSP5) amid expanding processes of globalisation and increased economic convergence amongst regions and Middle Road 4C (SSP2) again explores how governance priorities and values similar to today's impact upon trade.⁶ Participatory approaches are valued for empowering stakeholders and ensuring scenarios are relevant to their needs, as well as enabling the inclusion a wide range of expert knowledge [26]; [27–29]. Thus, workshops were used to elicit expert input from industrial,⁷ academic,

³ Table 4 of the Appendix presents all commodity groups and a summary of estimation methods applied to them.

⁴ International Standard Industrial Classification of All Economic Activities.

⁵ Table 4 of the Appendix contains the breakdown of ISIC commodities per broad commodity category.

⁶ See O'Neill et al. [25]; Section 1.2, and Section C of the Appendix for more details.

⁷ The term “Industrial” in this case refers to companies that are directly involved in maritime sector or closely involved in production of materials for whom maritime trade is essential, such as energy commodities.

² We do not study the categories “Manufacture of tobacco products” and “Mining of uranium and thorium ores” due to data paucity. We do not expect any non-negligible effects in world maritime trade from omission of these commodities.

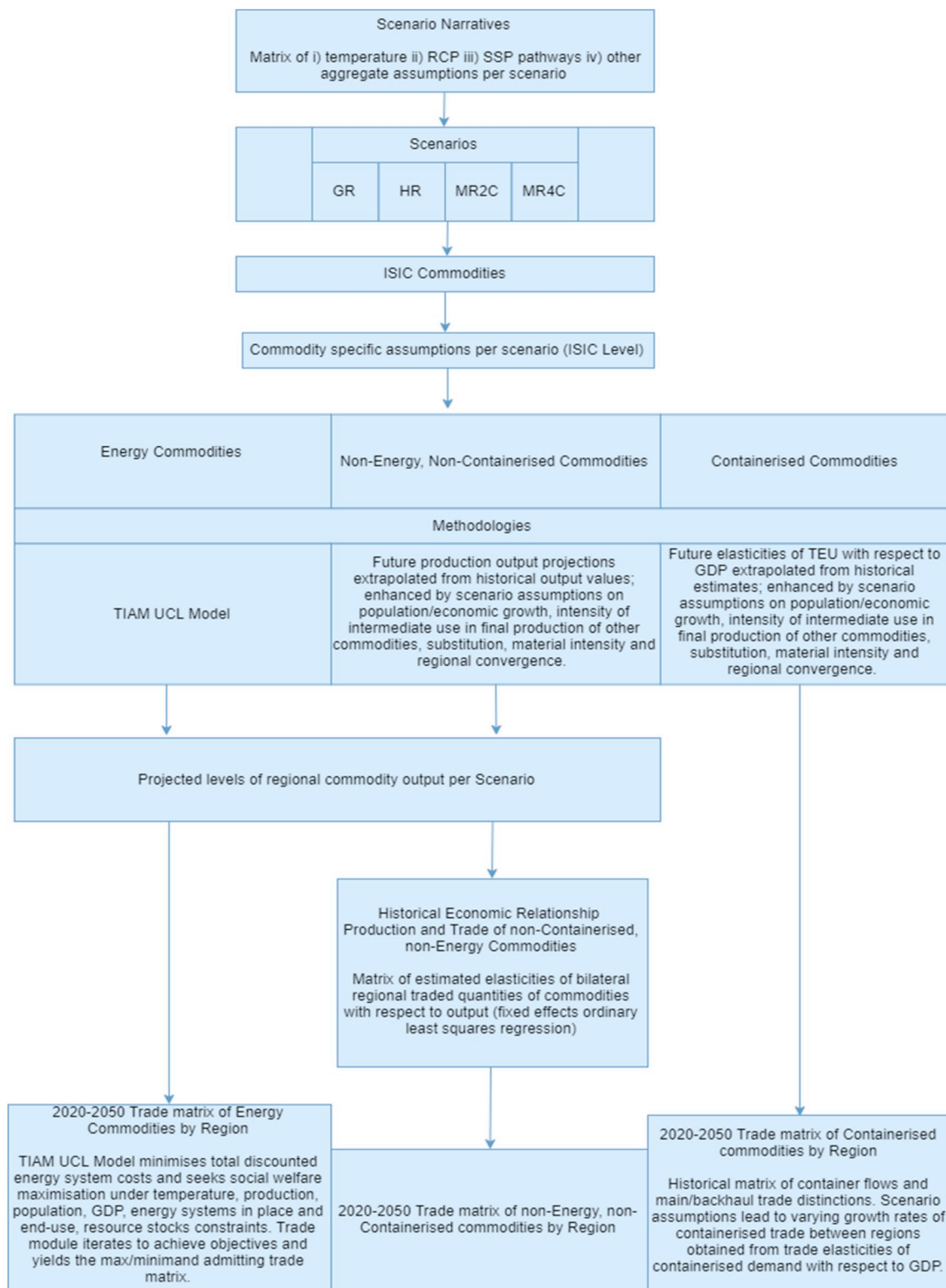


Fig. 1. Method flowchart.

and non-governmental stakeholders, and helped define the narrative of each scenario. Stakeholders were chosen to reflect a diverse range of opinion, knowledge of the maritime sector, as well as specific commodity, region or and trade. Section E in the appendices summarises the main stakeholder, distinguishing those who provided specific data sources. In that regard stakeholders play three primary roles, that of advice and review on the framing and generation of the scenarios, a

broader steering capacity (e.g. beyond just trade scenarios), direct provision of datasets.

For example, the experts' input informed the choice of climate constraints, the appropriate SSP/RCP alignment, and the most relevant SSP sub-elements for trade. The draft trade scenario narratives were further subjected to a process of stakeholder validation and review, to ensure that they meet the criteria of relevance, plausibility, consistency,

Table 1
Summary of exemplar linkages between climate change and trade.

Climate Measure and Scenario	Commodity	Bounding Conditions	Response by 2050.
Mitigation of emissions in order to minimise global temperature increase to 2 °C by 2100. (GR Scenario).	Coal.	Domestic production reduced in order to maintain global CO ₂ concentrations consistent with defined climate thresholds and emission budgets. Established limits on allowable consumption of fossil fuels and scale of negative emissions necessary.	By 2050 97% reduction (vs 2010) in use of coal within electricity generation. 88% reduction in trade following 80% reduction in production (in energy terms) and changes in centres of demand and supply. (e.g. 90% reduction in coal exports from Australia).
	Biomass and Bio-energy crops.	Satisfaction of consumptive energy demand for domestic heating, transport, industry etc. Trade estimated by balancing supply and demand in the most cost effective manner.	By 2050 a 6-fold increase in production (in energy terms vs 2050) following displacement of coal, emergence of new trading routes especially African exports post 2030 based on efficient expansion of under-utilised land.
Mitigation of emissions in order to minimise global temperature increase to 4 °C by 2100 with low adaptive capacity. (MR4C Scenario) and response to climate change impacts.	Net primary production of crops and livestock products (excluding Biomass).	Regional temperature increase by 2050 consistent with 4 °C scenario (approximately 2–3 °C increase relative to 1985–2005 reference by 2050). Domestic production consistent to meet basic human requirements. Trade estimated by balancing supply and demand in the most cost-effective manner.	Output by 2050 10% higher than to 2010 levels (excluding biomass). Significant reduction in output from regions such as Middle East as yields decrease by > 50% based on the regional temperature increase and high sensitivity of agriculture due to low adaptive capacity. Moderate (+10%) increase in production from regions currently seen as future centres of production such as Africa. Increasing dependence on production in regions such as Canada and former USSR due to expansion of productive areas. Global average per capita food (primary crop and livestock equivalents) at 2010 levels. Global trade in 2050 (including biomass) increases by 70% in response to regional shortfalls in production.
Mitigation of emissions in order to minimise global temperature increase to 2 °C by 2100. (GR Scenario).	Iron Ore.	Global energy mix necessary to maintain global CO ₂ concentrations consistent with defined climate thresholds. Informs the energy consumption allowable for the steel sector by region and by fuel type. Satisfaction of demand for domestic steel products. Trade estimated based on the elasticity of output with exports.	The reduction of the coal use in the manufacturing of steel is based on an increase in the use of electric arc furnaces displacing traditional integrated steel works. This reflects an increase in steel recycling and a reduced demand for primary ore. By 2050 domestic production decreases by approximately 40% but trade decreases by a lesser margin (approximately 10%) as imports must compensate for a depletion of Chinese domestic ore reserves.

creativity, and consistency e.g. whether (or should) related sectors respond in a similar way to climate framing? [30]. The main scenario characteristics stemming from each narrative are summarised in Table 1. Table 6 of the Appendix. The projection of seaborne trade of energy commodities is described in the following section.

