UNICA

UNIVERSITÀ
DEGLI STUDI
DI CAGLIARI

Ph.D. DEGREE IN
Civil Engineering and Architecture

Cycle XXXVIII

TITLE OF THE Ph.D. THESIS

Investigating the decarbonization process of the maritime transport sector
Quantifying and reducing greenhouse gas emissions

Scientific Disciplinary Sector(s)

08/CEAR-03/B

Ph.D. Student:	Daniel Mark Vitiello
Supervisor	Prof. Gianfranco Fancello
Co-Supervisor	Prof. Patrizia Serra Prof. Thierry Vanelslander

Final exam. Academic Year 2024/2025
Thesis defence session: February 2026

Daniel Mark Vitiello

Investigating the decarbonization process of the maritime transport sector

Quantifying and reducing greenhouse gas emissions

Thesis for the Degree of Ph.D. in Civil Engineering and Architecture

Cagliari, February 2026

University of Cagliari
Faculty of Engineering and Architecture
Department of Civil and Environmental Engineering and Architecture

UNICA

UNIVERSITÀ
DEGLI STUDI
DI CAGLIARI

To my large family,
To the loved ones.

Acknowledgements

If you are reading these words, it means that I have finished to write this Ph.D. thesis. But behind this work, more than anything else, there's people. People that I have known since the beginning, people I have met during this journey, people who have left me with memories. And I would like to use this white page to thank all these people.

First of all, I would like to thank to my supervisor Professor Fancello, the one that five years ago welcomed me in his research group, and from who I learn every day. Thank you for this opportunity and for your constant support throughout this work.

I would also like to thank my co-supervisor, Professor Serra, for dedicating her valuable time to my research, sharing valuable insights, and helping me successfully complete this thesis.

Thank you, Gianfranco and Patrizia, for your kindness and patience, in particular in the difficult moments.

I am very grateful to my co-supervisor Prof. Vanelslander, and to all the Department of Transport and Regional Economics of the University of Antwerp, for the precious opportunity that I had to immerse myself in a new environment, where I have definitely learnt a lot – in many ways. Thanks also to the medical team that operated on me.

I wish to thank the reviewers for their valuable comments on the previous versions of the thesis.

Thanks to my colleges (and ex colleagues) with who I share most of my time during the week. Thank you for the support, Alessandra, Alessandro, Carla, Mara, Mattia, Michela, Michele, Silvia, Simone.

A big *dank je well* goes to all the people with who I spent the six months in Antwerp, guys, you will always be in my memory. Best wishes to all. A particular thank you goes to Felipe and Max, for helping me during the first period, for the support, for the home cooking, and all the rest!

A warm big hug goes to my parents, my brother, my (large) family, and all my friends. I really believe in family love, and in these three years, I have received much of it. Thank you for the Christmas dinners, for the birthday cakes, for the joy, the noise, the wine. Thank you for understanding and supporting my work.

And last, but not least, I would like to say a very special THANK YOU to Maria Carla, known also as Carla or *. My friend, my colleague, my accomplice, my love. I'm not sure that starting one Ph.D. is easy, but starting two is certainly a challenge….a challenge that we overcame together! Thank you for your support in the difficult moments, for your positive attitude towards life, for your pancakes, for your smile. Thank you for sharing the same important beliefs, and, overall, your time.

Abstract

The maritime freight transport sector is a significant contributor to the global greenhouse gas (GHG) emissions, which are expected to increase further in the coming decades unless action is taken. The need to reduce them is pressing. In order to achieve this, decarbonisation strategies must be adopted. Decarbonisation strategies involve the setting of environmental targets, the quantification and reporting of GHG emissions, and the implementation of reduction measures.

The environmental targets focus on reducing both the total amount of GHG emissions (measured in CO_2 equivalent - CO_2e) and the GHG emission intensity (measured in CO_2e/t-km or CO_2e/TEU-km). While the total aggregate GHG emissions are essential for understanding the environmental impact of a transport mode, the emission intensity measures the environmental efficiency, and its commonly used as an indicator for environmental friendliness. Emission intensity can also be used to compare the (environmental) efficiency of different modes of transport. Based on this metric, it is known that maritime transport is more efficient than other modes of transport. The correct and accurate quantification of GHG emissions and GHG emission intensity is essential for their reduction and for determining the most impactful reduction measures. Furthermore, from the polluters-pay point of view, the GHG emissions must also be fairly allocated to the quantity of goods transported. Therefore, a comprehensive, transparent and standardised methodology for the quantification, allocation and reporting of GHG emissions from maritime freight transport is required. Furthermore, the identification, implementation and adoption of reduction measures is central in the decarbonization strategies. In the case of the maritime freight transport sector, these measures can be classified in technical, operational, and market-based measures (MBMs). A significant example of MBMs is the European Emissions Trading System (EU-ETS), closely connected to the polluters-pays principle, which involves the implementation of tradable carbon allowances (which grant companies the right to emit CO_2e) operating on a "cap-and-trade" system.

