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The economic implications of carbon neutrality ambitions in extra-European freight transport

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ABSTRACT

Achieving net-zero emissions in international freight transport is crucial, but the European Union's current policies fall short of mandating full climate neutrality mainly due to economic concerns. A major gap in scientific impact assessments is the lack of product-level and transport mode-specific trade elasticities. This study addresses this gap by estimating trade elasticities, analyzing transport cost increases, and assessing economic impacts under different EU carbon policies. The results show that maritime transport faces higher relative cost increases, while air transport sees greater absolute increases, leading to sharper price hikes for air transport goods (0.1%–0.5%) compared to sea transport goods (0.1%). Under the carbon neutrality scenario, European imports drop by €24.7 billion and exports by €27.4 billion. Kerosene and fuel oil demand decrease by 4.2 and 0.9 million tons, respectively. The findings suggest that more ambitious EU climate policies are feasible with manageable economic impacts.

1. Introduction

The international freight sector is an integral part of the European economy but also contributes significantly to its greenhouse gas (GHG) emissions, accounting for 7% of total emissions (EEA, 2023). In 2023, the maritime sector was responsible for transporting goods worth €1833 billion across the common border of the European Union (EU), while the airborne transport sector accounted for €830 billion (Eurostat, 2024). The usage of sustainable fuels, such as bio- or e-fuels, offers a proven technological pathway to decarbonize freight transport. However, the extraction and use of fossil fuels, without accounting for the costs of climate damage, will very likely remain cheaper than the production and use of sustainable fuels.

To address this politico-economic challenge, internalize the external costs of transportation, and promote the adoption of climate-neutral technologies in the air and maritime freight sectors, the EU has introduced several regulations, including REFuelAviation, FuelEU Maritime, and the expansion of the EU Emissions Trading System (ETS). In addition, the International Civil Aviation Organization (ICAO) has launched the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which applies to international airborne routes outside of the European Economic Area (EEA). Furthermore, the recent approval by the International Maritime Organization (IMO) of a global pricing mechanism for GHG emissions (IMO, 2025), set for formal adoption in October 2025, marks a significant step towards harmonizing carbon policies across the maritime industry.

However, the existing policies do not require complete carbon neutrality. Efforts to raise ambition face political resistance, primarily due to concerns over potential negative economic impacts. One key argument is that higher transportation costs may be

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passed on to consumers through increased product prices, potentially undermining the EU's export competitiveness and driving up import prices.

Impact assessments evaluating these economic effects of carbon policies in freight transport on import and export volumes require reliable estimates of trade elasticities. Specifically, these assessments need either transport demand elasticities with respect to transport or fuel prices, or import/export demand elasticities with respect to goods prices. Notable studies analyzing the elasticity of cargo demand with respect to freight rates include Chi and Baek (2012) and Lo et al. (2015) for airborne transport, as well as Coto-Millán et al. (2005), Bensassi et al. (2014), and Merkel et al. (2022) for maritime transport. However, these existing studies on transport demand elasticities do not account for differences between product groups. Conversely, research on product-specific elasticities generally lacks differentiation by transport mode, as seen in studies such as Hummels et al. (2009) and Fontagné et al. (2022). Therefore, the existing literature leaves several research gaps.

First, existing studies lack estimates for trade elasticities that account for the heterogeneity of products transported by sea or air. This gap introduces significant uncertainties in the evaluation of the demand-side effects of rising freight rates at a highly granular product level. Without disaggregated trade elasticities, existing analyses fail to capture the nuanced and mode-specific responses of individual product categories. Second, the combined effects of current emission reduction policies on freight costs in extra-EU transport remain unexplored. Detailed estimations and direct comparisons between transport modes are absent, limiting insights into the trade-offs and synergies between policies.

To address these gaps, our approach involves estimating the transport mode and product-specific trade elasticities using a structural gravity model, leveraging the most recent available data on product-level tariffs and extra-EU[1] trade. By applying these estimated trade elasticities within a policy impact assessment framework, the effects of currently implemented carbon policies can be analyzed. In addition to this *Current Policies Scenario*, we evaluate an alternative scenario in which the ambitions for climate neutrality are increased. The results are analyzed across various European countries, product groups, and transport modes.

2. Literature review

Impact assessments evaluating the effects of decarbonization measures in international freight transport have been conducted for the prices of goods transported by air and for seaborne transport, though not specifically for the combination of policy programs mentioned above. An impact assessment by Pons et al. (2021) suggests that the expansion of the EU ETS to the maritime sector would have limited effects on commodity prices. While goods like iron ore and cereals may see price increases of up to 2%, other goods such as crude oil and organic chemicals would remain largely unaffected by higher shipping costs. The demand effect, which is the response to this increase in prices, varies significantly between different commodities between a trade decrease of 0.1% and 2.4% and depend strongly on the assumed price elasticities (Pons et al., 2021). Other assessments focus on general proposed market-based measures such as a global maritime carbon dioxide (CO_2) tax. Sheng et al. (2018) investigate the economic impacts of a global bunker emission charge. In their baseline scenario, they assume an introduction of a bunker emission charge of $18 per ton of CO_2 in 2010, which increases by 4% each year. Their findings suggest that for the EU25 member states average prices would rise by about 0.3% for exports and 0.15% for imports by 2030. As a result, exports from EU25 member states would fall by almost 0.15% and imports by about 0.05%. Faber et al. (2010) study the design and impact of a global maritime emissions trading system. They estimate that a CO_2 emission charge of $30 per ton would increase global import prices by about 0.4% for crude oil, 0.4–0.8% for manufactures, 1% for agricultural products, and 2%–3% for raw materials such as ores and coal. Mundaca (2024) examines the short- and long-term effects of carbon taxation on the prices of products shipped by sea, focusing on the heaviest goods, which represent 75% of global maritime trade by weight. The author finds that export price elasticities with respect to bunker fuel price range from 0.07 (for automobiles) to 1.01 (for cement), indicating that a carbon tax equivalent to a 1% increase in fuel price would raise export prices of the heaviest goods by between 0.07% and 1.01%.

For air cargo, there are, to the best of our knowledge, no impact assessments of emission charges on either the prices of goods transported by air or air freight volumes. However, Chao (2014) investigates the impact of the EU ETS on air freight rates and finds for a scenario with a CO_2 allowance price of €30 per ton and 85% freely allocated allowances transportation costs increases of up to 1.8%. In addition, there are several studies that estimate the impact of EU ETS, CORSIA, or Fit-for-55 policies on air passenger fares or traffic. ICF Consulting et al. (2022) find under the assumption of a 100% cost pass-through, an increase in intra-European fares of around 1.1% due to CORSIA. Oesingmann (2023) evaluates the impact of the Fit-for-55 measures in aviation and calculates price and demand decrease of up to 20% for intra-European aviation.

3. Methodology

This section outlines the methodology employed in this paper. It is divided into two parts: the empirical estimation of transport mode-specific trade elasticities and the methods utilized for applying these elasticities within a policy impact assessment.

[1] Extra-EU trade refers to all trade flows that cross the common border of the EU. This excludes both trade outside the EU (e.g., between the USA and China) and trade within the EU (e.g., between Sweden and France).

3.1. Trade elasticities

To enhance impact assessments of EU decarbonization policies on the international transport sector, as well as their effects on extra-EU trade and freight transport demand, we apply a structural gravity model to estimate product-level and transport mode-specific trade elasticities. Following the approaches of Costinot and Rodríguez-Clare (2014), Head and Mayer (2014) and Fontagné et al. (2022), we apply product tariffs as the identifying variable.

The state-of-the-art structural gravity framework[2] offers several advantages in estimating trade elasticities. First, the micro-founded framework allows us to account for countries' resistance factors by incorporating importer and exporter time-fixed effects (Anderson and Van Wincoop, 2003), known as multilateral resistance terms (MRT).[3] Second, we can address omitted variable bias and cross-sectional dependencies by including MRT's together with time-invariant country-pair fixed effects (Baldwin and Taglioni, 2007). Third, following Baier and Bergstrand (2007) by introducing these time-invariant country-pair fixed effects within a panel data framework endogeneity issues can effectively be addressed.[4]

Our approach utilizes bilateral trade flows and Most Favored Nation (MFN) tariffs between 189 countries. Since tariff data are only available in a three-year window for the period 2001 to 2016, this timeframe is used for our estimation. To control for heteroscedasticity and zero trade flows, we use the nonlinear Poisson-Pseudo Maximum Likelihood (PPML) estimator, which avoids biases from Jensen's inequality (Silva and Tenreyro, 2006, 2011). For both transport modes, air and maritime, and each of the 5050 product categories k we estimate the following model:

$$X_{ijk,t} = \exp\left[\theta_{ik,t} + \theta_{jk,t} + \beta_k \ln(1+\tau_{ijk,t}) + \gamma_k \ln(d_{ij}) + \zeta_k Z_{ij}\right] \times \varepsilon_{ijk,t}, \quad \forall i \neq j \tag{1}$$

$X_{ijk,t}$ is the Free On Board (FOB) value of imports in destination country j of product k originating in country i in year t as dependent variable.[5] As the identifying variable we use ad-valorem MFN tariffs ($\tau_{ijk,t}$) derived from Fontagné et al. (2022).[6] $\tau_{ijk,t}$ represents the product level tariffs in the destination country j of the product k originating in country i in year t. $\theta_{ik,t}$ are exporter-product-time and $\theta_{jk,t}$ importer-product-time fixed effects to control for omitted variable bias, as well as to account for countries resistance factors and other observable and unobservable country-specific characteristics in the panel (Olivero and Yotov, 2012; Yotov et al., 2016). The variable d_{ij} controls for bilateral distance of the trading partners and Z_{ij} indicates the control on traditional bilateral-specific geographic-related trade costs as common language, common border and common colony. The air distance variable is obtained from Conte et al. (2022), while sea distances are taken from Bertoli et al. (2016).

The trade elasticity at the product level (ϵ_k) can be derived with $\epsilon_k = 1 + \beta_k$. This is theory-consistent within the framework of Constant Elasticity of Substitution (CES) (see Fontagné et al., 2022).[7]

Due to the high disaggregation of product-specific trade data, trade flows were insufficiently available for some of the 5045 product categories, leading to a lack of significant trade elasticity estimates at the most disaggregated product level (HS-6 level) in these cases. To ensure a reliable dataset for the impact assessment, we applied a structured, multi-step imputation procedure to address missing or implausible values (outlined in Appendix A). This procedure adjusted elasticities for a total of 4061 (Air) and 3589 (Maritime) HS-6 level product categories due to insignificance or extreme values. The largest part of insignificant elasticities could be filled using estimates aggregated at the HS-4 or HS-2 level, which is a standard practice in the literature (Fontagné et al., 2022). This left only 107 product categories for Maritime and 86 categories for Air requiring further refinement using estimates from the combined estimation (Air and Maritime together) or literature-based values, as detailed in the Appendix A. No product categories were excluded; all were retained through the imputation process.

3.2. Policy impact assessment

To assess the impact of different carbon policies on extra-EU trade, we apply the trade elasticities along with the policy-specific increase in transportation costs within the following impact assessment framework. Within this framework, the expected changes in price levels, trade volumes and transport work at the HS-6 level are calculated. The year 2023 serves as the base year for

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[2] For a comprehensive overview of the theoretical and econometric foundations of gravity trade models, see Anderson (2011) and Yotov et al. (2016).

[3] MRT capture (mostly) unobservable trade barriers, such as rejection or discomfort faced by exporters (outward resistance) or importers (inward resistance), as well as bilateral trade frictions.

[4] Egger and Nigai (2015) and Agnosteva et al. (2014) suggest using country-pair fixed effects instead of traditional gravity variables to measure bilateral trade costs. Fontagné et al. (2022) demonstrate the robustness of estimates against endogeneity concerns.

[5] The use of ad-valorem FOB value, valued at the export price before duties and transport costs, reduces the susceptibility to measurement errors and simultaneity bias of disaggregate trade unit values (Fontagné et al., 2022). The trade value variable $X_{ijk,t}$ is utilized from the COMEXT database (Eurostat, 2024), filtered by transport mode to separately estimate the elasticities for air and maritime freight. The data is separated into 5050 product categories at the 6-digit level of the Harmonized System (HS-6).

[6] Following Fontagné et al. (2022) the trade elasticities used in this study are estimated from variation in tariff rates across products and countries. While tariffs and transport costs differ in their origin, both increase the delivered price of traded goods and function as exogenous cost shocks from the importer's perspective. This conceptual equivalence is formalized in the structural gravity model of Anderson and Van Wincoop (2003), where trade costs include tariffs, transport expenses, and other frictions. In applied models, both tariffs and iceberg-type transport costs are often treated as ad valorem equivalents (e.g. Parro, 2013; Costinot and Rodríguez-Clare, 2014).

[7] Under the standard assumption of the CES demand system, the trade elasticity ε is equal to one minus the elasticity of substitution σ. However, using CES-based preferences can result in biased gravity estimations when applied at a highly disaggregated level (Carrère et al., 2020). Robustness checks by relaxing the CES assumption suggests that the baseline results based on the CES demand system can be considered valid and unbiased (Fontagné et al., 2022).

the trade structure and volumes of extra-EU trade, as it represents the most recent year with available data, sourced from Eurostat (2024).[8]

The evaluation starts with Eqs. (2) and (3), where the trade data is categorized by trade direction ($f = \{exports, imports\}$) and transport mode ($m = \{air, maritime\}$).

$$P_{m,k,ex} = \frac{\sum_{i\in \text{EU}, j\notin \text{EU}} \left(v_{m,k,i,j} \cdot P_{m,k,i,j}\right)}{\sum_{i\in \text{EU}, j\notin \text{EU}} v_{m,k,i,j}} \tag{2}$$

$$P_{m,k,im} = \frac{\sum_{i\notin \text{EU}, j\in \text{EU}} \left(v_{m,k,i,j} \cdot P_{m,k,i,j}\right)}{\sum_{i\notin \text{EU}, j\in \text{EU}} v_{m,k,i,j}} \tag{3}$$

For each subset, average product prices $P_{m,k,f}$ are calculated as weighted means for each HS-6 product category (k), using the monetary value of individual trade flows ($v_{m,k,i,j}$) as weights. This approach ensures consistent average prices for both exports and imports across all European countries.