2.2. Trade of energy commodities

Projections of trade flows for these commodities are constructed using the TIAM-UCL global energy system model.⁸ Whilst the optimisation provides useful insights, it is also a limitation of the approach, which will be biased towards future technological solutions over short-term demand-side change [31]. The model can be constrained to a certain average global surface temperature rise using its climate module. Some of the quantitative and qualitative elements are direct inputs, including variables such as GDP, population, energy systems in place, land availability for bioenergy feedstock production etc. Such process necessitates assumptions on the point at which key technologies, such as Carbon Capture and Storage (CCS) becomes viably scalable. In GR, bio-energy land is limited to, in units of primary energy production per year, 350 EJ. In MR2C, a tighter limit of 130 EJ is set (in line with SSP narratives). For MR4C and HR, characterised by low levels of mitigation, land availability limits do not become relevant. The

resulting energy trade flows are converted from energy units into tonnes, yielding the projections of inter-regional trade in energy commodities in each of the four scenarios. The inputs to the TIAM-UCL model are summarised in Table 6 of the Appendix. The output of the TIAM-UCL simulations for each scenario is a bilateral matrix of regional trade flows of energy commodities expressed in common weight units or volume, which admit global social welfare maximisation and minimisation of the total discounted energy system costs in each time step.

2.3. Trade of non-energy commodities

This section summarises the approach for deriving scenario trade projections for all commodities not classified as Energy commodities. Section 2.3.1 and 2.3.2 describe the method for projecting trade of non-energy non-containerised commodities using econometric estimation. Section 2.3.3 describes the method for generation of containerised commodity projections.

2.3.1. Historic trends in output and future projections

For each non-energy commodity, the historical (1970/80–2010) output by region measured in tonnes by extracting national level data expressed in the International Standard Industrial Classification of All Economic Activities (ISIC) classification and aggregating to the regional level. Details of production estimates by commodity are summarised in Table 7 of the Appendix, along with data sources.

We develop regional production models for each commodity to project future production in tonnes for the period 2020–2050, consistent with trends in historical data. In addition, for each commodity output projection is framed by the SSPs, RCPs, and stakeholder-

⁸ TIAM-UCL is a linear programming cost optimisation model, which minimises total discounted energy system costs and maximises social welfare (Anandarajah [44]; Anandarajah et al. [45]; Price and Keppo [46], and Raucci, [47].

informed scenario narratives; and is constrained by regional limits to production, such as reserves. For example, ISIC 5 -fisheries- projects future production based on trends in global population and per capita fish consumption. A key feature in incorporating commodity specific elements is ensuring projections of dependent commodities are not independent of each other, but models for individual commodities are interlinked to ensure internal consistency within each scenario. For example, the quantity of metal ore (ISIC 13) produced depends on the amount of steel output by production technology (ISIC 27). The latter is linked to the energy consumed by energy carrier and region, by the iron and steel sector, which itself is an output of the energy scenarios from the TIAM-UCL model. Fossil fuels that are discrete commodity categories in their own right, such as ISIC 10 referring to coal and lignite, are excluded from the table as they are exclusively projected within TIAM-UCL.

2.3.2. Econometric analysis of non-energy, non-containerised commodities

Quantities of traded commodities, irrespective of mode of transport are taken from the UN Comtrade database for the period 2000–2010 [32], subsequently translated into estimates of seaborne trade based on the percentage that is transported by sea.⁹ For each commodity, the historical values of bilateral trade and production by commodity and region form the inputs to the econometric assessments of the elasticity of trade with respect to output and are used for the final extrapolation up to 2050 using the starting values contained in the baseline dataset. We estimate the elasticity of export supply with respect to output using panel data fixed effects estimation for each exporting region and ISIC category. We control for variation across destination and underlying sectors comprising each ISIC category and exploit time variation. Where estimates could not be obtained due to data paucity or were insignificant, we imputed them with a region or ISIC category average. The mean elasticity of export supply with respect to output across all regions and ISIC categories stands at 1.73 with a standard deviation of 0.69. Utilising the elasticity of export supply and the future projection of production output described in 2.3.1, we obtain predicted exports of each specific region to the rest of the world per year and ISIC commodity. Region to region trade is then calculated using the ratios of bilateral regional to rest of the world exports of the 2010 baseline year.

2.3.3. Containerised commodities

For manufactured commodities that are likely to be shipped in containers, the techniques applied in sections 2.3.1 and 2.3.2 were not viable as it was not possible to generate robust estimates of historic production quantity by region –historical output data, if at all, are available in numbers of products, but not in weight. Therefore a separate approach was developed which treats container trade as a discrete commodity:

Future projections of Twenty-foot Equivalent Units (TEU) trade flows are, in the first instance, produced from a dataset, provided by MSI containing TEU flows along defined corridors such as Inter-Asia, Asia to Europe etc., between 1995 and 2013 [33]. These data distinguish direction and whether the routes reflect main or backhaul trade.

Employing a) country level GDP data associated with each country along the trade corridor, expressed in 2005 international dollars for consistency with the SSPs [34], and b) the container trade in TEU along designated corridors such as Asia to Europe, the historic trend in the

year on year elasticity of the importing region's trade in TEU and GDP from 1999 to 2010 ($\Delta \text{TEU}/\Delta \text{GDP}$) is obtained. This provides an account of both the baseline (2010) multiplier of trade and GDP growth as well as an indication of the direction of regional trends.

Starting from the calculated elasticities, for each trade corridor, trade elasticities ($\Delta \text{TEU}/\Delta \text{GDP}$) are projected over the period to 2050, in a scenario-building process aiming to reflect the qualitative scenario elements (cf. Table 6 of the Appendix). For example, as a reduced material intensity and regionalisation are manifest features of SSP1, the GR scenario container trade within key regions (e.g. intra-Asia or inter-Latin America) is projected to grow at a faster rate than more established routes. Alternatively, as HR projects increased material intensity and increased regional convergence this scenario projects a decrease in the disparity of trade across established main haul and backhaul routes.

Future trade in TEU along each trade corridor is calculated from GDP projections of importing regions (as per the underlying SSP scenario and the countries that comprise the regional groupings), and from the projected elasticity for this trade corridor, including when it reaches parity and/or < 1 (i.e. trade stagnates). The steps above project trade across trade corridors not in terms of the 16 study regions used for other commodities. Therefore, using both the baseline (2010) trade data supplied by both NEA and MSI as well as the individual countries that comprise the regional groupings used in *both* datasets, container trade across the NEA corridors is mapped to trade across the regional groupings used elsewhere, which is retained for future trade. See Section E of the appendices.

2.4. Mapping commodities to ship types

A final step assigns commodities to ship types, preventing the existence of excess trade which is constrained by the global fleet availability and capacity in each time step. By doing so (e.g. using baseline trade data to remove the containerised portion of each projected commodity) we also ensure that double counting of future trade between the methods described in Sections 2.3.1 and 2.3.3 is prevented.

Collating the results from the three methods of projecting trade flows, we obtain a matrix of quantities traded between regions, for specific commodities expressed either at the ISIC or NST/R levels (cf. Section B of the Appendix). For validation and with a view to providing insight of greatest relevance to the shipping sector, trade in each commodity is also expressed in the 3 main ship types - dry bulk, wet bulk, and containers, such that the total weight per ship type in 2010 is consistent with the ship specific totals reported for year 2010 in Ref. [35].

In this way, we confirm whether the calculated 2010 quantity transported for each ship type, is neither over nor under-estimated relative to the actual quantity transported per ship type. The evolution of transport demand per ship type allows for comparison with other works, as further discussed in Section 3.5.

3. Results and discussion

The projection of shipping demand reflects efforts to mitigate emissions as well as varying degrees of adaptation and responses to climate impacts. The effects of climate change will manifest directly in the emergence of new patterns of commodity trades or more indirectly in the distribution of centres of production. Different commodities will embody specific responses to these pressures, whilst also by necessity, reflecting a response to distinct consumptive demand. Table 1 summarises some of the most visible processes whereby the diverse effects of climate change ultimately manifest in significant changes in output and trade for specific commodities. Table D6 in the appendices provides additional information by commodity. These points will be discussed in the following sections.

The remainder of the section presents the four trade scenarios. First, growth in total maritime trade is discussed and compared with the

⁹ Unless specifically stated otherwise, this paper analyses commodities using the ISIC classification to facilitate the exposition of results. The conversion from HS into ISIC takes place using the intermediate step of converting to the NST/R classification. This operation ensures that UN Comtrade data is commonly expressed in these taxonomies and no information is lost in the process. Supporting documentation for the match is available at the index of Correspondence tables, RAMON, Eurostat, and Muendler, M.-A [48]. 'Converter from SITC to ISIC', University of California-San Diego, unpublished mimeo.