Given this context, this doctoral thesis will focus on decarbonisation processes in the maritime freight transport sector. The aim is to provide useful and original insights into a possible integration between GHG emissions quantification methodologies and emissions reduction measures, identifying also critical aspects and weaknesses.

This Ph.D. thesis is based on an application approach. It starts with an overview of the Regulatory context, a critical analysis of the potential greenhouse gas emission reduction measures and policies, and an analysis and classification of the latest available methodologies for quantifying greenhouse gas emissions in maritime freight transport chains. The methodological framework adopted was then developed and validated through two case studies: 1) An application of the quantification methodology, proposed by the ISO 14083:2023 standard and the GLEC Framework of the Smart Freight Centre, to a real case study involving a maritime Ro-Ro (roll-on/roll-off) transport chain in the Mediterranean area; 2) An evaluation of the economic impact of the maritime EU-ETS extra-costs using an economic and environmental model implemented in two case studies.

The first application revealed some of the operational difficulties that companies may encounter when using this methodology to quantify their carbon footprint. One of the main issues is acquiring and monitoring primary data, which is highly recommended for accurate results. Furthermore, the results of the case study highlighted a critical issue in the GHG emission intensity metric recommended by the ISO 14083 standard. The emission intensity is indeed calculated based on the quantity of goods transported in tonnes. However, this is not always appropriate for pure Ro-Ro maritime transport, particularly when combined with other modes of transport. This highlights the need for alternative metrics, for example, based on lane metres or vehicles.

The second application shows that, from the carrier's perspective, technical and operational reduction measures can, in general, help to contain the extra-costs related to the implementation of the maritime EU-ETS. However, these additional costs are often passed on by the carrier to the shippers, resulting in increased transport costs. This is particularly the case for the European Ro-Ro segment, which is strongly affected by these extra-costs due to its high fuel consumption and the nature of its services. These surcharges are applied based on the quantity of freight. In the case of containerized transport, the cost is defined per TEU (twenty-equivalent unit), whereas for Ro-Ro transport, it is defined per lane metre or per vehicle, in line with how Ro-Ro freight is priced. Therefore, the results of the application highlight the need to introduce appropriate emission intensity metrics for the various segments of the shipping sector, in order to allocate the correct amount of emissions to transported cargo.

In summary, this Ph.D. thesis investigated the decarbonisation process in the maritime freight transport sector, offering valuable insights into the potential integration between quantification methodologies and reduction measures. The results emphasised the importance of selecting appropriate metrics for evaluating the GHG emission intensity of different maritime transport segments. Indeed, the outcomes of the case studies analysed in this work suggest that, in the case of pure Ro-Ro maritime transport, GHG emission intensities should be based on lane metres or vehicles rather than tonnes. In fact, using this alternative metric would allow the actual loading capacity of the ship, including empty semi-trailers, to be assessed and represented more immediately and directly. Furthermore, it would establish a relationship between the methodologies for calculating emissions and the reduction measures associated with the polluter-pay principle, enabling the GHG emissions to be allocated more coherently to the transported freight.

Table of content

List of Tables

List of Figures

1. Introduction

Freight maritime transport plays a key role in global trade, facilitating the movement of more than 80% of goods around the world. In the period 2025-2029, total seaborne trade is expected to grow at an annual average of 2.4 per cent and containerized trade by 2.7 per cent (UNCTAD, 2024). This traffic growth is followed by higher greenhouse gas (GHG) emissions, that are expected to further increase in the coming decades if no action is taken. The need to reduce them is pressing.

In order to mitigate these emissions, decarbonisation strategies must be adopted. Decarbonization strategies involve: 1) Quantification and reporting of the GHG emissions, 2) Setting environmental targets for GHG reductions, 3) Implementation of GHG emission reduction measures.