The next step is to calculate the mode-specific increase in transportation costs resulting from carbon policies (referred to hereafter as $\Delta c_{m,t}$). The calculation is detailed in Appendix C and involves modeling the transport-mode-specific cost impact of the following four carbon policies:

- ReFuelEU Aviation:
  - Mandates progressively increasing sustainable fuel (SF) quotas over time for the aviation sector (Regulation (EU) 2023/2405).
- FuelEU Maritime:
  - Requires progressively increasing SF quotas for ships (Regulation (EU) 2023/1805).
- Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA):
  - Requires airlines to offset the growth of GHG emissions in international aviation, which are not covered by the EU ETS (developed by the ICAO).
- EU ETS Expansion for Maritime Emissions:
  - Effective from January 2024.
  - Extends the EU ETS to include GHG emissions from large ships entering EEA ports.
  - Covers 50% of emissions for voyages outside the EU and 100% for intra-EU voyages, as detailed by Regulation (EU) 2015/757.

A crucial input parameter to the transport cost modeling are the SF cost assumptions. In Appendix E we detail the assumptions and provide a sensitivity analysis regarding different fuel-cost trajectories.

In addition to the impact assessment of the currently implemented carbon policy level (*Current Policies Scenario*), we model an alternative policy scenario in which the ambition towards climate neutrality is increased (*Climate Neutrality Scenario*). Within this alternative scenario, the mandatory sustainable fuel quota for air transport is increased from 70% to 100% and for maritime transport from 33% to 100% (see Table D.1). The cost impact of each policy scenario can be described by Eq. (4).

$$\Delta c_{m,t} = \begin{cases} \Delta c_{m,t}^{SF} + c_{m,t}^{CORSIA}, & \text{for } m = \text{Air} \\ \Delta c_{m,t}^{SF} + c_{m,t}^{ETS}, & \text{for } m = \text{Maritime} \end{cases} \tag{4}$$

where m denotes the mode of transport, t the year, $\Delta c_{m,t}^{SF}$ additional costs for sustainable fuel, $c_{m,t}^{ETS}$ costs for ETS allowances in the case of maritime transport, and $c_{m,t}^{CORSIA}$ costs for CORSIA offsets in the case of air transport. The calculations for the different cost components are detailed in the following.

Eq. (5) calculates the absolute price increase for each trade flow ($\Delta P_{m,k,i,j}$) based on the scenario specific increase in transportation cost. This is determined by multiplying the transport mode-specific increase in transportation cost in euros per ton-kilometer ($\Delta c_{m,t}$) for a given scenario year (t) by the distance of each trade flow ($d_{m,k,i,j}$).[9]

$$\Delta P_{m,k,i,j} = \Delta C_{m,k,i,j} = \Delta c_{m,t} \cdot d_{m,k,i,j} \tag{5}$$

[8] The data set contains trade flows determined by an importer (i), an exporter (j), the product traded (k), and the transport mode (m). In addition, the sum over the monetary value (v) and the quantity in kilograms (q) is provided. We denote the monetary value of each trade flow as $v_{m,k,i,j}$ and the quantity of each trade flow as $q_{m,k,i,j}$. Dividing $v_{m,k,i,j}$ by $q_{m,k,i,j}$, the average unit value is derived, which is referred to as the product price ($P_{m,k,i,j}$) in the following.

[9] Distances are mode-specific, with sea distances based on Bertoli et al. (2016) and air distances sourced from Conte et al. (2022).

This calculation assumes a full cost pass-through from transport operators to product prices ($\Delta P_{m,k,i,j} = \Delta C_{m,k,i,j}$), which provides a transparent and conservative upper-bound estimate of potential economic impacts. Recent literature emphasizes that pass-through dynamics are highly context-dependent. Koopmans and Lieshout (2016) highlight that the extent of cost pass-through is strongly influenced by the competitive environment and the nature of the cost shock. In markets characterized by monopolistic or oligopolistic structures, firms may be more selective in passing on costs, especially if these are firm-specific. In contrast, cost increases that apply uniformly across the industry, such as those arising from climate regulations, are more likely to result in higher average pass-through rates (Koopmans and Lieshout, 2016). In the case of freight transport, companies often operate in an oligopolistic market where they compete on output volumes, but adjust prices strategically using yield management systems (Barbot et al., 2014; Brander and Zhang, 1990; Nava et al., 2018). This leads to heterogeneity in pricing behavior, meaning that not all companies will respond identically to cost increases. Therefore, while our assumption of full pass-through may overstate the real-world effect, it serves as a conservative estimate that ensures we do not understate the potential economic impacts of carbon policies.[10] This approach is consistent with standard practices in evaluating the macroeconomic effects of environmental regulation (cf. Nava et al., 2018; Oesingmann, 2023).

By dividing the calculated absolute price increase (Eq. (5)) by the average product prices (Eq. (2) for exports and Eq. (3) for imports), the relative price increase per trade flow is calculated:

$$\Delta p_{m,k,i,j} = \frac{\Delta P_{m,k,i,j}}{P_{m,k,f}} \tag{6}$$

This relative increase in product price is then multiplied by the transport mode and product-specific price elasticity ($\beta_{m,k}$) to calculate the expected relative change in trade value per product category and per trade flow ($\Delta x_{m,k,i,j}$):

$$\Delta x_{m,k,i,j} = \beta_{m,k} \cdot \Delta p_{m,k,i,j} \tag{7}$$

4. Results

This section presents the findings from the trade elasticity estimation, the results of our transport cost model, the subsequent impact assessment on trade flows, and a discussion of policy implications. In Section 4.3, we explore in greater detail the additional impact of raising current EU policy ambitions to achieve climate neutrality by 2050.

4.1. Trade elasticities

Table 1 presents the set of trade elasticities which were estimated and selected within the refinement process described in Section 3.1

The average trade elasticities across the different HS sections reveal notable differences between maritime and air transport, highlighting the heterogeneity of products transported. For example, Mineral products, a standardized category, exhibit a high average trade elasticity of −8.7 for maritime transport. In contrast, the average elasticity for air transport in this section is much lower, at −2.8, reflecting the differing product varieties transported by sea versus transported by air. Differentiated products, such as Footwear, Headgear, and Umbrellas, show average elasticities of −3.3 for maritime and −2.3 for air, suggesting relatively lower price sensitivity overall, with air transport favored for higher-value or time-sensitive goods. Overall, the arithmetic mean and weighted average values (−5.2 and −6.8 for maritime, −6.6 and −6.3 for air, respectively) indicate that the difference between the transport mode in mean elasticities and weighted average elasticities is not substantial but remains significant.

Robustness checks support the regression estimation results. Considering the economic robustness of the results, one sample excludes the United States, which is the largest importer of European products. Another sample excludes China, the largest exporter to Europe. The results show highly similar distributions, without providing any indication of biases by countries or country groups. Fig. B.1 (Appendix B) shows a comparative analysis of the empirical distribution of the trade elasticities for each transport mode. In addition, the results were tested for their methodological robustness (see e.g. Fontagné et al., 2022). Consequently, each sample was estimated using country-pair fixed effects and included controls for the presence of bilateral trade agreements, specifically Free Trade Agreements (FTAs), to mitigate potential omitted-variable bias. The results including FTAs as an explanatory variable show very similar results, suggesting that there is no systematic bias. Regressions using country-pair fixed effects are widely discussed in the context of gravity models. These fixed effects absorb systematic patterns between specific country pairs. Consequently, they also absorb the bilateral control variables as well as much of the variation in bilateral applied tariffs (Fontagné et al., 2022). Estimates with country-pair fixed effects exhibit lower magnitudes, suggesting that the results are in line with findings by Boehm et al. (2023) and Fontagné et al. (2022). Fig. B.2 (Appendix B) shows the empirical distribution of trade elasticities for each estimation specification and transport mode.

[10] Notably, real-world responses to policy-driven cost increases are subject to time-lags due to gradual adjustments in logistics, fleet composition, procurement practices, and infrastructure. While our model does not explicitly simulate transitional dynamics, the estimated trade elasticities are based on data in three-year intervals, allowing time for such adjustments and thus reflecting medium- to long-term trade responses (cf. Olivero and Yotov, 2012). Incorporating explicit lag structures into the assessment framework would likely shift the maximum impact to a later year but would not fundamentally alter the magnitude or direction of the projected effects.

Table 1
Descriptive statistics for trade elasticities by HS section used in the scenario simulation.
Source: Authors' calculations.

Sec.	Description	Maritime			Air		
		Avg	Std dev	Min	Avg	Std dev	Min
1	Live animals and animal products	−7.0	8.8	−25.0	−7.1	5.1	−25.0
2	Vegetable products	−8.3	7.5	−25.0	−10.0	8.3	−25.0
3	Animal or vegetable fats and oils	−21.1	7.7	−25.0	−17.2	6.3	−25.0
4	Prepared foodstuffs, beverages and tobacco	−4.9	6.5	−25.0	−5.8	8.5	−25.0
5	Mineral products	−8.7	4.1	−18.4	−2.8	2.5	−11.5
6	Products of chemical industries	−9.0	7.9	−25.0	−9.9	8.6	−25.0
7	Plastic and articles thereof	−12.2	8.7	−25.0	−11.0	8.8	−25.0
8	Raw hides, skins, leather	−2.0	2.5	−8.8	−6.1	3.4	−9.1
9	Wood/Cork and articles thereof	−7.6	6.0	−23.8	−4.2	4.2	−18.7
10	Pulp of wood or cellulosic materials	−6.3	4.8	−16.4	−12.8	9.8	−25.0
11	Textile and textile articles	−8.2	7.6	−25.0	−9.2	7.8	−25.0
12	Footwear, Headgear, Umbrellas	−3.3	4.2	−18.5	−2.3	3.1	−20.0
13	Articles of stone, plaster, ceramics	−3.9	3.6	−13.7	−2.4	2.3	−11.8
14	Natural pearls, precious stones/metals	−0.4	0.0	−0.4	−20.0	9.1	−24.2
15	Base metals and articles thereof	−6.1	6.6	−23.1	−4.0	4.0	−25.0
16	Machinery, appliances, electricals	−3.6	4.0	−21.6	−5.1	5.1	−25.0
17	Vehicles, aircraft, transport equipment	−6.2	6.1	−25.0	−4.5	3.9	−25.0
18	Optical, photographic, precision instruments	−3.3	3.5	−24.9	−6.3	5.9	−20.7
19	Arms and ammunitions	−1.2	0.0	−1.2	−6.5	0.5	−7.2
20	Miscellaneous	−2.3	2.5	−15.5	−5.2	3.9	−23.6
21	Works of art	−0.5	0.0	−0.5	−1.3	0.5	−2.1
	Arithmetic mean	−5.2	6.3		−6.6	6.8	
	Weighted average	−6.8	6.3		−6.3	7.0	

Notes: This table lists the descriptive statistics (mean, standard deviation, and minimum values) for the ε_k parameter estimated as in Section 2.1 for each HS section.

4.2. Transport costs

Fig. 1 presents the results of our cost model analysis for maritime and airborne transport under different carbon policies. Fuel costs are disaggregated to show base fuel expenditures alongside the additional costs associated with the usage of sustainable fuel (cf. Appendix C), specifically the cost of substituting methanol for heavy fuel oil in maritime transport and SAF for fossil kerosene in air transport.

For air transport, a projected maximum increase in transport costs of 21% by 2050 is observed under the *Current Policies Scenario*. In contrast, under the more ambitious *Carbon Neutrality Scenario*, the cost increase peaks earlier, reaching 27% in the year 2044. Similarly, for maritime transport, the maximum projected cost increase under the *Current Policies Scenario* is 23%, while the *Carbon Neutrality Scenario* results in a steeper increase of up to 39% by 2044. Afterwards, the projected transport costs decrease, due to the assumed decreasing costs for the production of SF and the increasing technical efficiencies (see Table C.1). A significant difference lies in the magnitude of the cost associated with compensating CO_2 emissions of air transport under CORSIA compared to submitting EU ETS allowances for maritime transport emissions. During the initial period 2024 to 2035, the assumed price of CORSIA offsets is minimal, at only €20 per ton of CO_2, while the anticipated price for EU ETS allowances is significantly higher, at an average of €70 per ton of CO_2. This could incentivize the earlier adoption of SF in the maritime sector beyond the required quota, particularly given the availability of relatively low-cost biofuels during this period.

4.3. Impact assessment

We apply the impact assessment framework (see Section 3.2) to the year 2044, as this year is projected to exhibit the highest increase in transport costs under the *Carbon Neutrality Scenario*. Anchoring the analysis in this peak-cost year allows us to assess the maximum projected changes in trade values, price levels, and transport work across sectors. This approach provides a conservative estimate of potential economic impacts under high-cost climate policy implementation.