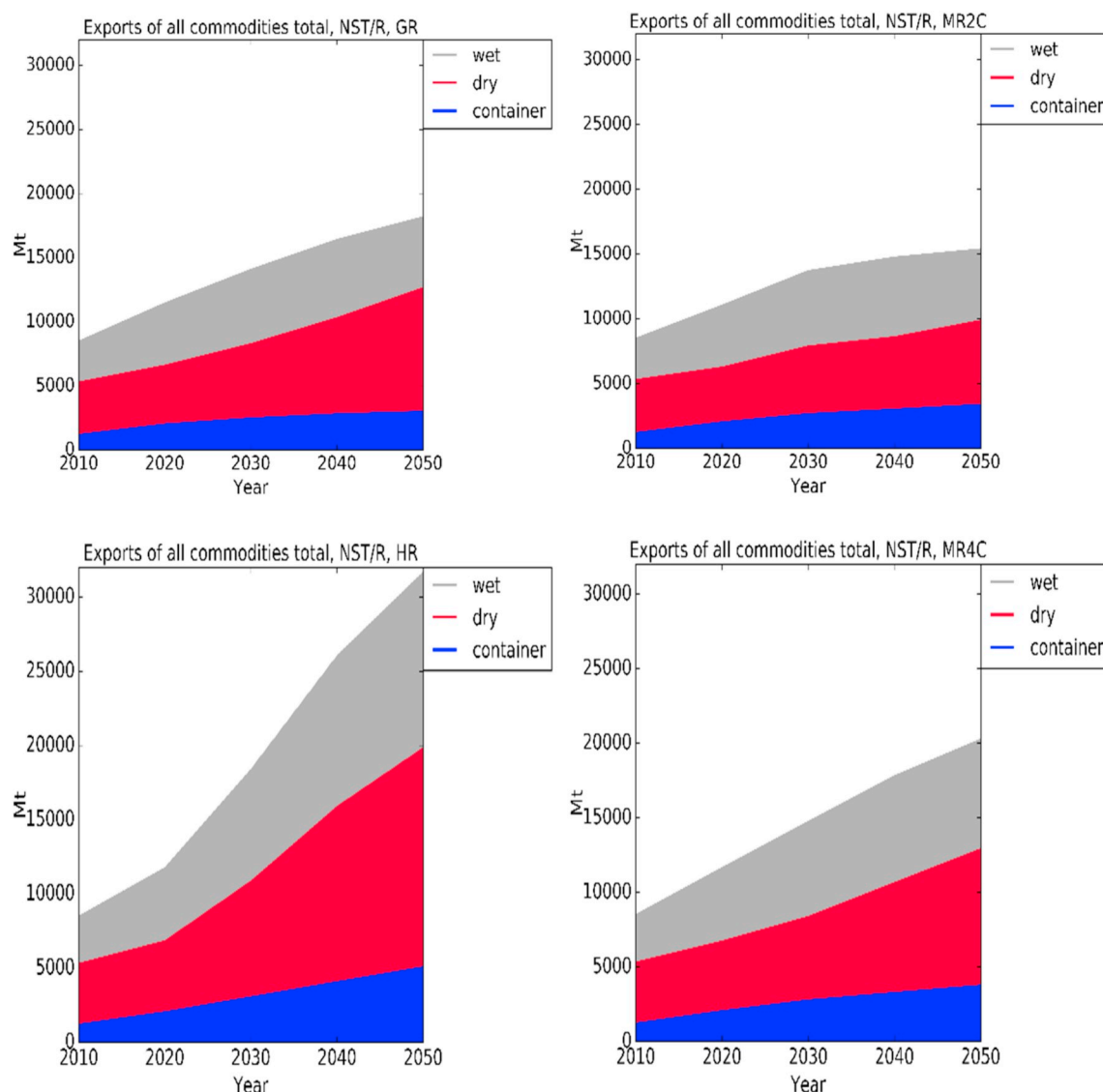


Fig. 2. World sea trade according to the four scenarios.

extant literature. Next, results are analysed for each of the broad category commodities: energy commodities, containers, and non-energy bulk. Aggregate results are compared against the extant literature. Finally, future trade in biomass, agricultural produce, and iron ore is discussed in more detail, as salient examples of how different climate change mitigation, adaptation, and impacts may affect trade in specific commodities, at the regional level.

3.1. Future development of world trade

Fig. 2 shows world trade, in terms of tonnes loaded, as the sum of the three modes of maritime transport – container, dry, and wet – where each panel represents one of the four scenarios. All scenarios show continuous and substantial growth for world trade. However, rates of growth vary between scenarios.

Trade in 2050 in the GR scenario is twice that in 2010. Characterised by low material intensity, the GR scenario foresees growth slowing down for containerised trade and, similarly, for wet bulk trade, which decreases over the decade 2040–2050. Spurred by trade in bioenergy commodities, growth in the dry bulk sector increases over the entire period 2010–2050.

The HR scenario exhibits the highest rates of growth in total trade, which quadruples over the period 2010–2050. This is the outcome of

unfettered growth in demand for oil and gas, ore, and coal, with no step changes in the generation mix. In 2050, the container and dry bulk fleets carry approximately 33% more tonnage relative to the GR scenario – but with a very different mix of dry bulk commodities (cf. Section 3.2). Wet bulk trade also quadruples in HR, resulting in twice the respective level seen in GR in 2050. Among the scenarios, HR experiences the highest growth in GDP. In addition, the absence of strong climate mitigation allows expansion of material intensive industries such as vehicle manufacturing, with associated growth in related sectors like mining and steel production.

Finally, the two MR scenarios exhibit modest growth rates leading to just below (MR2C) or above (MR4C) double the 2010 amount in 2050. In terms of total trade, MR2C follows a similar trajectory as MR4C until 2030. From 2030 onwards, however, the different climate change futures represented by MR2C and MR4C, respectively, are reflected in differing rates of growth in world trade. In the latter, the total quantity of production follows an approximately linear trend out to 2050.

An additional consideration is the impact of changes of trade on the composition of the fleet and therefore is of interest to ship-owners as well as producers and consumers. Especially given the long-life cycle of maritime vessels and the time lag between market signal and eventual vessel deployment. This is relevant to commodities which grow quickly

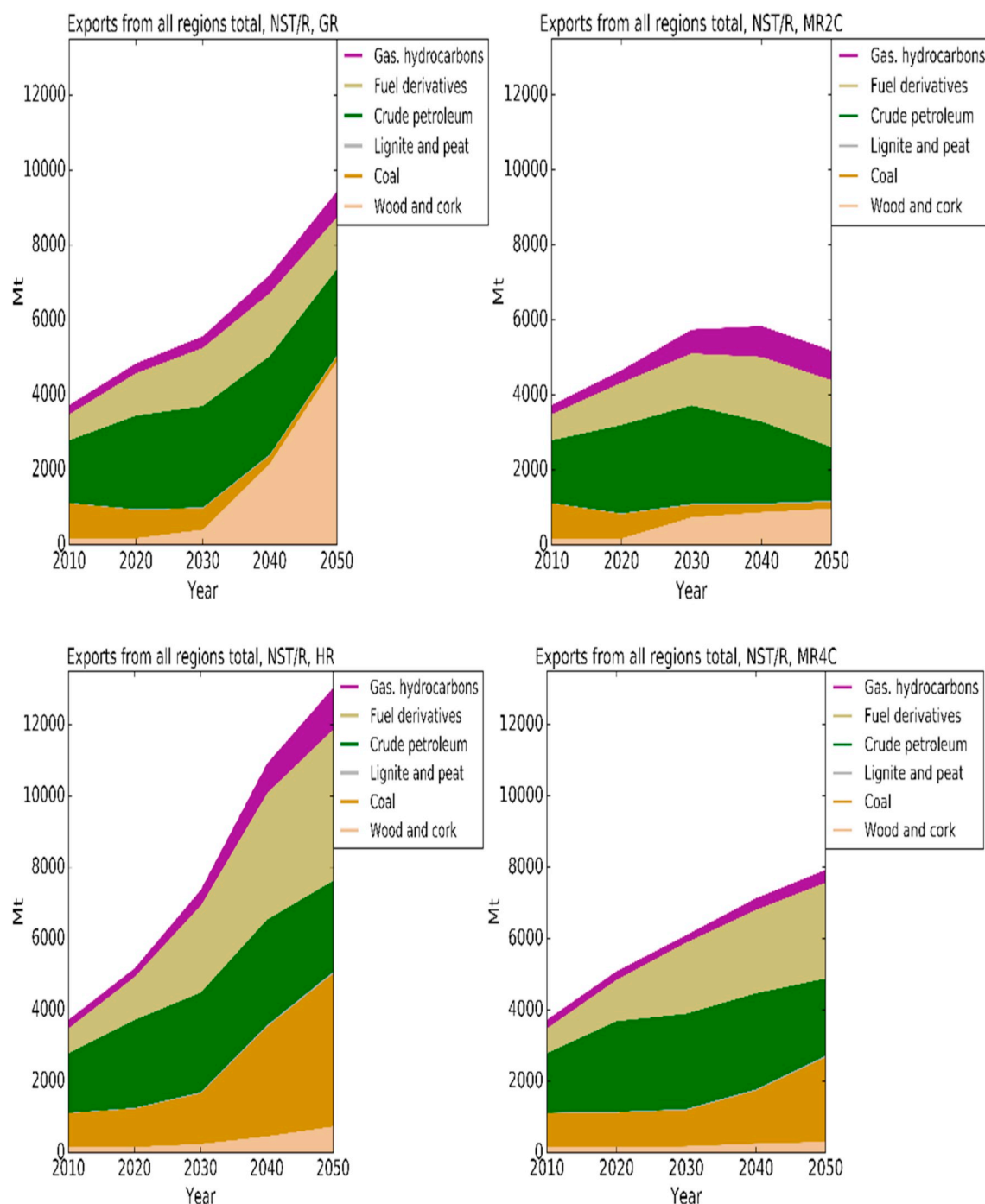


Fig. 3. Global trade in energy commodities in the four scenarios.

beyond a certain point in time (such as biomass in HR) or decline after a period of growth (as seen for crude oil in MR2C). Another consideration (beyond the scope of this work) is the potential emergence of novel trades such as bulk transport of potable water.