Many reduction targets have been set at the international and the regional levels. Environmental targets focus on reducing both the total amount of GHG emissions (measured in CO_2 equivalent - CO_2e) and the GHG emission intensity (measured in CO_2e/t-km or CO_2e/TEU-km). While the total aggregate GHG emissions are essential for understanding the environmental impact of a transport mode, the emission intensity measures the environmental efficiency, and its commonly used as an indicator for environmental friendliness. Emission intensity can also be used to compare the (environmental) efficiency of different modes of transport.

The correct and accurate quantification of GHG emissions and GHG emission intensity is essential for their reduction and for determining the most impactful reduction measures. Furthermore, from the polluters-pay point of view, the GHG emissions must also be fairly allocated to the quantity of goods transported. Therefore, a comprehensive, transparent and standardised methodology for the quantification, allocation and reporting of GHG emissions from maritime freight transport is required. Furthermore, the identification, implementation and adoption of reduction measures is central in the decarbonization strategies. In the case of the maritime freight transport sector, these measures can be classified in technical, operational, and market-based measures (MBMs). A significant example of MBMs is the European Emissions Trading System (EU-ETS), closely connected to the polluters-pays principle, which involves the implementation of tradable carbon allowances (which grant companies the right to emit CO_2e) operating on a "cap-and-trade" system.

This Chapter introduces the purpose and the methodology of the research. First, the background and the key elements are presented. Subsequently, the problem statement, the aim and the objectives, as well as the methodological framework of this study will be discussed. Finally, the structure of the thesis will be illustrated.

1.1. Background

1.1.1. Global warming and anthropogenic climate change

Anthropogenic climate change is recognized by the scientific community as a key challenge for human society, with the greenhouse gas emissions as one of the main drivers (World Meteorological Organization, 2025). Therefore, to limit and stop climate change, we need to greatly reduce global emissions of greenhouse gases.

In December 2015, 196 member parties of the United Nations Framework Convention on Climate Change (UNFCC) unanimously agreed to adopt the Paris Agreement at the Paris Climate Change Conference (COP21). The Agreement aims to limit the global average temperature increase to below 2°C above pre-industrial levels and to work towards limiting it to below 1.5°C (UNFCC, 2015). It outlines plans for global action to address climate change after 2020 in response to rising global greenhouse gas concentrations and temperatures (Berndes et al., 2016). However, the existing policies and the political responses to mitigation are so far insufficient to achieve the goals of the Paris Agreement (Santos et al., 2022).

The growth of global warming is roughly proportional to the cumulative amount of carbon dioxide (CO_2) released into the atmosphere (IEA, 2024; Rogelj et al., 2019), so temperature targets mean emissions reduction targets. Therefore, carbon emissions play an important part in controlling climate change (Zhang et al., 2022).

Carbon neutrality is a goal or process that the GHG emissions generated by human economic and social activities are captured to use or store for net-zero emissions to the atmosphere through carbon sink and other technical means. The concept of carbon neutrality is derived from net-zero emissions (Jia and Lin, 2021). As of February 2021, 124 countries worldwide have declared their intention to become carbon neutral and achieve net zero carbon emissions by 2050 or 2060 (Chen, 2021). In order to achieve the goals outlined in the Paris Agreement and promote sustainable development, it is crucial not only to reduce CO_2 emissions, but also to remove CO_2 from the atmosphere to achieve net-zero or negative carbon emissions. This can be achieved through various social, economic, environmental and technological measures.

Annex A of the Kyoto Protocol lists the primary greenhouse gases commonly included when considering GHG emissions. The gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases, of which nitrogen trifluoride (NF_3), sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs). The common standard unit used to quantify greenhouse gas emissions is the carbon dioxide equivalent (CO_2e or CO_2eq). It expresses the impact of various greenhouse gases as a single value by converting them into the corresponding amount of carbon dioxide. This conversion is obtained by multiplying the mass of each gas by its Global Warming Potential (GWP), a measure of how much heat it traps in the atmosphere compared to CO_2 over a specific time period. Table 1.1 shows the GWP, over a period of 100 years, for the considered greenhouse gases, while Figure 1.2 provides the global trend of GHG emissions for the three main gases, from 1850 to 2023.