The detailed transport mode-specific results are shown in Table 2, while Table 3 depicts the overall effects on imports, exports, and transport work reduction. It should be noted that, due to the relatively small share of transport costs in most product prices, a 20% increase in transportation costs results in a product price increase of only 0.1% to 0.5%.

In the *Current Policies Scenario*, our analysis reveals that the value-weighted average increase in product prices imported by air is 0.5%, while prices for goods imported by maritime transport show a smaller increase of 0.1% (see Table 2). This difference in product price changes reflects the differing impact of transport costs by mode and the different trade structures of the transported goods. Although maritime transport faces a higher percentage increase in transport costs (see Fig. 1), the proportion of these costs relative to product prices is relatively low compared to air transport due to absolute cost differences between modes. This trend is similarly observed in exports, where air-transported goods exhibit an average price increase of 0.4%, while maritime exports experience a more modest increase of 0.1%.

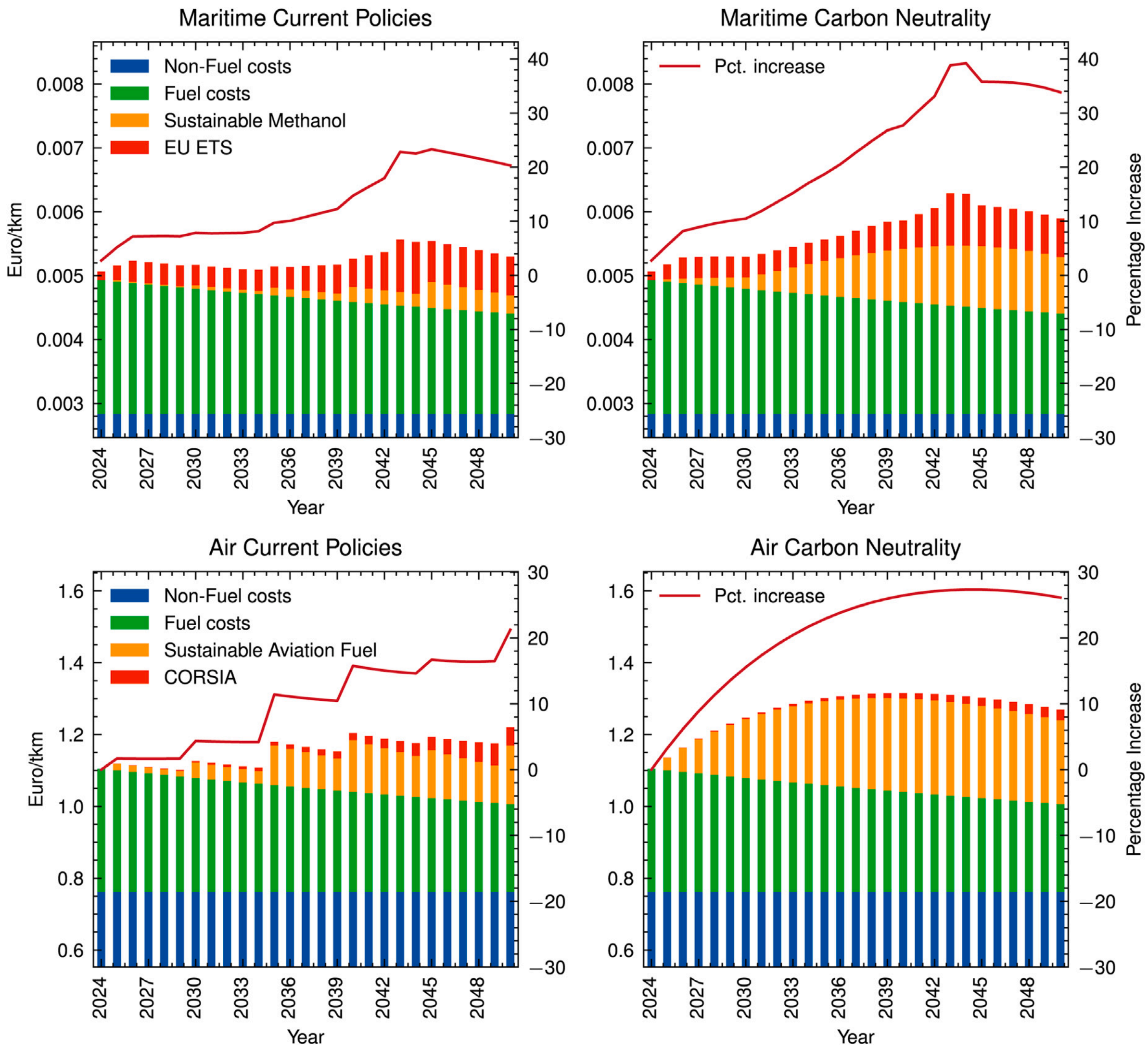

Fig. 1. Results of the transport cost models by scenario and by transport mode. Sustainable fuel costs represent the price difference between transport-mode-specific conventional fuel and the corresponding climate-neutral alternative. Cost values for the maritime sector correspond to the container ship cost model, as it serves as the default option within the impact assessment.

Table 2
Percentage changes in price levels (Eq. (F.1)), trade values (Eq. (F.2)), and transport work (Eq. (F.3)) by transport mode, scenario, and trade flow for anchor year: 2044.

Scenario	Mode and trade flow	Price level %	Trade value %	Transport work %
Current policies	Air imports	0.5	−2.2	−15.7
	Air exports	0.4	−1.9	−10.6
	Maritime imports	0.1	−0.7	−1.0
	Maritime exports	0.1	−0.8	−3.9
Carbon neutrality	Air imports	0.9	−3.7	−21.5
	Air exports	0.8	−3.4	−16.9
	Maritime imports	0.2	−1.2	−1.7
	Maritime exports	0.2	−1.3	−6.5

Under the *Carbon Neutrality Scenario*, the impact on price levels becomes more pronounced. The average product price increase for air-imported goods nearly doubles to 0.9%, with air exports rising by 0.8%. In comparison, the price impact on maritime trade flows remains moderate, with a 0.2% increase for both imports and exports.

Table 3
Comparison of impacts on trade value, transport work and fuel demand under *Current Policies* and *Carbon Neutrality* scenarios, differentiated between trade direction.

		Current Policies	Carbon Neutrality
Impact on imports	Trade value [€] Percentage	−14.3 billion −1.0%	−24.7 billion −1.8%
Impact on exports	Trade value [€] Percentage	−15.6 billion −1.2%	−27.4 billion −2.1%
Transport work	Air Maritime	−12.8% −1.7%	−18.9% −2.9%
Fuel demand	Air [Kerosene eq.] Maritime [Fuel oil eq.]	−2.8 million tons −0.5 million tons	−4.2 million tons −0.9 million tons

For the second column of Table 2 we use the estimated product-level trade elasticities and calculate changes in trade values measured in Euros, based on Eq. (7). The column "Trade Value" represents the aggregated result of our highly disaggregated scenario analysis. The results demonstrate a decline in trade value in both air and maritime modes, particularly under the *Carbon Neutrality Scenario*. The trade value for air imports decreases by 2.2%, while air exports drop by 1.9%. In contrast, maritime imports and exports show a smaller reduction in trade value, at 0.7% and 0.8%, respectively.

We observe significant reductions in transport work in both scenarios, which are closely related to corresponding decreases in energy demand. In the *Current Policies Scenario*, air imports and exports experience reductions in transport work of 15.7% and 10.6%. Maritime transport shows a more moderate response, with reductions of 1% for imports and 3.9% for exports. Under the *Carbon Neutrality Scenario*, the reductions become more substantial, increasing to 21.5% for air imports and 16.9% for air exports. For maritime transport, reductions rise to 1.7% for imports and 6.5% for exports.

The aggregated results of the scenario simulation are summarized in Table 3. Under the *Carbon Neutrality Scenario* scenario, the results indicate a larger reduction in trade values, with imports and exports decreasing by €24.7 billion and €27.4 billion, respectively. Transport work also shows a more substantial decline in this scenario, particularly for air transport, which decreases by 18.9%, compared to a 12.8% decrease under the *Current Policies Scenario*. This reduction in transport work demand translates into a decrease in fuel demand which sums up to 3.3 million tons under the *Current Policies Scenario* and increases to 5.1 million tons of fuel equivalents under the *Carbon Neutrality Scenario*.

In the following, the simulation results of the *Carbon Neutrality Scenario* are examined in more detail, with a focus on product-level trade value reductions and country-specific impacts. Similar to the aggregated results in Table 3, these reductions result from multiplying the expected price increases by the estimated price elasticity for each trade flow, considering the origin, destination, and product category. This method identifies product categories and country pairs particularly vulnerable to rising transport costs. Significant effects arise from factors like low average unit value (€ per kilogram), long transport distances, high price elasticities, or their combination.

In Fig. 2, the results for the nine most affected European countries are shown individually, while all other European countries are grouped into Rest of Europe (RoE).

The results indicate that, in the air transport sector, the impact on certain product categories, such as 39 (Plastics) and 85 (Electrical equipment), is comparatively high. In contrast, in the maritime sector, the impacts are more evenly distributed between product categories and countries.

Fig. 3 gives a more detailed overview of the HS2 product categories that contribute the most significantly to the overall decreases in trade value. The reduction values are presented for both imports and exports, across air and maritime transport modes, under the "Carbon Neutrality" scenario.

The total reduction in the trade value of air imports (Fig. 3, upper left) is €7.3 billion. In which the product category "Plastics and articles thereof" (HS Code 39) contributes the most with a trade value decrease of €2.4 billion to the overall reduction. Other significant reductions in trade value are expected primarily in high-value categories. The import of electrical machinery and equipment (HS Code 85) is projected to decrease by €2.2 billion, representing 17.5% of the total reduction in trade value and a share of 5.3% in overall transport work decrease. This is particularly impactful for major importers such as Germany (DEU), the Netherlands (NLD) and France (FRA). A closer examination of this HS Code 85 product category reveals that the largest share of the decrease in trade value within this category comes from the subcategory "Telephones for cellular networks" (HS Code 85172), i.e., mobile phones, with China being the main import source, with a share of 34%, followed by Taiwan with 15%. Although this subcategory represents the second largest contributor to the overall decrease in trade value in air imports, the expected percentage point decrease in imports of this specific category is only 1%. On the HS2 level, the product categories following, in terms of the largest trade value reduction, are Machinery (HS Code 84), Optical and medical instruments (HS Code 90), Apparel (HS Code 62), and Edible fruits and nuts (HS Code 08).

For **air exports** (upper right), projected reductions in trade value are concentrated in high value product categories. Machinery (HS Code 84) sees an export trade value decrease of €3.4 billion, with Germany (DEU) and Italy (ITA) among the most affected exporters. Electrical machinery and equipment (HS Code 85) is expected to show declines of around €3.2 billion. Subcategories such as AC generators (HS Code 850152) and parts for switchgears (HS Code 853890) are among the most affected, showing significant value decreases, including relative reductions of around 4%–5% in their trade volumes.

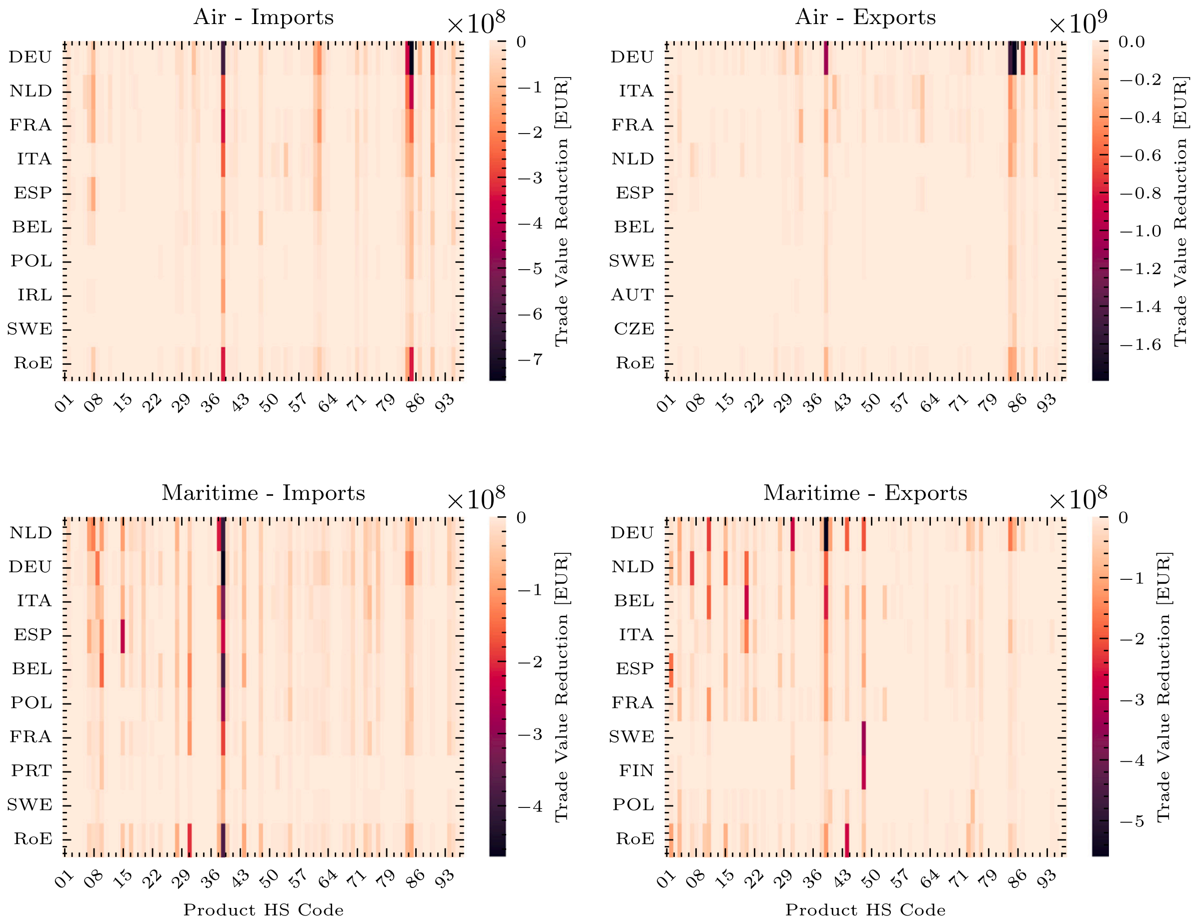

Fig. 2. Disaggregated results of trade simulations for the Carbon Neutrality scenario. This heat map shows the reduction in trade value per product category, transport mode and trade direction for transport cost scenario year 2044, RoE: Rest of Europe, Product HS Code corresponds to HS2 product level.