3.2. Trade in energy commodities

The highest trade in energy commodities is projected in HR, followed by the GR scenario and with MR4C projecting greater growth than MR2C (See Fig. 3). Trade in biomass is significant in the GR scenario increasing from 12 Mt to over 4 Gt by 2050, associated with near total uptake of bioenergy with carbon capture and storage (BECCS) within the electricity sector, underpinned by output from those regions

with greatest capacity for land expansion, Africa and South America foremost.

In contrast, the HR scenario sees no major step changes in the energy sector, with continued use of coal for electricity generation. By 2050 the quantity of electricity generated increases threefold, with approximately half of the total generated through coal combustion. Consequently, the quantity of coal traded between 2010 and 2050 increases fourfold.

In comparison to other scenarios MR2C demonstrates a much more modest (+30%) increase in the trade of energy commodities. Whilst there are similarities to the GR scenario (coal is displaced in the electricity generation mix), a lower increase in traded biomass is observed as BECCS is not as prominent (cf. Table C.6 in the Appendices). In

contrast, this scenario projects large growth in nuclear energy which by 2050 contributes approximately 50% of the electricity generation mix, following growth in Chinese, US, and Western European nuclear capacity. MR4C shares commonalities with the HR scenario, with an increase in coal, both with and without CCS. A 147% increase in coal trade is mainly attributable to a growth in absolute electricity demand rather than growth in the proportion of coal in the generation mix.

All scenarios project an increase in refined oil trade by 2050; this increase is most pronounced for HR, whereby the quantity of refined oil shipped grows six-fold by 2050. This is attributable to a proportional increase in road vehicle kilometres associated with economic growth particularly in regions including China and other developed Asia, where the refined energy demands of the car and commercial vehicle sector increases ten-fold by 2050. This rise is only facilitated under a strict carbon budget if net negative emissions through BECCS materialise at a large scale. Similar pressures manifest in the Middle Road scenarios but in MR2C increased electrification of transport contributes to a continued reduction in crude oil trade and a peak in refined oil trade in 2040, sufficient to reduce total energy trade after 2035. However, in absolute terms, an increase in refined petroleum trade is observed due to concentration of demand in regions which do not exhibit a commensurate increase in domestic production. Specifically, by 2050 China accounts for 67% of road diesel and gasoline demand and 62% of refined oil imports. This is in contrast to decarbonisation of the Chinese (and global) electricity sector, reinforcing that for large economies, decarbonising distinct sectors at different rates can affect patterns of global trade. It is this nexus of locational and technological elements which reinforces that decarbonisation may not necessarily manifest a reduction in trade. Indeed, all scenarios project increased trade of liquid LNG. What drives this growth is different in each scenario with the HR scenario projecting increased demand due to growing electricity consumption along with increased export capacity in the Middle East and Russia. The GR scenario foresees growth in its use in the transport sector, specifically the light commercial vehicle sector.

3.2.1. Biomass trade

Holding the global temperature increase to below 2 °C requires drastic cuts to greenhouse gas emissions, which in turn implies fundamental changes to the global consumption of energy commodities. By weight, energy commodities make up about 40% of world seaborne trade [5].

The role of bioenergy is one of the most salient differences between the 2 °C and 4 °C scenarios, and in between the two 2 °C scenarios. In the climate change literature, most scenarios characterised by successful climate change mitigation rely heavily on the deployment of BECCS at extremely ambitious rates [31,36]. In GR, BECCS constitutes 42% of global electricity generation, comparable to total electricity generation in 2010. It is this very high, arguably implausible amount of BECCS assumed in many integrated assessment modelling studies, that allows continued growth in other energy commodities, such as refined oil products for transport. As such, this raises important questions regarding underpinning assumptions within integrated assessment models.

The availability of land suitable for the production of bioenergy commodities is one (of many) crucial criteria that will determine the role bioenergy can play in decarbonising the world's energy supply. In the scenarios presented here, it is also the key parameter differentiating the role of bioenergy between GR and MR2C, the two climate change mitigation scenarios (cf. Section 2.2). Similar to coal, and oil, there is a distinct geography of bioenergy production and trade, with the latter illustrated in Fig. 4.

In GR, biomass exports are dominated by Africa, and Central and South America. In the MR2C scenario, Africa is also the top exporter, with the remainder more evenly distributed among the other regions. More importantly, total African exports in GR are five times higher than in MR2C, by 2050. In HR and MR4C, bioenergy plays only a minor role, by comparison.

In summary, within just a few decades, the climate change mitigation scenarios foresee a trade in bioenergy commodities springing up and reaching one to five billion tonnes by 2050. For the shipping sector, this increase holds a sizable opportunity, albeit an uncertain one given the wide range across the scenarios and unproven scalability of this technology.

3.3. Trade in containerised non-energy commodities

Container trade is found to grow across all four scenarios (See Fig. 5). At an aggregated level GR demonstrates relative decoupling of GDP with growth by 2040, due to a reduction in material intensity, through circular economy principles. With regionalisation a key element of the GR scenario, trade in highly manufactured goods between Asia and Europe, and on other established trade routes stagnates as markets mature by 2030. Most of the growth takes place in intra-regional trade.

In contrast, container trade in the HR scenario grows at rates comparable to GDP growth. This reflects growth across both developing and developed markets, as GDP remains materially intensive amid a globalised economy. Within this context, one of the most important drivers is convergence of economies between consumers and producers with back-haul across mainline trades (i.e. the return leg from export markets) increasing rapidly to reach parity in absolute terms by 2050. In that regard no one region dominates growth in trade.

Both MR scenarios are placed in the middle ground between the GR and HR scenarios, in a world with barriers to trade in place. In these scenarios trade along many emergent routes continues to grow but levels off by the 2040s. At this stage, interregional trade remains static but remains a significant contributor by 2050. The main distinguishing element between both scenarios is the point at which growth in established mainline trade levels off, prior to 2040 in MR2C, post 2040 in MR4C.

3.4. Trade in non-containerised, non-energy commodities

Non-energy commodities carried in bulk show comparable growth rates until 2020 and diverge afterwards. The growth rates of maritime trade for each scenario follow directly from the mean growth rates of production of non-containerised, non-energy goods.

The HR scenario sees a growth factor of 3.5 between 2010 and 2050 which is positively correlated with GDP growing by a factor of about 4. This pronounced trade growth originates from increased demand. The MR4C scenario experiences near-linear growth, doubling between 2010 and 2050. The GR scenario experiences the same growth as MR4C until 2030, then growth slows and, from 2040, trade decreases, mainly due to the decline of iron ore production and exports from Central and South America, and Australia.

The MR2C scenarios grow continuously, but slowly, with trade in non-energy, non-containerised cargoes just above the GR scenario in 2050.

3.4.1. Trade in agricultural commodities (excluding biomass)

Trade is projected based on the agricultural production through modifications to regional trends in land use/availability, yield and relationship between crop and livestock output, such that global demand, aggregated from regional per capita demand is satisfied.¹⁰ Non-energy agricultural commodities, mainly food and animal feed, will be affected by climate change impacts, most directly through impacts on growing conditions and other socio-economic drivers. Within the suite of scenarios, GR faces the fewest climate change impacts, and the lowest population growth (cf. Section C of Appendix). Besides population growth, the per capita demand for grain and other food commodities is

¹⁰ See Tables 5 and 6 of the Appendix.

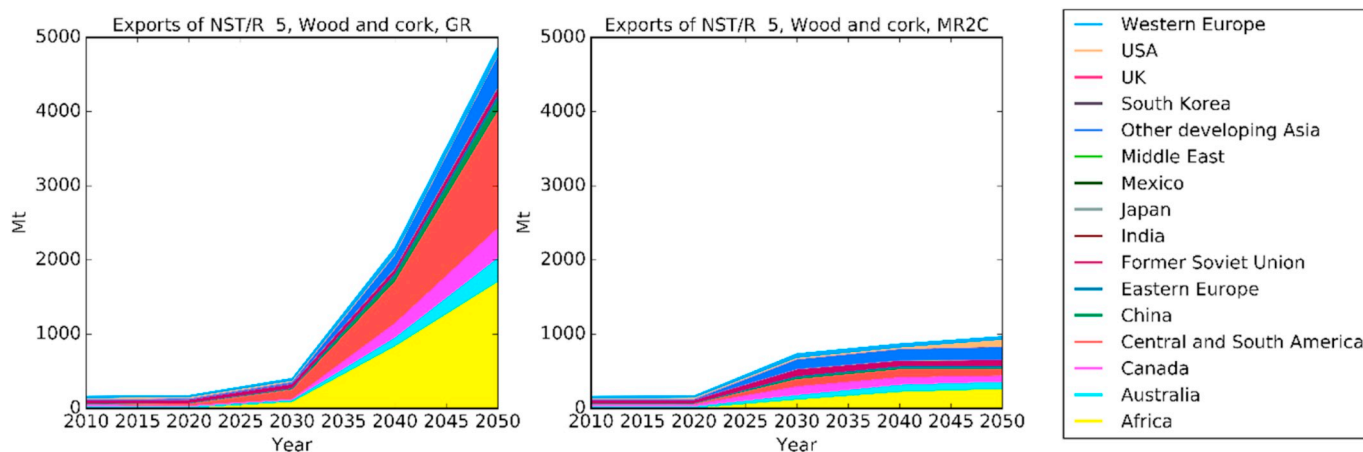


Fig. 4. Trade in category wood and cork, which includes bioenergy commodities in scenarios GR (left) and MR2C (right).

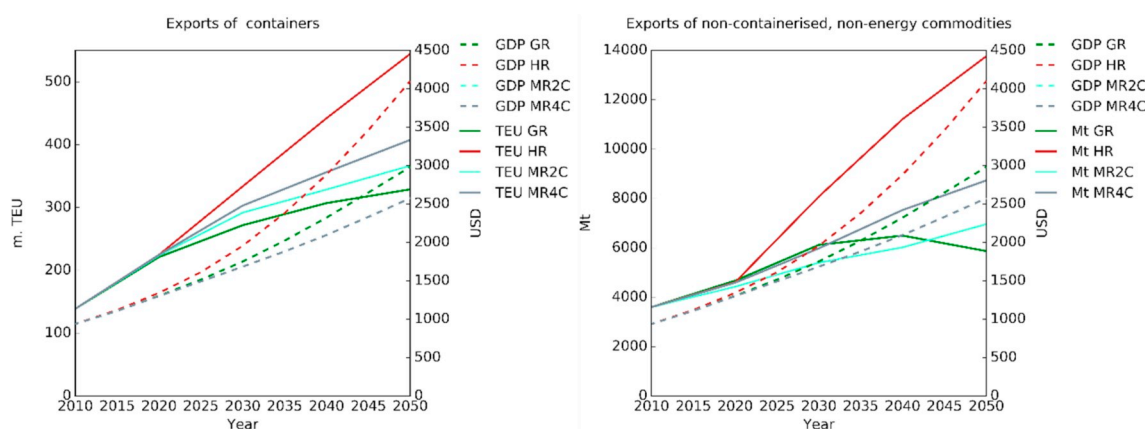


Fig. 5. Global container trade (left) and trade in non-containerised, non-energy commodities (right) in the four different scenarios, presented beside GDP (in 2005 intl. USD) in the underlying SSP scenarios.

a key driver, and a main parameter for this driver is meat consumption. Since the latter is also comparatively low in GR, this is the scenario with the lowest levels of trade in food commodities.

The MR scenarios face difficulties in adaptation (cf. Section C of the Appendix), as well as the highest growth in population. In MR2C, regions with large land availability that will benefit from higher temperatures¹¹ increase their production and exports, with a corresponding growth in world trade. In comparison to MR2C, the MR4C scenario, faces far more severe impacts on agricultural production seeing lower global production and lower trade (with the latter declining in absolute terms between 2040 and 2050).

Finally, HR is characterised by successful adaptation measures and although population grows more slowly than in the MR scenarios there is higher meat consumption. Taken together, this leads to the highest levels of both production and trade, although the extent to which effective adaptation can be maintained beyond the temporal setting of this exercise.

3.4.2. Iron ore trade

Iron ore trade has significant variation across the range of scenarios. Beside the underlying demand for steel there are two main drivers. The first is the underlying assumption on the share of steel recycled in electric arc furnaces, demonstrating a linkage between decarbonisation and trade of non-energy commodities (i.e. iron ore). As a consequence, ore

production by mid-century increases in the 4 °C scenarios, by 77% compared to the 2010 baseline in HR, and by 30% in MR4C; conversely, in the 2 °C scenarios production reduces, by 34% in MR2C, and by 41% in GR.

The second is the geographical pattern of production and, in turn, trade: relatively few countries or regions dominate the production of iron ore – Australia, Central and South America, and China foremost. Iron ore mining in China expanded rapidly during the first decade of the 21st century [37]. Further expansion, coupled with slowing demand growth, could squeeze other producers, and it might also bring China close to depleting its resources, as seen in HR, leading to drastic swings in the global pattern of trade. In contrast, the pattern of iron ore trade evolves more smoothly in the other scenarios, with one exception: the appearance of Africa as a major exporter by 2050. Although the inherent uncertainty associated with all scenario exercises bears reminding, indeed the recent imposition by the US administration of tariffs on steel and aluminium imports, has been viewed by key exporting nations as adding further instability to the market [38].

3.5. Comparison with the literature

Fig. 6 portrays the evolution of the projected trade flows according to the four scenarios vis-à-vis historical trade flows expressed in millions of tonnes loaded. Historical flows come from UNCTAD [35]¹² and

¹¹ With Russia the stand-out example, although there is uncertainty on the suitability of land for cultivation in the areas that will likely improve under climate change.

¹² Historical totals are the aggregates of the categories: “main bulks”, “other dry cargo”, “containers” and “oil and gas” according to the classification of UNCTAD [35]; p. 5).

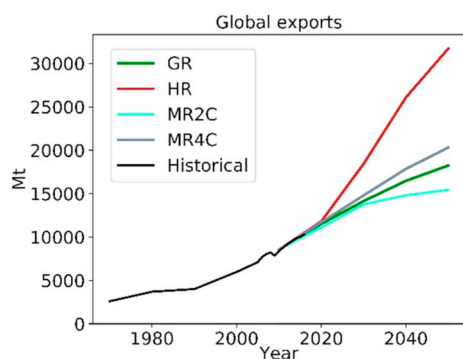


Fig. 6. Comparison of trade projection volumes with historical volumes.

span 1970–2015 while the projected totals are aggregated across the three ship types considered in our scenarios and cover the 2010–2050 period. During the transition period 2010–2020 no marked deviation between realised volumes of trade flows with the projected volumes under the scenarios are observed. Growth rates of the three scenarios approximately average 21% (GR), 39% (HR), 16% (MR2C), 24% (MR4C) per decade. Of the four scenarios only the HR case produces a growth rate comparable to historical growth rates. These ranged from approximately 40%–50% per decade with the exception of the 1980's slowdown. Growth rates in the HR scenarios are about the same for all three cargo types considered, containers, wet, and dry, leading to a less conservative projection, which is, however, placed at the lower bound of the extant literature.

Fig. 7 illustrates this by comparing the scenarios with selected references from the literature (cf. Section 1.1), for world container trade in tonnes loaded. This commodity is chosen as it has in previous decades demonstrated periods of high trade growth, therefore projections of total trade are sensitive to assumptions on how the global container market will evolve in the future. As the Third IMO GHG Study [8] and its update [39] only project transport work, in tonne-miles, this is used as a proxy for trade in tonnes loaded, to allow comparison with this study. Historical data indicate this assumption is reasonable [5].

A striking result of this scenario exercise is that the plausible range of the volume of future trade in 2030 and 2050 is lower than the scenarios in the Third IMO GHG Study [8], and its update [39]. This result is an illustration of focusing on granularity, which aims to address complexity and is much more strongly driven by climate mitigation coupled with impacts, than others that have gone before. For instance, the Third IMO GHG Study uses future GDP (according to the SSP scenarios) as an indicator variable for container trade, fitting a curve to historical data (cf. Sections 1.1 and E of the Appendix). That the difference in methodologies produces such distinctive results is in itself instructive, in terms of the implied deviation in the rates of change and the absolute levels of trade from more recent trends. Furthermore, the update of the scenarios in the original IMO study brings the projections closer towards the scenarios of this study, reflecting a more challenging economic environment whereby the processes that drive globalisation, such as industrial expansion in emerging regions is seen to peak amid eventual saturation of consumer demand. Similarly, more recent industry outlooks have aligned with lower projections, as exemplified by Ref. [23]. While other lines of evidence [40,41] also support lower growth expectations whereby the drivers for globalisation do not persist, we re-emphasise that the scenarios do not constitute forecasts but rather explore plausible future developments under climate constraints.