The overall reduction in the trade value of **maritime imports** is €12.2 billion, with significant losses expected in the category "Plastics and articles thereof" (HS Code 39). This category represents the largest share (23.1%) of the total reduction, contributing a decrease of €2.8 billion in trade value. The main import countries for this category are China (42%) and Korea (21%). Although "Plastics" represented a smaller share in terms of the overall trade value of 2.8% in 2023, its high trade decrease is notably influenced by a high elasticity of −16, a relatively low unit value of €9.08 per kilogram and an average transport distance of 11,612 km. These factors result in an average increase in transport cost of €0.02 per kilogram, leading to a relative price increase of 0.5%. When multiplied by the elasticity, the projected relative trade decrease is significant, reaching −10.9%.

The reduction in the trade value of **maritime exports** is €10.5 billion and the largest impact originates again from the product category "Plastics" with €1.5 billion. Other HS2 groups with large trade value reductions are Paper and paperboard (HS Code 48) with €1.3 billion, Milling industry products (HS Code 11) with €0.8 billion, Prepared vegetables, fruits, and nuts (HS Code 20), with €0.8 billion, and Wood and wood articles (HS Code 44) with €0.7 billion.

Fig. 4 illustrates the impact on net exports for each European country under the *Climate Neutrality Scenario*. These country-specific results are driven by the underlying trade structure of 2023. Countries with a trade surplus, such as Germany, France, and Italy, are projected to experience a slight decline in net exports. In contrast, countries like the Netherlands, Belgium, and Spain show a relative increase in net exports, as their imports decline more than their exports.

A positive impact on net exports is driven by structural characteristics of trade. First, imported goods may be transported over longer distances (e.g., from China), while exported goods may be shipped to closer destinations (e.g., the USA), leading to a greater cost and price impact on imports. Second, the composition of imported goods may be more sensitive to price changes. As a result, countries with a high share of such imports experience a sharper reduction in imports than in exports, contributing to a relatively positive effect on the trade balance.

The first mechanism is illustrated in Fig. G.1 (Appendix G), which shows the density of trade-weighted distances for air and maritime freight transport. Imports are generally associated with longer transport distances than exports, particularly in maritime trade. This leads to a greater increase in ad valorem transport costs for imports and underpins the observed asymmetry in trade adjustments.

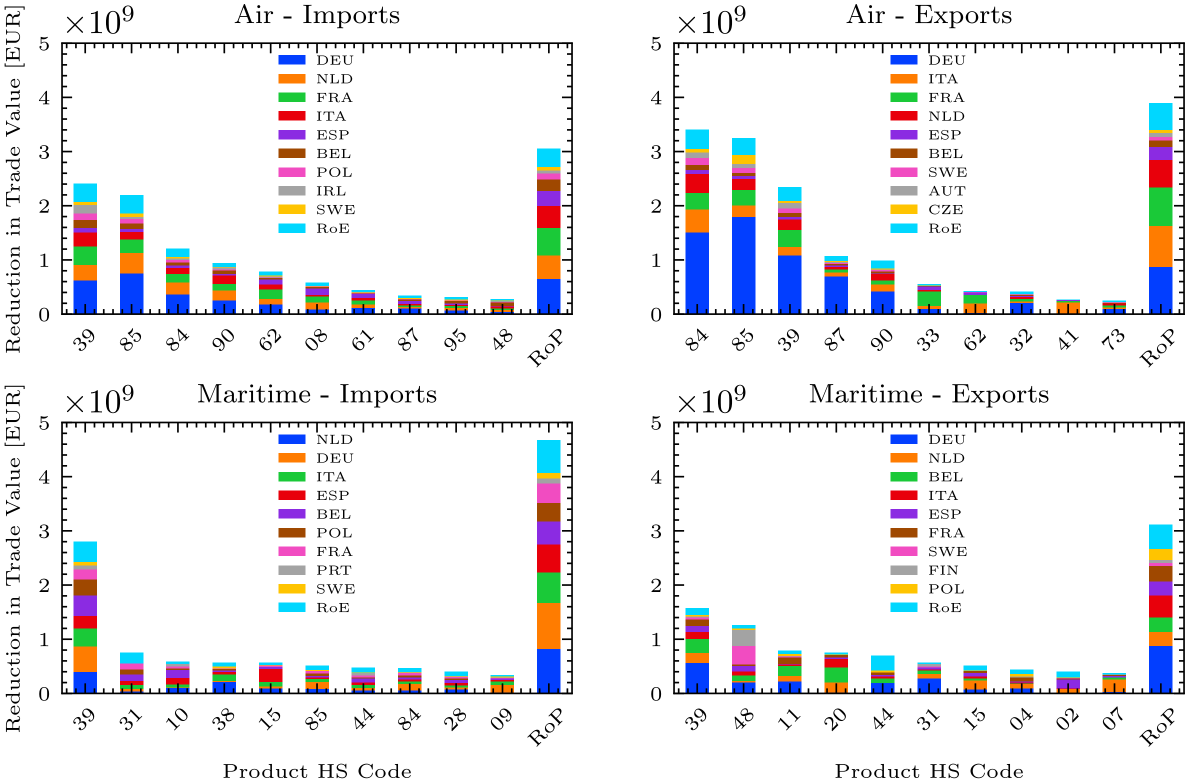

Fig. 3. Reduction in trade values under the *Carbon Neutrality Scenario* for 2044 as the scenario year, RoP: Rest of Products, RoE: Rest of Europe.

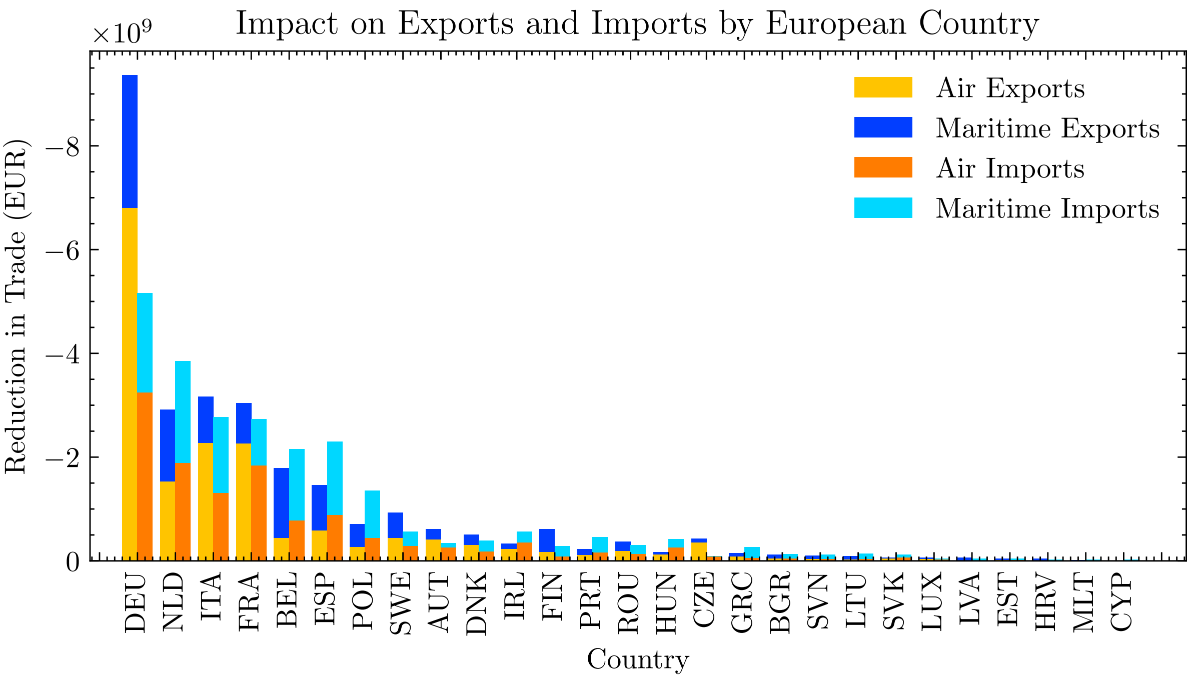

Fig. 4. Impact on trade flows per European country under the *Carbon Neutrality Scenario*.

The isolated effect of changes in maritime trade value on European net exports is positive (€1.6 billion). Only if the net negative effect of air transport is added with a decrease of €4.3 billion in net exports, the overall net effect on European GDP becomes negative (€2.7 billion).

4.4. Discussion and policy implications

Our analysis indicates that the environmental policies currently implemented by the European Commission and the ICAO to reduce greenhouse gas emissions in extra-European transport have a modest but noticeable impact on product prices and trade values. The order of magnitude of the aggregated increase in price levels found in this study, ranging from 0.1% to 0.9%, is comparable to findings in the literature. For example, Sheng et al. (2018) calculate price level increases of 0.3% for exports and 0.15% for imports based on a bunker price charge of US$32 per ton of CO_2 in 2030. Similarly, Faber et al. (2010) estimate that a CO_2 emission charge of US$30 per ton would increase global import prices by approximately 0.4% for crude oil, 0.4–0.8% for manufactures, 1% for agricultural products, and 2%–3% for raw materials like ores and coal.

The aggregated transport mode-specific price elasticity, which can be derived from the findings in Table 2 highlights the significant differences between sea and air transport. For goods transported by sea, the price elasticity is between −7 and −8, while for goods transported by air, the aggregated price elasticity lies between −4.4 and −4.8. This underscores the importance of differentiating between transport modes when estimating product-level elasticities and conducting policy scenario simulations.

Another implication of our study is that as transport work declines significantly in response to simulated carbon policies, questions arise about the projected demand for sustainable fuels. Our findings on the decreasing demand for transport work, could imply that sustainable fuel demand may be overestimated in current energy scenario studies, which do not account for this economic demand side effect. Under the *Current Policy Scenario*, it is projected that the demand for SAF, such as e-Kerosene, will decrease by approximately 12.8%, which equates to a reduction of approximately 2.8 million tons of e-Kerosene, or 31.4 terawatt hours (TWh). Similarly, the demand for sustainable maritime e-fuels is expected to decline by approximately 1.7%, translating into a decrease of roughly 6 TWh. Taking into account the efficiency of fuel synthesis, this translates into an aggregated reduction in electricity demand of 124 TWh or 5% of the EU's electricity generation of 2023.

The trade analysis indicates that increasing the sustainable fuel quota to 100% to achieve carbon neutrality would lead to only a marginally higher economic impact compared to the *Current Policies Scenario*. Export values would drop by an extra 0.9 percentage points, while imports would decrease by 0.8 percentage points. The EU GDP would see a negligible decrease of 0.01%.[11] In contrast, the additional energy savings are substantial, including reductions of approximately 1.4 million tons of e-kerosene for aviation and 0.4 million tons for maritime fuels. These savings predominantly affect long-distance and heavy-goods trade. Broadening the perspective to consider the wider economic implications of the regulations analyzed, it is essential to account for the positive effects on GDP and employment within sectors involved in the production and distribution of sustainable fuels. As highlighted in Aigner et al. (2023), these sectors are expected to generate notable economic benefits, contributing positively to overall economic growth and job creation.

4.4.1. Policy implications

While the overall impact on European GDP is negligible, our disaggregated analysis reveals clear heterogeneity in the distribution of trade effects across sectors and countries. Sectors most affected include those which may be highly reliant on air-freight for high-value, time-sensitive goods, particularly in product categories such as electrical equipment (HS Code 85), machinery (HS Code 84), and optical instruments (HS Code 90). Countries with a strong export focus in these categories, such as the Netherlands, France, Germany and Italy, are projected to experience notable reductions in exports and may require targeted support.

In the maritime sector, product categories such as plastics (HS Code 39), paper and paperboard (HS Code 48), and milling industry products (HS Code 11) are among the most affected, with substantial reductions in export values. Countries that are reliant on imports of goods such as plastics (HS Code 39), fertilizers (HS Code 31), or grain (HS Code 10), particularly from distant suppliers such as China and Korea, are likely to face higher costs and disruptions to their supply chains.

In light of these results, policymakers should consider targeted compensation or adjustment assistance for sectors and regions facing disproportionately high costs. Revenues generated from the ETS could be strategically allocated to support these efforts. In addition, flanking measures, such as reducing tariffs or administrative trade barriers, could help mitigate the net negative effects on trade in the short-to-medium term.