In the Third IMO GHG Study, both coal and oil trade reduce

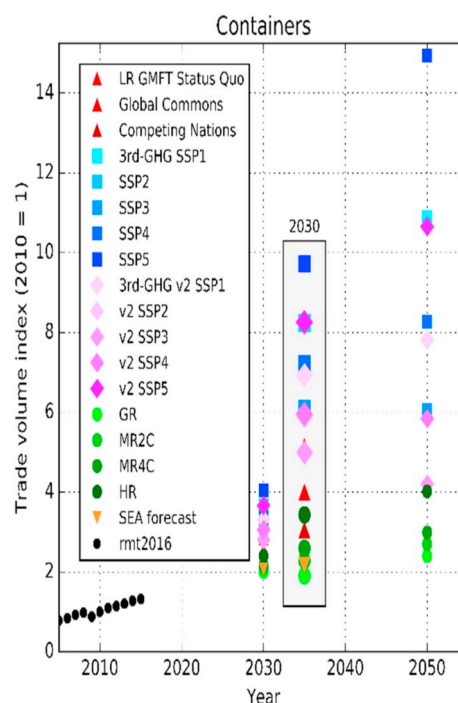


Fig. 7. Comparison of container trade projections with the literature.

significantly under the RCP 2.6 scenario. Due to differing assumptions on negative emissions technologies, as well as the availability and cost of the variety of energy sources in the underlying integrated assessment models, this stands in contrast with both the GR and MR2C scenarios. Both foresee a near-total drop in coal trade by mid-21st century while reliance on oil is far more persistent, with trade in crude and fuel derivatives peaking in 2030. Trade in bio-energy (cf. Section 3.2.1) shows the biggest variation across the scenarios, highlighting a potentially crucial element of the world's future energy mix and, by implication, the future basket of shipped commodities, which is omitted altogether in the IMO Studies. Beyond total headline numbers, the suite of scenarios covers a level of detail, in terms of commodities and geographical resolution, which goes beyond the existing literature.

3.6. Uncertainty

All scenarios and models entail an inherent degree of uncertainty, given their projective rather than predictive role. Refsgaard et al. [42] distinguish between lacking awareness of imperfect knowledge and possessing awareness of the limits the reliability of knowledge. Studies such as Walker et al. [43] categorise different sources of uncertainty depending on where they manifest within the scenarios/modelling process, such as input or framing uncertainty. Particularly given the presence of different methods and components, it is difficult to unequivocally state whether a scenario projection is 'right' or 'wrong', however individual elements may be deemed as representing unfeasible versions of the future. Whilst uncertainty is unavoidable, the scenario process described in this study incorporated a number of steps to mitigate risks, including both internal processes, validation against existing datasets and review/interaction with stakeholders. Table 2 summarises the most important steps to mitigate the model/scenario risks identified by Walker et al. [43].

Table 2

Summary of measures to mitigate uncertainty within the scenario process, adapted from Walker et al. [43].

Error Type	Description	Comment on uncertainty mitigation activities
Context and framing	Appropriate boundaries and agreed description of the system.	Scenario framing is influenced heavily by SSPs which have been widely applied with narratives developed in conjunction with stakeholders. Choice of geographic and temporal boundaries (regional groups as opposed to countries and ending projections at 2050) due to the difficulty in accurately reflecting individual countries across multiple commodities, particularly the scale of climate impact by 2100. Energy system model encompasses all major economic sectors.
Input uncertainty	Uncertainty related to external driving forces or dependent variables that influence model outcomes.	Economic and population projections are taken from SSPs. Baseline (2010) trade data provided by NEA and MSI and validated against UNCTAD data. Production inputs based on official datasets (such as UNIDO, FAO, World bank etc.) See point below on regional production models. Energy system model inputs are taken from external sources (e.g. SSP GDP estimates), and reflect fundamental constraints (e.g. Bio-mass availability) which are influenced by both literature sources and both internal and external review.
Model structure uncertainty	Simplified descriptions of modelled processes.	The choice of three methods to model the global trade system reflects its inherent complexity. Econometric models are compared with existing studies on the relationship between trade and output. Where a statistical relationship between regional output and trade is not available, projection is based on the econometric relationship between trade and GDP and SSP GDP projections. Commodity specific production models (which serve as inputs to the econometric projection) are simplified representations, entailing a source of uncertainty. This allows fundamental constraints i.e. regional limits to production to be readily and explicitly reflected and linked across related commodities. The levels of growth in commodity trade by 2020 are compared against estimates for 2015 ensure a sudden unrealistic change in the economic system is not reflected.
Parameter uncertainty	Uncertainty in the variables associated with models.	All variables used in the quantification and projection of production are taken from literature sources or established datasets. For all such commodities and regions the production model outputs are validated against baseline (2010) data, whilst future projections reviewed in the context of historic levels of growth. The energy system model has been applied extensively including within the IPCC scenario database.

4. Conclusions

We present a suite of world maritime trade scenarios using a novel disaggregated, commodity specific interdisciplinary methodology which contributes to the futures literature. The scenarios explore the possibility space for how climate change mitigation, adaptation and impacts, along with different socio-economic framings, may drive and influence international maritime trade. Scoping future maritime trade is essential for appreciating the scale and extent of technical and operational change required across the shipping sector, to mitigate emissions in line with international agreements. This is equally relevant to inform ship-owners, whose choices (in the form of vessel builds) will ultimately have a functional life measured in decades.

The scenarios illustrate higher amounts of world maritime trade in a 4 °C future than in a 2 °C future. However, they also show that trade can evolve very differently, even in worlds with similar amounts of climate change. Overall, future trade in fossil fuels will necessarily be lower in a world with more emphasis on climate change mitigation. However, other assumptions relating to wider energy system change also alter the amounts and patterns of trade of particular energy-related commodities: Coal trade is significantly reduced in a 2 °C world compared to a 4 °C world, but trade in refined oil products depends in these scenarios on the electrification of transport. Trade in oil is also significantly influenced by the amount of BECCS deployment assumed within energy system scenarios by 2050. Furthermore, extensive BECCS deployment will drive production and potential trade of biomass, which could offer a significant opportunity but also a risk, for the shipping sector.

Trade in non-energy commodities, both containerised and non-containerised is higher in the 4 °C scenarios compared to 2 °C. Nevertheless, projections for containerised trade are a cautionary reminder to the sector that it cannot assume previously observed levels of growth persist, which is perhaps at odds with elements of some studies [39]. An analogous caveat also manifests in Constantinescu et al. [40];

suggesting that markets for goods may saturate, mature further or shift to new, less globalised, business models, particularly in more established markets, with a corresponding impact on trade. It is evident from the scenarios presented that the shipping sector must become resilient and agile to respond to a range of possible futures. Such futures may entail the emergence of new, or contraction of established, markets, such as biomass and coal; and also changing centres of demand, as observed in containerised trade. Furthermore, stakeholders in this sector would be wise to note that the extent and timing of CO₂ mitigation in shipping depends on the level of trade and transport work. Even scenarios with 4 °C of warming in future require the sector to make efforts to decarbonise, and whether 2 °C or 4 °C is aimed for, this challenge becomes greater as absolute volumes of trade increase.

Disclaimer

“The views and opinions expressed in this paper are of the authors and do not necessarily reflect the official policy or position of the Council of Economic Advisors of the Hellenic Ministry of Finance nor the incumbent Government of the Hellenic Republic.” Disclaimer: During the period in which this research was undertaken the first and second author were based in the institutions respectively designated ‘d’ and ‘e’ in the affiliation list.

Declarations of interest

None.

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Appendix

A. 16 study regions

Within our scenarios global trade is explored across 230 countries categorised into 16 regions (cf. Table 3 and Fig. 8. A map with the 16 regions colour-coded.), and is grouped in terms of carriage by 3 main vessel types: dry bulk, wet bulk and containers.

Table 3
Broad Commodity Categories.

Region
Africa
Australia
Canada
Central and South America
China
Eastern Europe
Former Soviet Union
India
Japan
Mexico
Middle East
Other Developing Asia
South Korea
UK
USA
Western Europe

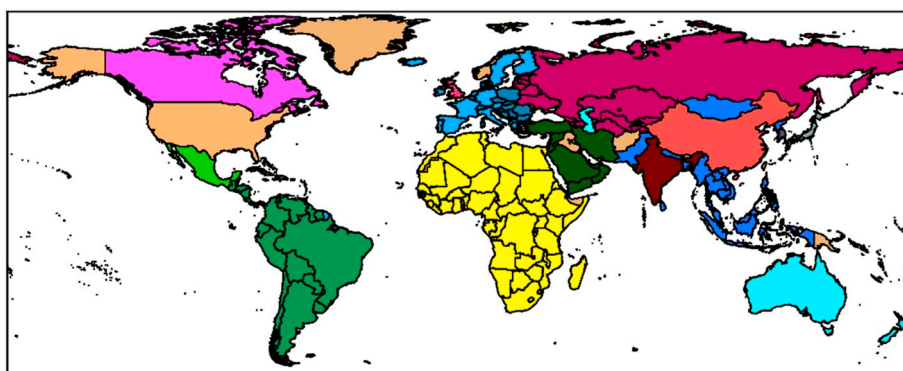


Fig. 8. A map with the 16 regions colour-coded.

B. Commodity groups

The trade scenarios cover nearly all traded commodities, which are expressed either at the ISIC classification as 31 aggregated categories, or the NST/R commodity classification as 52 aggregated categories. By way of example the commodity classification NST/R is expanded in Tables 4 and 5 while the ISIC classification is presented in 4.

Table 4
ISIC Classification for traded and produced commodities; the column on the right indicates the type of the commodity, with respect to the trade projection method (cf. Section 2).

ISIC	ISIC Title	Type of commodity/projection method
01,02	Agriculture and Forestry	Non-energy, non-containerised commodity; containerised share of 18% (cf. Section 2.4) Bioenergy from TIAM
05	Fishing	Non-energy, non-containerised commodity; containerised share of 21% (cf. Section 2.4)
10,11	Coal, Lignite, Crude oil, Natural Gas	Energy commodities
12	Mining of Uranium	Excluded (as negligible in absolute terms)
13,14	Ores, Mining and Quarrying	Non-energy, non-containerised commodity; containerised share of 10% (cf. Section 2.4)
15–19	Food and Textiles	Non-energy, non-containerised commodity; containerised share of 37% (cf. Section 2.4)
20–22	Wood and Paper Manufacturing	Non-energy, non-containerised commodity; containerised share of 31% (cf. Section 2.4) Bioenergy from TIAM
23–26	Chemicals, rubber, refined fuels, coke, non-metallic minerals	Non-energy, non-containerised commodity; containerised share of 18% (cf. Section 2.4)
27–29	Basic and Fabricated Metal Commodities	Non-energy, non-containerised commodity; containerised share of 24% (cf. Section 2.4)
30–33	Manufactured Electronic Equipment	Container commodity.
34–35	Manufacture of Motor and other Vehicles	Container commodity.
36–37	Other Manufacturing	Container commodity.

Table 5
NST/R Classification for traded and produced commodities

NST/R Code	NST/R Description	NST/R Code	NST/R Description
0	Live animals	52	Semi-finished rolled steel products
1	Cereals (including cereals used for animal feed)	53	Bars, sections, wire rod, railway and tramway track construction material of iron or steel
2	Potatoes	54	Steel sheets, plates, hoop and strip
3	Other fresh or frozen fruit and vegetable	55	Tubes, pipes, iron and steel castings and forgings
4	Textile materials and man-made fibres	56	Non-ferrous metals
5	Wood and cork	61	Sand, gravel, clay and slag
6	Sugar beet	62	Salt, iron pyrites, sulphur
9	Other raw animal and vegetable material	63	Other stone earths and minerals
11	Sugars	64	Cement, lime
12	Beverages	65	Plasters
13	Stimulants and spices	69	Other manufactured building materials
14	Perishable foodstuffs	71	Natural fertilizers
16	Other non-perishable foodstuffs and hops	72	Chemical fertilizers
17	Animal food and foodstuff waste	81	Basic chemicals
18	Oil seeds and oleaginous fruit and fats	82	Aluminium oxide and hydroxide
21	Coal	83	Coal chemicals
22	Lignite and peat	84	Paper pulp and waste paper
23	Coke	89	Other chemical products
31	Crude petroleum	91	Transport equipment
32	Fuel derivatives	92	Tractors, agricultural machinery and equipment
33	Gaseous hydrocarbons, liquid or compressed	93	Other machinery, apparatus and appliances, engines, parts thereof
34	Non-fuel derivatives	94	Manufactures of metal
41	Iron ore	95	Glass, glassware, ceramic products
45	Non-ferrous ores and waste	96	Leather, textiles and clothing
46	Iron and steel waste and blast furnace dust	97	Other manufactured articles
51	Pig iron and crude steel; ferro-alloys	99	Miscellaneous articles

C. Scenario narrative elements and inputs to TIAM-UCL

The projections of trade and output are framed by both qualitative and quantitative characteristics. These contextualise the system in which trade occurs and determine trade in specific commodities.

Table 6
Underpinning scenario characteristics.

Scenario name	Green Road	Middle Road 2C	Middle Road 4C	High Road
Temperature framing*	2 °C	2 °C	4 °C	4 °C
RCP*	2.6	2.6	8.5	8.5
SSP*	1	2	2	5
Economic growth*	GDP from SSP1	GDP from SSP2	GDP from SSP2	GDP from SSP5
Adaptation capacity	High	High	Low	Low
Final energy demand**	Based on SSP1; adjusted to reflect scenario narrative; ~ 546 EJ in 2050	Based on SSP2	Based on SSP2	Based on SSP5
Biomass availability	350 EJ/y	130 EJ/y	130 EJ/y	38 EJ/y
Material intensity*	Low	Moderate to high	Moderate to high	High
Energy Intensity	Low	Varied amongst regions	Varied amongst regions	High
Population growth*	SSP1	SSP2	SSP2	SSP5
CCS availability*	High (max. rate of capacity growth 15%/y)	Moderate (max. rate of capacity growth 10%/y)	Moderate (max. rate of capacity growth 10%/y)	Low (max. rate of capacity growth 5%/y)
Trade barriers*	Low	Moderate	Moderate	Low

Note: Elements marked with an asterisk * are also input to the Integrated Assessment Model TIAM-UCL. Final energy demand, marked with two asterisks **, is an output from TIAM-UCL, mainly based on GDP and population from the SSP. In the case of SSP1 this has been adjusted to reflect the energy efficiency scenario narrative.

D. Projection methods and sources of uncertainty

For each commodity the historical estimate of production is expressed in units that form a basis for future projection. Table 7 summarises the units, data sources, methodological basis for projection of future production, as well as the means by which climate sensitivities are manifest in each commodity. Crucially wherever possible fundamental linkages between commodities are represented, in some cases this requires individual

commodities to be grouped (such as non-energy wood and manufactured wood which is a component of ISIC 2 below which is linked to an aggregated category which includes manufactured wood and paper).

Table 7

Summary of methods for deriving future production estimates by commodity group (references in footnote).

ISIC no. & name	Unit	Means of projection	Climate sensitivities	Bounding data
01 Agriculture	Mt net aggregate production in crop and livestock products. (Based on FAO datasets). [1]	Assumptions on land availability and baseline productivity. Informed by population projections. [16]	Reduction in availability and productivity of land due to climate change impacts and levels of adaptation.	Population (SSP) temperature increase (RCP)
02 Forestry and Logging	Mt production of raw wood equivalent. (Based on FAO datasets). [2]	Assumptions on land use and baseline productivity [12]. Projections based on ratio between harvest and growth at regional scale [13].	Initial projections on fuel wood production replaced by solid bioenergy from TIAM.	Population (SSP) temperature increase (RCP)
05 Fishing, operation of fish hatcheries and fish farms	Mt production of whole fish equivalent. (Based on FAO datasets). [3]	Assumptions on change in global per capita consumption and global distribution of production centres [14].	Identification of current areas of (near-) depleted stocks and regions at risk from climate change. (Based on FAO datasets).	Population (SSP) temperature increase (RCP)
13 Metal ores	Mt Iron Ore (Based on World Steel [4] and U.S. [5] and British Geological Survey [6], mineral commodity summaries for iron ore).	Steel production by technology inferred from TIAM sectoral energy demands. Translated into demand based on technology pathways and reserves.	Future energy consumption by steel sector taken from TIAM, based on SSP and RCP framing.	GDP (SSP) temperature increase (RCP)
14 Other mining	Mt production. Based on UN production survey statistics [7].	Trends in the regional production intensity of GDP	None	GDP (SSP)
15 Food manufacture	Mt production. Based on UN production survey statistics [7].	Based on historic ratio between regional output of ISIC 01 [1-2] and ISIC15.	As for ISIC 01	As for ISIC 01
17–19 Textiles, clothes, and fabrics	Mt production. Based on UN production survey statistics [7].	Due to data issues production is projected at the global level based on historic trends and population growth.	None.	Population (SSP)
20–22 Paper, and wood manufacture	Mt production. Based on FAO production statistics [7].	Based on historic ratio between regional output of ISIC 02, and aggregate output of ISIC 20-22.	As for ISIC 02	As for ISIC 02
24 Chemicals, and chemical products	Mt production. Based on total global production taken from the American Chemical Council (AAC) [8] and disaggregated based on regional output in USD [9].	Based on projections of sectoral energy demand (TIAM), and average energy intensity of chemicals [15]. Allocated to regions based on narrative.	Assumptions on future trends in energy intensity based on likely demand for energy intensive chemicals such as fertilisers, based on climate adaptation narrative.	GDP (SSP) temperature increase (RCP).
25 Plastics, and plastic products	Mt production. Based global production from Plastics Europe (assoc. of plastic manufacturers) [10], disaggregated based on regional output in USD.	Based on historic trends in production and industrial energy use. Allocated to regions based on narrative.	Future energy consumption by industrial sector taken from TIAM.	GDP (SSP) temperature increase (RCP).
26 Other non-metallic mineral products	Mt Cement (proxy). US Geological Survey, mineral commodity summaries for cement [11].	Based on historic trends in proportion of CO ₂ emissions from cement production. Projected based on future emissions (TIAM), share from cement, and carbon intensity. Regional Allocation based on narrative.	Future CO ₂ emissions from TIAM	GDP (SSP) temperature increase (RCP)
27 Basic metals	Mt production. Based on data taken from world steel [4].	Based on historic ratio between regional output of ISIC 27 and steel production (taken from ISIC 13).	As for ISIC 13.	As for ISIC 13.
28-29 Manufacture of fabricated metal products and machinery	Value for ISIC 27 used as proxy for these two categories.	As for ISIC 27.	As for ISIC 27.	As for ISIC 27.
30–36	Included in separate container trade projections. No production estimates.	–	–	– ^a