Carbon policies affecting international trade necessitate alignment with global partners to avoid competitive disadvantages for European businesses. The EU should continue to engage with international organizations such as the IMO and the ICAO to promote global standards for sustainable fuels and carbon pricing and ensure a level playing field. This approach would substantially reduce the economic impact compared to the one-sided policies currently implemented and analyzed in this study. Notably, the IMO's recent approval of a global pricing mechanism for emissions (IMO, 2025), set to be formally adopted in October 2025, represents a significant step towards harmonizing carbon policies across the maritime industry.

Beyond immediate emission reductions, the shift to sustainable fuels could position the EU as a global leader in green technologies, potentially creating new economic opportunities in the clean energy sector. Policymakers could leverage this transition to boost innovation, enhance energy security by reducing fossil fuel dependence, and generate green jobs. Strategic investments in sustainable fuel production and logistics infrastructure could also create long-term competitive advantages for European industries. These effects have the potential to outweigh the net negative effect of additional transport costs.

[11] EU GDP in 2023 was €18.530 trillion. In the *Carbon Neutrality Scenario* imports are projected to decrease by €24.7 billion, while exports decrease by €27.4 billion, resulting in a net effect of −€2.7 billion.

4.4.2. Limitations

A common limitation of using trade data is the potential for systematic misreporting of HS classifications to avoid specific tariffs. This could affect the accuracy of the trade data used in this study. Another potential limitation of our study is that modal shifts are not explicitly modeled, which introduces uncertainty about whether reduced demand, for example, for air transport, might imply increased maritime transport demand (c.f. Halim et al., 2019). In particular, rising air freight costs may trigger a modal shift towards maritime transport, which is more cost-efficient. This could dampen the decline in maritime fuel demand and reallocate part of the emissions burden from air to sea. The reverse shift, from maritime to air, is highly unlikely under structural higher-cost conditions. Future studies could benefit from models that address these limitations to improve precision in estimating the impacts of carbon policies on international freight transport.

5. Conclusion

In this study, we estimate product-level and transport mode-specific price elasticities for extra-European freight transport, calculate transport cost increases due to carbon policies, and analyze their economic impacts under different policy scenarios. The results of our cost model show that while maritime transport experiences a larger relative increase in transport costs, air transport faces a greater absolute increase. As a result, the price levels for goods transported by air rise more significantly. The price increase ranges from 0.1% to 0.5% for goods transported by air and 0.1% for goods transported overseas, with slight variations depending on the direction of trade. Based on the estimated trade elasticities, we project a reduction of €24.7 billion (2.1%) in imports and €27.4 billion (1.8%) in exports under the ambitions of carbon neutrality. The net impact on European GDP is negligible. The decrease in trade value is mainly driven by heavy goods transported over long distances, resulting in a disproportionate decrease in transport work. The projected reduction in transport work for the *Carbon Neutrality Scenario* translates into a reduction in fuel demand of 4.2 million tons of kerosene and 0.9 million tons of fuel oil. Given the urgent need to reduce greenhouse gas emissions, our policy recommendation is to increase the ambitions for carbon neutrality by implementing a regulation that demands a quota of 100% sustainable fuels in 2050 in both air and maritime freight transport. The economic implications for the European Union would remain within a manageable range, making it a viable option to achieve significant emission reductions. This work helps identify specific sectors and countries that are particularly impacted and may require targeted support.

CRediT authorship contribution statement

Jonas Eschmann: Writing – original draft, Writing – review & editing, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karsten Mueller:** Writing – original draft, Writing – review & editing, Validation, Software, Methodology, Formal analysis. **Katrin Oesingmann:** Writing – original draft, Writing – review & editing, Software, Methodology, Formal analysis. **David Ennen:** Writing – original draft, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Imputation strategy for estimated trade elasticities

This appendix outlines the sequential imputation process used to generate a complete and theory-consistent set of trade elasticities across all 5045 HS-6 level product categories. A coefficient is defined as theory-consistent if it is statistically significant at $p > 0.99$ and non-zero or non-negative, following Fontagné et al. (2022). In total, 4061 (Air) and 3589 (Maritime) HS-6 level product categories required at least one refinement step to resolve insignificance or implausibility. For coefficients not meeting this criterion, we applied a multi-level imputation strategy:

1. If the HS-6 level estimate was inconsistent, we imputed the average elasticity from the corresponding HS-4 or HS-2 level.
2. If no aggregate-level average was available (due to insignificant estimates), we substituted estimates from a combined baseline regression (Air and Maritime pooled).
3. If neither was available, we filled in values using HS-6 elasticities from Fontagné et al. (2022).

To address implausibly high (in magnitude) coefficients, we defined a lower-bound threshold of −25. Any elasticity falling below this threshold was considered implausible and replaced:

1. First, from the combined baseline regression (Air and Maritime pooled), provided it met the plausibility criteria.
2. If still below the threshold, by the corresponding HS-6 value from Fontagné et al. (2022).

This structured procedure ensures consistency with theoretical expectations, allows full product coverage, and aligns with standard approaches in the trade elasticity literature. Summary statistics for each refinement step are reported in Tables A.1 and A.2.

Table A.1
Number of product categories with insignificant elasticity estimates after each refinement step.

	Initial regression results	HS-4 Level/HS-2 Level	Baseline	Fontagné et al. (2022)
Maritime	3589	107	8	0
Air	4061	86	20	0

Note: The total number of product categories is 5045.

Table A.2
Number of product categories with plausible (i.e. below the threshold) elasticity values after each step.

	Before	Baseline	Fontagné et al. (2022)
Maritime	648	34	0
Air	1072	70	0

Appendix B. Trade elasticities: Robustness checks

See Figs. B.1 and B.2.

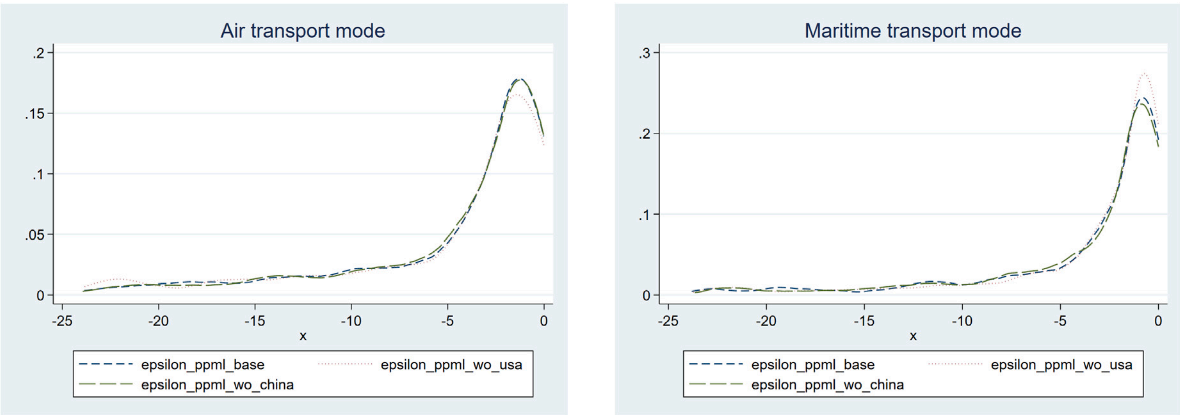

Fig. B.1. The empirical distribution of trade elasticities for each transport mode. The empirical distribution is calculated on HS-6 products with $\epsilon_k < 0$.
Source: Authors' calculations.

Appendix C. Transport cost modeling

The following sections provide a detailed overview of the methods used to estimate the mode-specific transport cost increases resulting from carbon policies.

C.1. Sustainable fuel quotas

The primary goal of the ReFuelEU Aviation and FuelEU Maritime regulations is to support and mandate the uptake of sustainable fuels (SF). To achieve this, mandatory SF quotas are established.[12] This study assumes that hydrocarbon-based fuels from renewable sources will be used to meet these policy requirements. These can be either biogenic in origin (such as bio-kerosene and bio-methanol) or synthesized using renewable electricity through hydrogen electrolysis and direct air carbon capture (DAC). For aviation, the use of e-kerosene is assumed. For maritime shipping, the use of sustainable methanol is assumed, including both bio-methanol

[12] The REFuelAviation regulation mandates airlines to meet a SAF quota, starting at 2% in 2025 and rising to 70% by 2050, for all flights from EU/EEA airports. The FuelEU Maritime regulation requires a gradual reduction in the intensity of greenhouse gases of fuels used by the shipping sector, starting at 2% in 2025 and reaching 80% in 2050. This requirement applies to 50% of the energy used on voyages into or out of the EU or EEA.

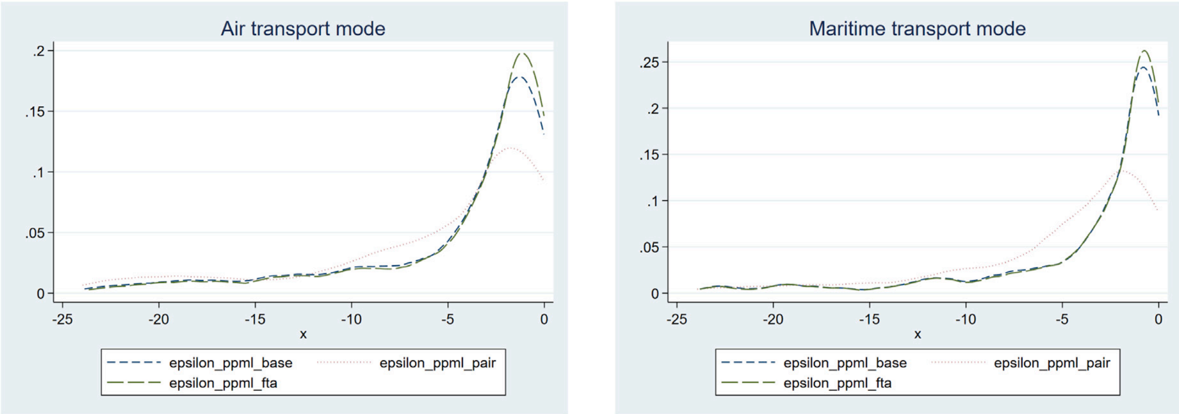

Fig. B.2. The empirical distribution of trade elasticities for each transport mode. The empirical distribution is calculated on HS-6 products with $\epsilon_k < 0$.
Source: Authors' calculations.

and e-methanol, with the required increase in the share of e-methanol mandated in the FuelEU Maritime regulation, reaching up to 80% by 2050. Eq. (C.1) is based on Oesingmann (2023) and provides the calculation of the additional costs per ton kilometer (tkm), attributed to the implementation of a sustainable fuel quota (q_m, t).

$$\Delta c^{SF}_{m,t} = (p^{SF}_{m,t} - p^{FF}_{m,t}) \cdot q_{m,t} \cdot F_{m,t} \tag{C.1}$$

The additional costs, denoted as $\Delta c^{SF}_{m,t}$, reflect the price difference between SF and fossil fuel (FF) multiplied by the sustainable fuel quota (q_t) and the fuel consumption per tkm (F_t). The index t represents the respective year of our analysis, which runs from 2024 to 2050. Based on the literature, we assume annual gains in technological and operational efficiency of 1.3% for air transport (Zheng and Rutherford, 2020) and 1.1% for maritime transport (Horvath et al., 2018). In addition, we account for projected cost decreases in the production of SF. For the product-group-specific analysis, we distinguish between different ship types, as fuel consumption varies significantly between these types. For clarity reasons, the subindex that corresponds to these different types of ship has not been included in the following equations. Detailed assumptions on fuel prices (SF and FF), efficiency gains, and fuel consumption can be found in and in the supplement material.

C.2. EU ETS expansion for maritime shipping

From January 2024, the EU Emission Trading System (EU ETS) has been expanded to include CO_2 emissions from large ships (5000 gross tonnage and above) entering EEA ports (Regulation (EU) 2015/757). This extension covers 50% emissions from voyages starting or ending outside the EU and 100% emissions between and within EU ports. Therefore, the costs for ETS allowances ($c^{ETS}_{m,t}$) using the calculation method introduced in Eq. (C.2) are included.

$$c^{ETS}_{m,t} = p^{ETS}_t \cdot \mathrm{sc}^{ETS}_t \cdot e_{m,t} \cdot (1 - q_t) \cdot F_{m,t} \tag{C.2}$$

Based on an ETS price forecast by Enerdata (2023), a gradual increase in the emission allowance price (p^{ETS}_t) is assumed. It starts from €70 per ton of CO_2 in 2024 and will increase to €250 per ton of CO_2 in 2050. The price of the ETS allowance is multiplied by the scope of the ETS (sc^{ETS}_t), which is continuously expanded during the period from 2024 to 2027.[13] The product of the carbon emission intensity ($e_{m,t}$) the fuel consumption ($F_{m,t}$), and the share of fossil fuel used $(1 - q_t)$ determine the amount of CO_2 (in kg) emitted, which is then subject to ETS.

C.3. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

For the aviation sector, the additional costs due to CORSIA, which applies to international aviation are considered. Since CORSIA is originally planned to be levied on emissions exceeding those of a base year (2019), this measure is more complex to calculate. Due to the COVID-19 pandemic, emissions have remained below 2019 levels in recent years. The ICAO, which adopted CORSIA, has therefore decided to use 85% of the 2019 emissions as a baseline for the years 2024 to 2035 (ICAO, 2024; Graichen and Wissner, 2023). We assume that in 2024, aviation emissions will relate to 85% of 2019 levels. Therefore, from 2025 on, CORSIA would cover additional emissions from global aviation. Based on current CORSIA offset prices, which range between €16 and €22 per ton of CO_2 (ICE, 2024), we start with a CORSIA offset price (p^{Offset}_t) of €20 per ton of CO_2 for the year 2025. Taking into account

[13] According to Regulation (EU) 2015/757 (2015) shipping companies must buy and surrender allowances for their emissions. To ease the transition, they are required to surrender allowances for 40% of their 2024 emissions in 2025, 70% of their 2025 emissions in 2026, and 100% of their emissions from 2027 onward.

Table C.1
Assumptions for air and maritime transport modes.

Assumption	Air transport	Maritime transport
Reference fossil fuel price (2024)	USD 788.47 ton/kerosene	USD 672 ton/VLSFO
Annual fuel efficiency gain	1.3%	1.1%
CO_2 emissions per ton of fuel	3.16 tons of CO_2	3.12 tons of CO_2
Average fuel consumption (2024)	0.472 kg/tkm	0,002 kg/tkm
SF price (2024)	€2740 per ton of SAF	€1590 per ton of Methanol
Cost reduction for SF	2.5% annual reduction in cost	1.5% annual reduction in cost
SF GHG reduction	70% reduction in emissions	100% reduction in emissions

forecasts that predict a much higher offset price of approximately €100 per ton of CO_2 by 2030 (Giannelos et al., 2021), we assume an annual increase of 10% in offset prices for the years following 2024.

The calculation for determining the costs associated with CORSIA is outlined in Eq. (C.3).

$$c_{m,t}^{CORSIA} = (1 - q_t) \cdot F_{m,t} \cdot e_{m,t}^{FF} \cdot p_t^{Offset} + q_t \cdot F_{m,t} \cdot e_{m,t}^{SAF} \cdot p_t^{Offset} \tag{C.3}$$

The equation consists of two components. The first component calculates the CORSIA offset costs associated with the share of fossil fuel used. This is determined by multiplying the amount of fossil fuel ($F_{m,t}$) consumed by its carbon emission intensity ($e_{m,t}^{FF}$) and the CORSIA offset price (p_t^{Offset}) in the respective year. The burning of a ton of kerosene, $e_{m,t}^{FF}$, is associated with 3.16 tons of CO_2 emissions (ICAO, 2018).[14] The second component of Eq. (C.3) accounts for the emissions resulting from the use of SAF. Although SAF has the potential to reduce CO_2 emissions by up to 100%, it is assumed that e-Kerosene achieves a reduction of 70%, based on the life cycle analysis of Braun et al. (2024). The second component incorporates the SAF quota (q_t), the amount of fuel used ($F_{m,t}$), its emission intensity ($e_{m,t}^{SAF}$), and the CORSIA offset price (p_t^{Offset}) to calculate the remaining emissions that require offsetting.

Table C.1 provides an overview of our assumptions about the transport cost model. Transport cost models can also be accessed through the supplementary data section.

C.4. Air freight

For aviation, current fuel prices for fossil kerosene are retrieved from IATA's Jet Fuel Price Monitor and refer to average prices paid at the refinery for aviation jet fuel (IATA, 2024). As of May 31, 2024, the global average price was USD 788.47 per ton of kerosene. In our model, we assume that kerosene prices remain fixed until 2050, excluding inflation. Since we use the Euro as our reference currency, we convert fuel prices from USD to Euro at the current exchange rate (Investing.com, 2024). The yearly average fuel efficiency gains in our model are set at 1.3%, based on long-term averages published by the International Council on Clean Transportation (ICCT) (Zheng & RutheSFord, 2020). The average air freight fuel consumption per ton-kilometer (tkm) in our model for the first year is calculated from data provided by Connekt/Topsector Logistiek (2021). Since we only consider air freight from EU/EEA countries to destinations outside this area, we omit data on fuel consumption for distances between 0–1000 km. For other distances, we have calculated averages, assuming 50% belly cargo and 50% all-freight operations. As the data on fuel consumption in air freight is from 2021, we have applied fuel efficiency gains of 1.3% to project the amount for 2024. The average fuel consumption of air cargo is 0.472 kg/tkm in 2024 in our model. By combining these figures on fuel consumption and CO_2 emissions, we can calculate average CO_2 emissions per ton-kilometer and fuel costs per ton-kilometer over the time horizon of our model (2024–2050).

The variable δ_t gives the obligatory SAF-quota in each year. As a reference price for SAF in 2024, we consider current prices for synthetic SAF (Power-to-Liquid) fuel, assuming that it will not be possible to meet demand for SAF using biofuels. According to Braun et al. (2024), the median price of PtL fuel is 3126.30 USD 2020 per ton. We used the average USD/Euro conversion rate from 2020 to determine a reference price in Euro. Due to economies of scale, it is assumed that production prices for SAF will decrease in the coming years as capacities and demand increase, although the exact amount of this decrease is uncertain. We assume annual efficiency gains and the corresponding cost reductions for the SAF of 2.5%.

C.5. Maritime freight

To obtain accurate estimates of fuel consumption for extra-European maritime transport, we analyzed data from the EU's Thetis MRV System for 2023. This system requires reporting the average fuel consumption per transport work for each ship. For each ship category, we calculated the weighted average fuel consumption, weighted by the total annual CO2 emissions of each ship. Figure XX displays the average fuel consumption per transport work for each type of ship.

Based on the findings of Bouman et al. (2017) and Joung et al. (2020), we assume a linear 25% decrease in average energy consumption for the entire fleet. This reduction is anticipated through the replacement of older ships with newer, more efficient vessels and various efficiency improvements. These improvements include increasing vessel size, optimizing hull shape, reducing

[14] We only consider carbon dioxide (CO_2) emissions in our analysis, even though CORSIA also applies to nitrous oxide (N_2O) and methane (CH_4) emitted by aircrafts.

Table C.2
HS code to ship type mapping with descriptions.

HS code	Description	Ship type
12	Oil seeds, oleaginous fruits, grains, seeds, fruits and plants.	Bulk carrier
151110	Crude palm oil, extracted from the fruit of the oil palm tree, used in food and industrial applications.	Oil tanker
151311	Refined palm oil, not fractionated, commonly used in cooking and food production.	Oil tanker
151321	Refined palm kernel oil, not fractionated, used in food products and industrial applications.	Oil tanker
151190	Other oils not specified elsewhere, including various vegetable and animal oils.	Oil tanker
151800	Animal or vegetable fats and oils, including processed and modified oils such as boiled or oxidized fats.	Oil tanker
151329	Other palm oils and their fractions, refined but not chemically modified.	Oil tanker
25	Salt, sulfur, earths, stones, plastering materials, lime, cement, and other similar bulk commodities.	Bulk carrier
23	Residues and waste from the food industries, as well as prepared animal fodder and feed.	Bulk carrier
26	Ores, slag, and ash, typically mined materials and industrial by-products.	Bulk carrier
27	Mineral fuels, oils, and products derived from their distillation, such as gasoline, diesel, and jet fuel.	Oil tanker
2707	Mineral oil, a refined form of petroleum, often used as a fuel or lubricant.	Oil tanker
2708	Petroleum oils and oils obtained from bituminous minerals, excluding crude oil, typically	Oil tanker
2709	Petroleum jelly, paraffin wax, and other petroleum-based products	Oil tanker
2710	Petroleum oils and preparations, including lubricating oils, oils used in machinery, and greases.	Oil tanker
271121	Liquefied natural gas (LNG), a fuel source derived from natural gas.	LNG carrier
29	Organic chemicals, including various synthetic chemicals.	Chemical tanker
47	Pulp of wood or other fibrous cellulosic material.	Bulk carrier
72	Iron and steel, basic metals used in construction, manufacturing, and various industrial sectors.	Bulk carrier
8701	Passenger vehicles, including automobiles, typically for personal transport and use.	Vehicle carrier
8702	Other motor vehicles, such as trucks and buses, used for cargo transport and public transport.	Vehicle carrier
8703	Motor vehicles for transport of persons.	Vehicle carrier
8704	Motor vehicles designed for the transport of goods, including various types of trucks and delivery vehicles.	Vehicle carrier

Table D.1
Carbon policy scenarios for air and maritime freight transportation across selected years (2025, 2035, and 2050).

	Current policies		Carbon neutrality	
	Air 2025, 2035, 2050	Maritime 2025, 2035, 2050	Air 2025, 2035, 2050	Maritime 2025, 2035, 2050
Sustainable fuel quotas	2%, 20%, 70%	0%, 7%, 33%	4%, 42%, 100%	0%, 33%, 100%
EU ETS scope	–	20%, 50%, 50%	–	20%, 50%, 50%
EU ETS prices	–	€70, €85, €250	–	€70, €85, €250
CORSIA scope	100%	–	100%	–
CORSIA price	€20, €57, €238	–	€20, €57, €238	–

ballast water, applying advanced hull coatings, and implementing hybrid power/propulsion systems and propulsion efficiency devices Bouman et al. (2017). Further emission reduction can only be made possible by speed reduction or by the use of alternative fuels such as methanol or Fischer–Tropsch Diesel.

The fuel consumption per transport work differs largely between ship types. In order to get accurate estimates for the transport cost increase, we have to make some assumptions on which product group is usually transported by which ship type. The assumptions that deviated from the default ship type (Container Ship) are depicted in Table C.2.

Appendix D. Scenario input parameters

In this study, we model two scenarios of carbon policies that differ in their ambition of carbon neutrality. The first scenario (Current Policies) includes policy measures currently implemented for both transport modes. Our second scenario (Carbon Neutrality) requires both transport sectors to achieve carbon neutrality by 2050 through the use of 100% SF. Table D.1 shows the policy parameters with their effective scope and prices for the scenario years 2025, 2035, and 2050.

Appendix E. Sustainable fuel cost assumptions and sensitivity analysis

This appendix provides details on the cost assumptions for sustainable fuels and a sensitivity analysis. The fuel cost trajectories used in this sensitivity analysis include three different scenarios: Base, Low, and High cost assumptions. These assumptions reflect various uncertainties in future technological advancements and scale effects in the production of sustainable fuels (cf. Braun et al., 2024; Kang et al., 2021).

The base case for SAF cost projections is derived from Braun et al. (2024), assuming a linear reduction in costs of 2.5% per year. In the high-cost scenario, a more conservative reduction rate of 2.0% per year is applied, while the low-cost scenario assumes a more rapid decline of 3.0% per year. These rates reflect different assumptions about technological progress, scale economies, and market dynamics influencing the future costs of SAF production.

For sustainable Methanol, the assumed base cost path is derived from the projections outlined in Kang et al. (2021). The fuel mix between bio- and e-methanol is drawn from Regulation (EU) 2023/1805 (2023). The low-cost trajectory assumes that the cost

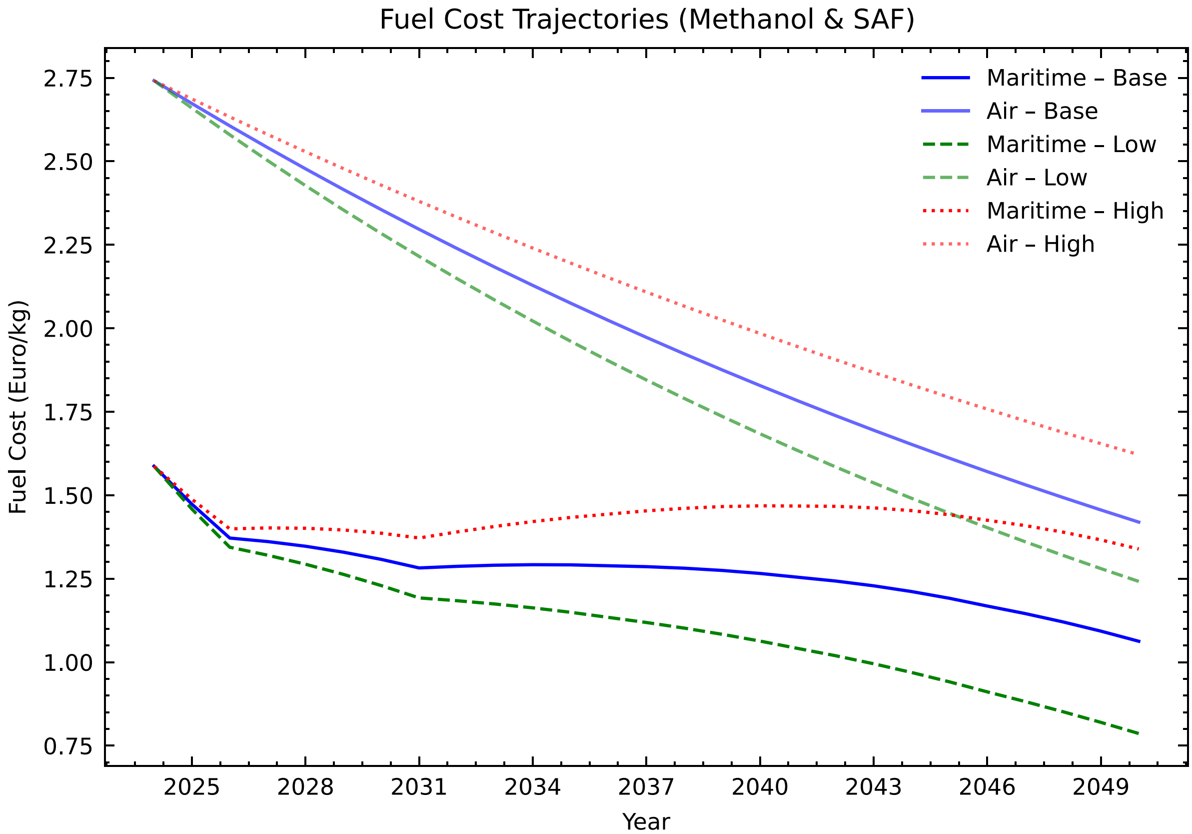

Fig. E.1. Fuel cost trajectories.

of methanol decreases relative to the base case at a fixed annual rate, with the price decreasing by 1% per year from the base cost in 2023.