^a [1] FAO (2017a) Primary crop and livestock food balance and land use statistics. Food and Agriculture. Statistical databases. Food and Agriculture Organisation of the United Nations. [2] FAO (2017b) Forestry products production and land use Statistics. Food and Agriculture. Statistical databases. Food and Agriculture Organisation of the United Nations. [3] FAO (2017c) Aquaculture and live catch Statistics. Food and Agriculture. Aquastat Statistical databases. Food and Agriculture Organisation of the United Nations. [4] World Steel Association, (1980–2015). World Steel Statistical year books. World Steel Association, Brussels. [5] United States Geological United States Geological Statistics (2014a) Mineral Statistics for Iron Ore. United States Geological Survey. [6] British Geological Survey (2011–2015) World Mineral Statistics. [7] United Nations Industrial Statistics (2014) Dataset of Industrial Commodity Statistics. United Nations Statistics Division [8] American Chemical Council (2016) Statistics bulletin. Washington, DC [9] United Nations Industrial Development Organisation (2014b) Dataset of Industrial Output (INDSTAT 2). United Nations Statistics Division [10] Plastics Europe Plastics Europe (2012) Global production statistics. Quarterly report. [11] United States Geological Statistics (2014b) Statistics for Cement Production. United States Geological Survey. [12] Raunekar, R., Buongiorno, J., Turner, J.A. and Zhu, S., (2010) Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change. Forest Policy and Economics, 12(1), pp.48-56. [13] Keenan, R.J., Reams, G.A., Achard, F., de Freitas, J.V., Grainger, A. and Lindquist, E., (2015) Dynamics of global forest area: results from the FAO global forest resources assessment 2015. Forest Ecology and Management, 352, pp.9-20. [14] Cochrane, K., De Young, C., Soto, D. and Bahri, T., (2009) Climate change implications for fisheries and aquaculture. FAO Fisheries and aquaculture technical paper, 530, p.212. [15] Saygin, D. and Patel, M.K., (2009). Chemical and Petro-chemical Sector. Potential of best practice technology and other measures for improving energy efficiency. International Energy Agency Information paper. [16] Lobell, D. B., and Gourdji, S. M. (2012). The influence of climate change on global crop productivity. Plant Physiology, 160(4), 1686-1697.

E. Summary overview of selected literature sources

By way of comparison, the results of a number of scenarios in the literature are summarised in Table 8, which presents the types of commodities included, the presence of a climate framing, and projected trade (either in terms of tonnage or transport work), expressed as multiples of baseline trade in 2010.

Table 8
Overview of selected trade scenarios from the literature

Scenario	Commodity and Region	Main Basis for Projection and Climate Framing	Time frame and results
Smith et al. [8]	Wet (oil), dry (coal and other), and unitised. Global.	RCPs and SSPs; resource production/consumption and GDP as indicator variables.	Projections to 2050. Transport work, relative to 2010 level: Unitised ~5.8–14.5 Wet bulk ~0.8–2.0 Dry bulk ~2.8–6.7
Lee [39]	Wet (oil), dry (coal and other), gas, unitised (container and other), and chemicals.	Update of [8] - same methodology, updated data.	Projections to 2050. Transport work, relative to 2010 level: Unitised ~3.3–8.3 Wet bulk ~0.7–2.3 Dry bulk ~3.7–9.4
Fontagne and Fouré [17]	Projections of volume of trade in goods aggregated to developing and developed nations, and global.	Trade elasticity with income, no explicit climate framing.	Projections to 2035. 1.3–4.3-fold increase in trade by 2035, expressed in average annual growth rate.
Château et al. [18]	As with Fontagné and Fouré [17].	As with Fontagné and Fouré [17].	Projection to 2060. 4-fold increase in trade by 2060, expressed in average annual growth rate.
Martinez et al. [21]	20 separate commodities and 12 regions but results presented in global aggregate and by corridor.	Trade projected based on commodity specific centres of production and consumption and weight to value ratio and modal share of each commodity. Trends in carbon intensity of transport work.	Projections of global transport work from 2010 to 2050, increasing four to five-fold.
Lloyds Register (2016a)	Four ship types considered: container, bulk/general cargo carrier, crude tanker, and products tanker.	Based on SRES scenarios.	Projections for trade over the period 2010 to 2030: 2.3–2.8-fold growth in containers.
SEA [23]	Global seaborne trade projections for oil, five major bulk, containerised, minor bulk, LNG, and LPG commodities.	Methodology/source of projection data not given.	Projections to 2035, with 1.9-fold increase in world trade in terms of tonnes loaded over the period 2010 to 2035.
This Study	16 regions and 36 individual commodities. Results aggregated to global level from regional results. Results also expressed in terms of Wet, Dry, and Containers type.	Varied based on commodity type, includes econometrics, commodity specific material flow analyses, energy system modelling, and bespoke container projection model. Explicit RCPs manifested for different energy commodity type.	2050. 1.8–3.7 increase in transport quantities.

E. The role of stakeholders

Within this project, a diverse array of stakeholders were consulted to support both over-arching direction specific advice on regional commodities, as well as review of both the scenario process and its results. In particular, stakeholders were asked ‘whether the scenarios are realistic, sufficiently distinguishable, and appropriate for the research question?’ Additionally, some stakeholders provided a vital role in the provision of data which is instrumental in development of scenarios themselves. The stakeholders represent a diverse group chosen based on existing professional networks which contain individual researcher involved in this area, as well as experts approached based on their presence and expertise in maritime research. Given this complexity it was deemed necessary to include a stakeholder cohort from a diverse array of individual specialisms.

Table 9
Summary of stakeholders

Organisation	Steering Role
B9 Shipping	Steering and scenario support with specific relevance to climatic mitigation and role of future markets for bio-fuels.
BAE systems	Steering and scenario support
BCS	Steering and scenario support
BPA	Steering and scenario support
CCC	Steering and scenario support with specific relevance to climatic mitigation or adaptation.
Chalmers	Steering and scenario support specifically use of energy scenarios and renewable fuel.
CWR	Steering and scenario support with specific relevance to climatic mitigation and the role of fleet in relation to trade.
David MacBrayne	Steering and scenario support
EA Gibson	Steering and scenario support
ECF	Steering and scenario support
ETI	Steering and scenario support
Exact Earth	Provision and support in use of AIS datasets.
FFF	Steering and scenario support
Fraunhofer	Steering and scenario support in particular technical aspects of scenario generation.
Hawkins Wright	Steering and scenario support
IEA	Steering and scenario support specifically use of energy scenarios and renewable fuels.
IMO	Steering and scenario support in particular potential wider regulatory elements.

(continued on next page)

Table 9 (continued)

Organisation	Steering Role
ISL	Steering and scenario support
ITF	Steering and scenario support
KfW	Steering and scenario support
KPMG	Steering and scenario support
MSI	Provision of historic and baseline container trade and scenario support and review.
NEA	Provision of historic and baseline trade data with a focus on inter regional flows by commodity.
RINA	Steering and scenario support
Seas at risk	Steering and scenario support
SSA	Steering and scenario support
Svitzer	Steering and scenario support
Teekay	Steering and scenario support
UK Maritime Foundation	Steering and scenario support
USP	Steering and scenario support
WWF	Steering and scenario support with specific relevance to climatic mitigation or adaptation.
Zodiac	Steering and scenario support with specific relevance to quantifying future shipping demand.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpol.2019.103537>.

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