Fig. E.1 shows the different fuel cost trajectories for methanol (Maritime) and SAF (Air) in the three modeled scenarios (base, low and high cost)

E.1. Implications for the trade assessment

As the relationships within the assessment framework detailed in Section 3.2 are linear, the percentage changes in transport costs translate directly into changes in other relevant metrics, such as trade value, transport work, and fuel demand.

The Sensitivity Analysis figure (Fig. E.2) shows the modeled increases in transportation costs resulting from the different fuel cost assumptions, including the regulatory impacts on air and maritime transport (see Appendix C).

To illustrate how changes in fuel cost assumptions impact these outcomes, consider the case of air transport under the *Carbon Neutrality* scenario E.1. Using the *base case* for fuel cost projections, the total impact on air transport work is projected to be a reduction of 18.9%. In the low-cost scenario, where fuel prices decrease at a faster rate, the impact on air transport work is estimated to be 16.9%, while in the high-cost scenario, with slower fuel cost reductions, the impact is expected to reach 20.9%.

Similarly, for maritime transport, under the *Carbon Neutrality* scenario, the total impact on maritime transport work is projected to be a reduction of 2.9% in the base case. In the low-cost scenario, the impact on maritime transport work is estimated to be 2.3%, reflecting the smaller increase in transportation costs due to the lower fuel price trajectory. In contrast, under the high-cost scenario, the impact is expected to increase to 3.5%, as higher fuel costs further escalate transportation expenses.

Appendix F. Aggregation method of product group-specific results

For the results section, the average price increase for imports and exports is calculated separately for both modes of transport. Based on the relative changes ($\Delta x_{m,k,i,j}$) and under the ceteris paribus assumption that trade volumes and trade structures of the year 2023 remain constant, the absolute change in trade volumes and transport work is derived.

The weighted average price increase for imports and exports, separately for each transport mode m, is calculated as:

$$\Delta P_{m,f} = \frac{\sum_k \sum_{i,j} \Delta P_{m,k,i,j} \cdot v_{m,k,i,j}}{\sum_k \sum_{i,j} v_{m,k,i,j}} \tag{F.1}$$

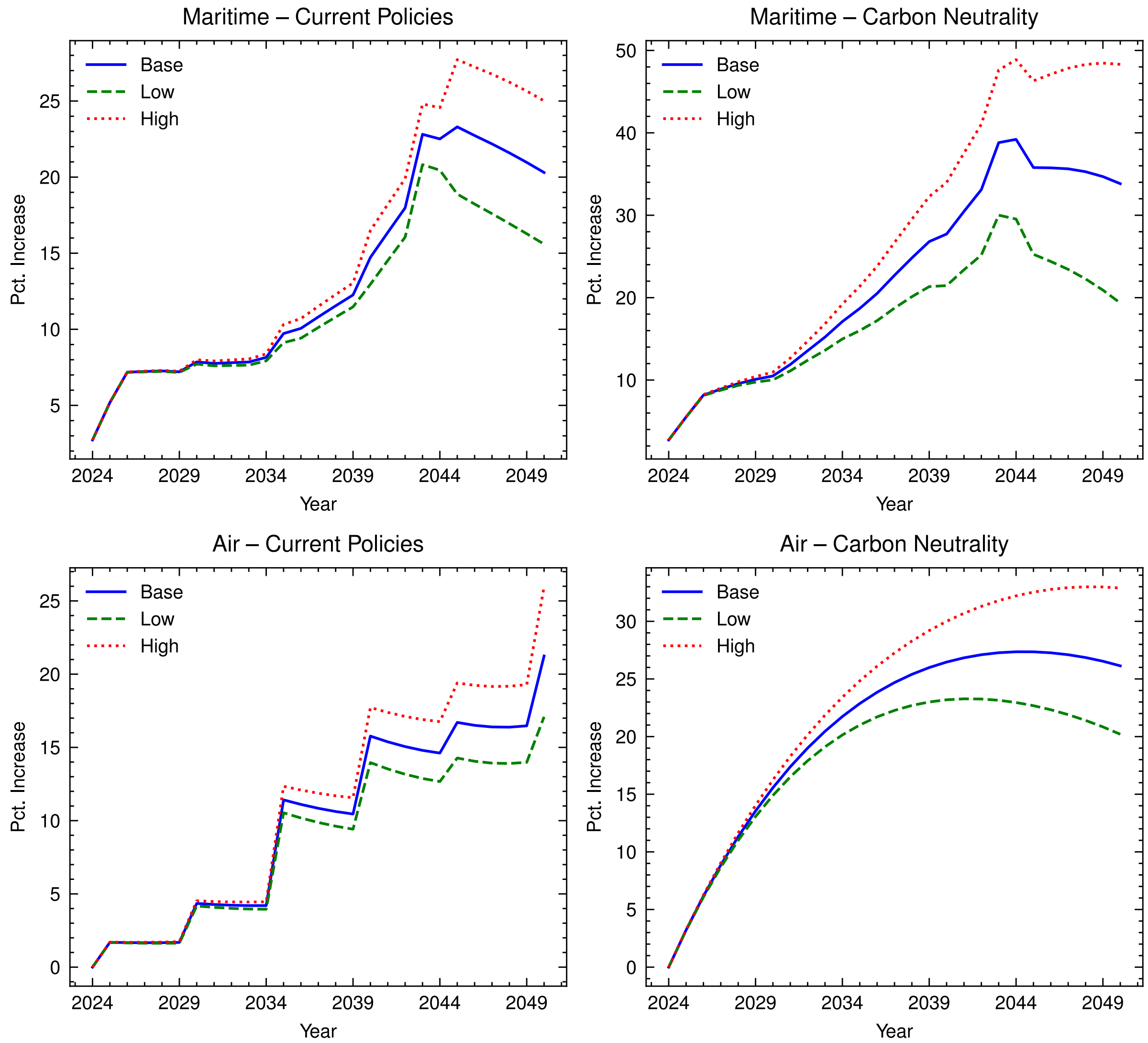

Fig. E.2. Sensitivity analysis - Fuel costs.

Table E.1
Comparison of impacts on trade value, transport work and fuel demand under *Current Policies* and *Carbon Neutrality* scenarios, differentiated between trade direction.

		Current policies	Carbon neutrality
Impact on imports	Base cost	−1.0%	−1.8%
	Low cost	−0.8%	−1.5%
	High cost	−1.2%	−2.1%
Impact on exports	Base cost	−1.2%	−2.1%
	Low cost	−1.1%	−1.7%
	High cost	−1.3%	−2.5%
Transport work air	Base cost	−12.8%	−18.9%
	Low cost	−11.7%	−16.9%
	High cost	−13.9%	−20.9%
Transport work maritime	Base cost	−1.7%	−2.9%
	Low cost	−1.6%	−2.3%
	High cost	−1.8%	−3.5%

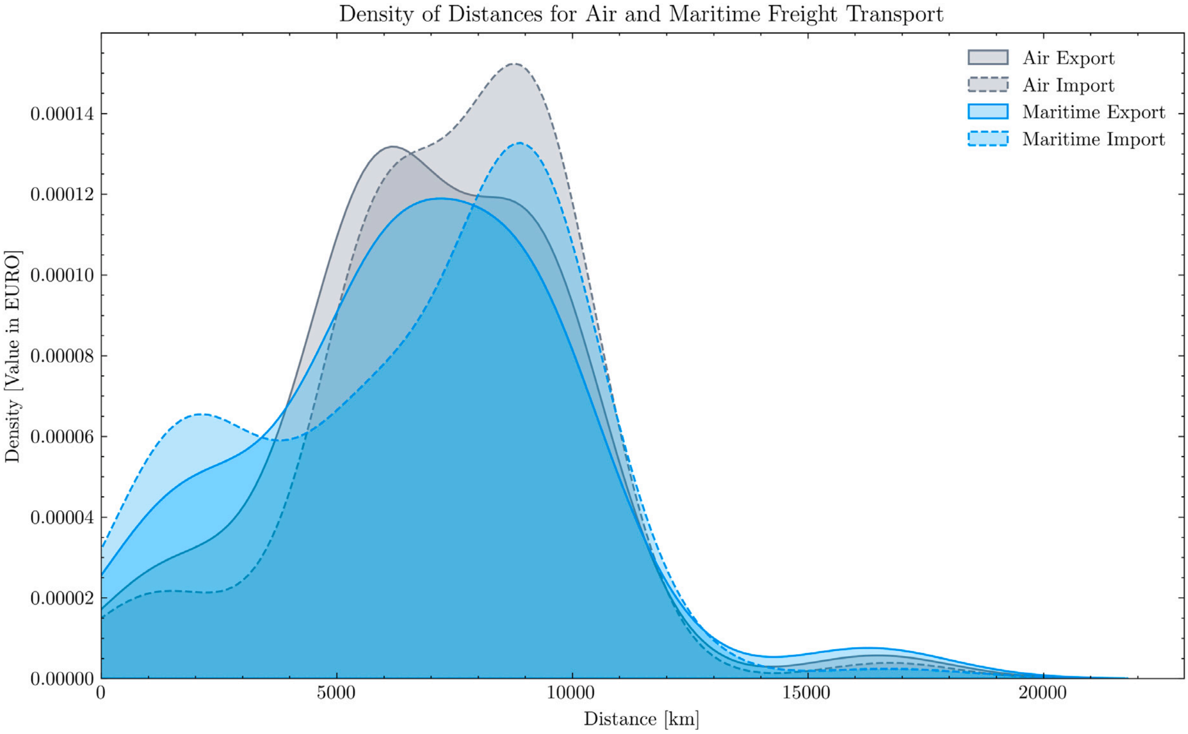

Fig. G.1. Densities of distances of air and maritime freight transport.

where:

- $\Delta P_{m,k,i,j}$: absolute price increase for a specific trade flow (Eq. (5)),
- $v_{m,k,i,j}$: monetary value of the trade flow.

The aggregate change in trade value ($\Delta X_{m,f}$) for each transport mode m and trade flow f (imports or exports) is calculated as

$$\Delta X_{m,f} = \sum_{k} \sum_{i,j} \Delta x_{m,k,i,j} \cdot v_{m,k,i,j} \tag{F.2}$$

where:

- $\Delta x_{m,k,i,j}$: relative change in trade value for a specific trade flow (cf. Eq. (7)),
- $v_{m,k,i,j}$: monetary value of the trade flow.

The change in transport work ($\Delta TW_{m,f}$), measured in ton-kilometers, is calculated as the product of the change in trade value, the trade quantity in tons, and the distance in kilometers for each trade flow:

$$\Delta TW_{m,f} = \sum_{k} \sum_{i,j} \Delta x_{m,k,i,j} \cdot q_{m,k,i,j} \cdot d_{m,k,i,j} \tag{F.3}$$

where:

- $q_{m,k,i,j}$: trade quantity (in tons) for a specific trade flow,
- $d_{m,k,i,j}$: distance for the trade flow,
- $\Delta x_{m,k,i,j}$: relative change in trade value for the specific trade flow (cf. Eq. (7)).

Appendix G. Weighted distances for exports and imports

See Fig. G.1.

Appendix H. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.trd.2025.104812. To support transparency and reproducibility, the supplementary material includes all key components of the analysis, including data processing,

Table H.1
Overview of supplementary scripts.

Filename	Description
01_data_download_comext.ipynb	Downloads Eurostat Comext trade data used as the primary input source.
02_data_preprocessing_trade.ipynb	Prepares trade data for elasticity estimation, including cleaning and aggregation.
03_estimate_trade_elasticities.do	Stata script estimating trade elasticities for air and maritime transport at the HS-6 level.
04_cost_scenarios_modeling.ipynb	Models transport cost increases under various carbon policy scenarios.
05_impact_assessment_scenarios.ipynb	Executes the scenario analysis and produces quantitative results on trade, GDP, and fuel demand.

elasticity estimation, and scenario modeling (see Table H.1). All supplementary scripts and data can be made available upon request through a secure file-sharing system. Please contact the corresponding author for access.

Data availability

Data will be made available on request.

References

Agnosteva, D.E., Anderson, J.E., Yotov, Y.V., 2014. Intra-National Trade Costs: Measurement and Aggregation. Technical Report, National Bureau of Economic Research.

Aigner, M., Aliabadi, D.E., Amri-Henkel, A., Anderson, J., Becker, L., Bergfeld, M., Brand-Daniels, U., Braun-Unkhoff, M., Brinkop, S., Brosowski, A., Deniz, Ö., Dietrich, R.-U., Eisenmann, C., Ennen, D., Eschmann, J., Frieske, B., Grimme, W., Haas, S., Hasselwander, S., Hauser, E., Heib, S., Heimann, N., Hendricks, J., Hildebrand, J., Hoyer-Klick, C., Jordan, M., Kronshage, S., Lutz, C., Mantke, H., Matschoss, P., Mertens, M., Neitz-Regett, A., Österle, I., Oswald, M., Pichlmaier, S., Prause, J., Pregger, T., Raab, M., Richter, S., Ruiz, E.S.A., Wulff, N., Zeck, B., 2023. Roadmap für Strombasierte Kraftstoffe [Roadmap for Electricity-Based Fuels]. Gesamtbericht zur Begleitforschung Energiewende im Verkehr (BEniVer) [Full Report on the Accompanying Research for the Energy Transition in Transport (BEniVer)], DLR, IZES, FfE, UFZ, DBFZ, GWS, URL: https://elib.dlr.de/200260/.

Anderson, J., 2011. The gravity model. Annu. Rev. Econ. 3 (1), 133–160.

Anderson, J.E., Van Wincoop, E., 2003. Gravity with gravitas: A solution to the border puzzle. Am. Econ. Rev. 93 (1), 170–192. http://dx.doi.org/10.1257/000282803321455214.

Baier, S.L., Bergstrand, J.H., 2007. Do free trade agreements actually increase members' international trade? J. Int. Econ. 71 (1), 72–95. http://dx.doi.org/10.1016/j.euroecorev.2015.06.003.

Baldwin, R., Taglioni, D., 2007. Trade effects of the euro: A comparison of estimators. J. Econ. Integr. 780–818. http://dx.doi.org/10.11130/jei.2007.22.4.780.

Barbot, C., Betancor, O., Socorro, M.P., Viecens, M.F., 2014. Trade-offs between environmental regulation and market competition: Airlines, emission trading systems and entry deterrence. Transp. Policy 33, 65–72. http://dx.doi.org/10.1016/j.tranpol.2014.02.008, URL: https://www.sciencedirect.com/science/article/pii/S0967070X14000390.

Bensassi, S., Martinez-Zarzoso, I., Suárez, C., 2014. The effect of maritime transport costs on the extensive and intensive margins: Evidence from the Europe–Asia trade. Marit. Econ. Logist. 16 (3), 276–297. http://dx.doi.org/10.1057/mel.2014.3.

Bertoli, S., Goujon, M., Santoni, O., 2016. The CERDI-seadistance database [Data set]. http://dx.doi.org/10.5281/zenodo.46822.

Boehm, C.E., Levchenko, A.A., Pandalai-Nayar, N., 2023. The long and short (run) of trade elasticities. Am. Econ. Rev. 113 (4), 861–905.

Bouman, E.A., Lindstad, E., Rialland, A.I., Strømman, A.H., 2017. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping — A review. Transp. Res. Part D: Transp. Environ, 52, 408–421. http://dx.doi.org/10.1016/j.trd.2017.03.022.

Brander, J.A., Zhang, A., 1990. Market conduct in the airline industry: An empirical investigation. Rand J. Econ. 21 (4), 567–583. http://dx.doi.org/10.2307/2555469, URL: https://www.jstor.org/stable/2555469. Publisher: [RAND Corporation, Wiley].

Braun, M., Grimme, W., Oesingmann, K., 2024. Pathway to net zero: Reviewing sustainable aviation fuels, environmental impacts and pricing. J. Air Transp. Manag. 117, 102580. http://dx.doi.org/10.1016/j.jairtraman.2024.102580.

Carrère, C., Mrázová, M., Neary, J.P., 2020. Gravity without apology: the science of elasticities, distance and trade. Econ. J. 130 (628), 880–910.

Chao, C.-C., 2014. Assessment of carbon emission costs for air cargo transportation. Transp. Res. Part D: Transp. Environ. 33, 186–195. http://dx.doi.org/10.1016/j.trd.2014.06.004.

Chi, J., Baek, J., 2012. Price and income elasticities of demand for air transportation: Empirical evidence from US airfreight industry. J. Air Transp. Manag. 20, 18–19. http://dx.doi.org/10.1016/j.jairtraman.2011.09.005.

Connekt/Topsector Logistiek, 2021. Guideline 8 - Air freight: Cargo aircraft and combination of passengers/freight: Carbon footprint in logistics. URL: https://carbonfootprinting.org/wp-content/uploads/2022/02/8-Air-freight.pdf.

Conte, M., Cotterlaz, P., Mayer, T., 2022. The CEPII Gravity Database. CEPII Working Paper 2022–05, CEPII.

Costinot, A., Rodríguez-Clare, A., 2014. Trade theory with numbers: Quantifying the consequences of globalization. In: Handbook of International Economics. Vol. 4, Elsevier, pp. 197–261.

Coto-Millán, P., Baños-Pino, J., Castro, J.V., 2005. Determinants of the demand for maritime imports and exports. Transp. Res. Part E: Logist. Transp. Rev. 41 (4), 357–372. http://dx.doi.org/10.1016/j.tre.2004.05.002.

EEA, 2023. Approximated estimates for greenhouse gas emissions, 2022. URL: https://sdi.eea.europa.eu/catalogue/srv/api/records/f86e5d0e-fb08-46ae-9cb9-e5338a2174dc.

Egger, P.H., Nigai, S., 2015. Structural gravity with dummies only: Constrained ANOVA-type estimation of gravity models. J. Int. Econ. 97 (1), 86–99. http://dx.doi.org/10.1016/j.jinteco.2015.05.004.

Enerdata, 2023. Carbon price forecast 2030–2050. URL: https://www.enerdata.net/publications/executive-briefing/carbon-price-projections-eu-ets.html.

Eurostat, 2024. Comext database: International trade data, DS-059334. https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/database. (Accessed 15 August 2024).

Faber, J., Markowska, A., Eyring, V., Cionni, I., Selstad, E., 2010. A Global Maritime Emissions Trading System - Design and Impacts on the Shipping Sector, Countries and Regions. Report Commissioned by the Bundesministerium für Umwelt, Naturschutzund Reaktorsicherheit [Federal Ministry for the Environment, Nature Conservation and Nuclear Safety], CE Delft, URL: https://cedelft.eu/publications/a-global-maritime-emissions-trading-system/.

Fontagné, L., Guimbard, H., Orefice, G., 2022. Tariff-based product-level trade elasticities. J. Int. Econ. 137, 103593. http://dx.doi.org/10.1016/j.jinteco.2022.103593.

Giannelos, G., Humphris-Bach, A., Davies, A., Baxter, B., Cames, M., Kasten, P., Siskos, P., Tsiropoulos, I., Kalokyris, T., Statharas, S., 2021. Study Supporting the Impact Assessment of the ReFuelEU Aviation Initiative – Final Report. Study Prepared for the European Commission, Publications Office of the European Union, http://dx.doi.org/10.2832/219963.

Graichen, V., Wissner, N., 2023. Aviation in the EU ETS and CORSIA in the 'Fit for 55' Package: The EU Agreement of June 2023. Fact Sheet, Umweltbundesamt [German Environmental Agency], URL: https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/09_2023_factsheet_aviation_in_the_eu_ets_and_corsia.pdf.

Halim, R.A., Smith, T., Englert, D.P., 2019. Understanding the Economic Impacts of Greenhouse Gas Mitigation Policies on Shipping: What is the State of the Art of Current Modeling Approaches? Policy Research Working Paper 8695, World Bank, URL: https://ssrn.com/abstract=3320893.

Head, K., Mayer, T., 2014. Gravity equations: Workhorse, toolkit, and cookbook. In: Handbook of International Economics. Vol. 4, Elsevier, pp. 131–195.

Horvath, S., Fasihi, M., Breyer, C., 2018. Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040. Energy Convers. Manage. 164, 230–241. http://dx.doi.org/10.1016/j.enconman.2018.02.098.

Hummels, D., Lugovskyy, V., Skiba, A., 2009. The trade reducing effects of market power in international shipping. J. Dev. Econ. 89 (1), 84–97. http://dx.doi.org/10.1016/j.jdeveco.2008.05.001.

ICAO, 2018. ICAO carbon emissions calculator methodology. URL: https://applications.icao.int/icec/Methodology%20ICAO%20Carbon%20Calculator_v11.1-2018.pdf.

ICAO, 2024. COVID-19 impacts and 2022 CORSIA periodic review. URL: https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-and-Covid-19.aspx.

ICE, 2024. CORSIA eligible emissions units (2024–2026) futures pricing. URL: https://www.ice.com/products/83046673/CORSIA-Eligible-Emissions-Units-2024-2026-Futures/data?marketId=7490945&span=2.

ICF Consulting, Air Transportation Analytics, NewClimate Institute, Cambridge Econometrics, HFW, Starckx, S., 2022. Assessment of ICAO's Global Market-Based Measure (CORSIA) Pursuant to Article 28b and for Studying Cost Pass-Through Pursuant to Article 3d of the EU ETS Directive. Study Prepared for the European Commission, Publications Office of the European Union, http://dx.doi.org/10.2834/714858.

IMO, 2025. IMO approves net-zero regulations for global shipping. URL: https://www.imo.org/en/MediaCentre/PressBriefings/pages/IMO-approves-netzero-regulations.aspx.

Joung, T.-H., Kang, S.-G., Lee, J.-K., and, J.A., 2020. The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050. J. Int. Marit. Safety Environ. Affairs Shipp. 4 (1), 1–7. http://dx.doi.org/10.1080/25725084.2019.1707938.

Kang, S., Boshell, F., Goeppert, A., Prakash, S.G., Landälv, I., Saygin, D., 2021. Innovation Outlook: Renewable Methanol. International Renewable Energy Agency, Abu Dhabi.

Koopmans, C., Lieshout, R., 2016. Airline cost changes: To what extent are they passed through to the passenger? J. Air Transp. Manag. 53, 1–11. http://dx.doi.org/10.1016/j.jairtraman.2015.12.013, URL: https://www.sciencedirect.com/science/article/pii/S096969971600003X.

Lo, W.W.L., Wan, Y., Zhang, A., 2015. Empirical estimation of price and income elasticities of air cargo demand: The case of Hong Kong. Transp. Res. Part A: Policy Pr. 78, 309–324. http://dx.doi.org/10.1016/j.tra.2015.05.014.

Merkel, A., Johansson, M., Lindgren, S., Vierth, I., 2022. How (in)elastic is the demand for short-sea shipping? A review of elasticities and application of different models to Swedish freight flows. Transp. Rev. 42 (4), 551–571. http://dx.doi.org/10.1080/01441647.2021.2010834.

Mundaca, G., 2024. Short- and long-term effects of carbon taxation on the prices of products shipped by sea. Energy Policy 193, 114292. http://dx.doi.org/10.1016/j.enpol.2024.114292.

Nava, C.R., Meleo, L., Cassetta, E., Morelli, G., 2018. The impact of the EU-ETS on the aviation sector: Competitive effects of abatement efforts by airlines. Transp. Res. Part A: Policy Pr. 113, 20–34. http://dx.doi.org/10.1016/j.tra.2018.03.032, URL: https://www.sciencedirect.com/science/article/pii/S0965856416310941.

Oesingmann, K., 2023. The economic impacts of EU climate policies on intra-European aviation. In: Demir, E., Bilgin, M.H., Danis, H., D'Ascenzo, F. (Eds.), Eurasian Business and Economics Perspectives. Springer, pp. 433–452. http://dx.doi.org/10.1007/978-3-031-30061-5_27.

Olivero, M.P., Yotov, Y.V., 2012. Dynamic gravity: endogenous country size and asset accumulation. Can. J. Econ. Rev. Can. Econ. 45 (1), 64–92.

Parro, F., 2013. Capital-skill complementarity and the skill premium in a quantitative model of trade. Am. Econ. J.: Macroecon. 5 (2), 72–117. http://dx.doi.org/10.1257/mac.5.2.72.

Pons, A., Martin, C., Andrew, E., Finney, H., Kwon, H., Millard, K., Budaragina, M., Scarbrough, T., Siskos, P., De Vita, A., Paroussos, L., Charalambidis, I., Tsiropoulos, I., Mavrouli, E., van der Laan, J., Lam, L., 2021. Study on EU ETS for Maritime Transport and Possible Alternative Options of Combinations to Reduce Greenhouse Gas Emissions – Final Report. Study Prepared for the European Commission, Publications Office of the European Union, http://dx.doi.org/10.2834/27271.

Regulation (EU) 2015/757, 2015. Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the monitoring, reporting and verification of greenhouse gas emissions from maritime transport, and amending Directive 2009/16/EC. URL: http://data.europa.eu/eli/reg/2015/757/2024-01-01.

Regulation (EU) 2023/1805, 2023. Regulation (EU) 2023/1805 of the European parliament and of the council of 13 september 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending directive 2009/16/EC. URL: http://data.europa.eu/eli/reg/2023/1805/oj.

Regulation (EU) 2023/2405, 2023. Regulation (EU) 2023/2405 of the European parliament and of the council of 18 october 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU aviation). URL: https://eur-lex.europa.eu/eli/reg/2023/2405/oj.

Sheng, Y., Shi, X., Su, B., 2018. Re-analyzing the economic impact of a global bunker emissions charge. Energy Econ. 74, 107–119. http://dx.doi.org/10.1016/j.eneco.2018.05.035.

Silva, J.S., Tenreyro, S., 2006. The log of gravity. Rev. Econ. Stat. 641–658. http://dx.doi.org/10.1162/rest.88.4.641.

Silva, J.S., Tenreyro, S., 2011. Further simulation evidence on the performance of the Poisson pseudo-maximum likelihood estimator. Econom. Lett. 112 (2), 220–222. http://dx.doi.org/10.1016/j.econlet.2011.05.008.

Yotov, Y.V., Piermartini, R., Larch, M., et al., 2016. An Advanced Guide to Trade Policy Analysis: The Structural Gravity Model. WTO iLibrary.

Zheng, X.S., Rutherford, D., 2020. Fuel Burn of New Commercial Jet Aircraft: 1960 to 2019. White Paper, International Council on Clean Transportation (ICCT), URL: https://theicct.org/publication/fuel-burn-of-new-commercial-jet-aircraft-1960-to-2019/.