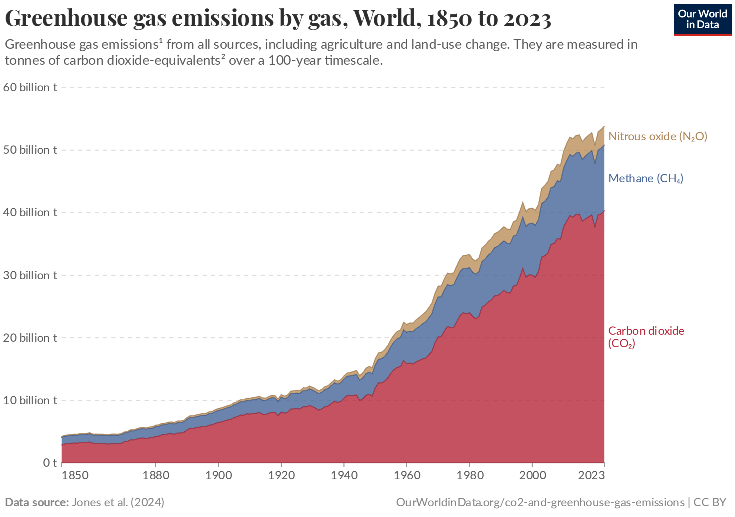


Figure 1.1: Greenhouse gas emissions by gas, World, 1850-2023. Source: www.ourworldindata.org.

Table 1.1: Global warming potential (GWP-100) for each type of gas.

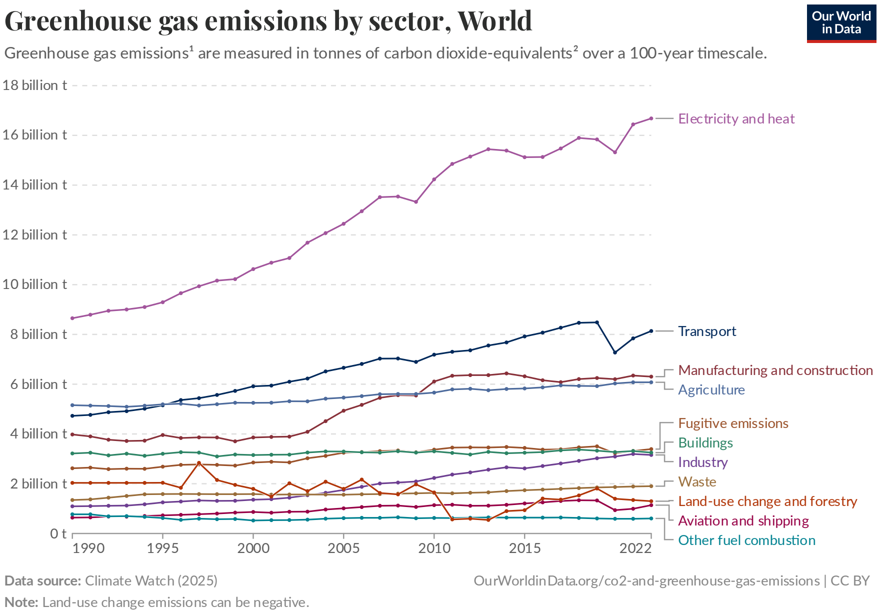
CO_2	CH_4-non fossil	CH_4-fossil	N_2O	NF_3	SF_6	HFC-134a*	PFC-4*
1	27	29.8	273	17,400	24,300	1,530	7,380

NOTE: *Chosen as representative of the typology of gas. Source: Sixth Assessment Report (IPCC, 2023)

1.1.2. Greenhouse gas emissions and the transport sector

In the last decades, decarbonising the transport sector has become a key objective of policies aimed at reducing greenhouse gas emissions (see, for example, the Kyoto Protocol, the United Nations Framework Convention on Climate Change and the Green Deal).

According to the data presented in Figure 1.2, the total net anthropogenic GHG emissions in 2023 reached 53.8 $GtCO_2e$, approximately 44% higher than in 1990 (Jones et al., 2024). Among the sectors, the transport sector (including transportation of people and goods, and logistics operations) is one of the main contributors to global GHG emissions (Cavallaro et al., 2024). In 2022 the net anthropogenic GHG (direct and indirect) emissions from the transport sector were about 9.3 $GtCO_2e$, accounting for 15% of the total (see Figure 1.2).


Greenhouse gas emissions by sector, World

Greenhouse gas emissions[1] are measured in tonnes of carbon dioxide-equivalents[2] over a 100-year timescale.

Data source: Climate Watch (2025)
OurWorldinData.org/co2-and-greenhouse-gas-emissions | CC BY
Note: Land-use change emissions can be negative.

Figure 1.2: Greenhouse gas emissions by sector, World, 1990-2022.
Source: www.ourworldindata.org.

Among the transport modes, road transport (including passengers and freight) is the largest source of transport emissions (6.1 GtCO2e in 2019; 69% of the transport sector), followed by international shipping (0.8 GtCO2e; 9%), and international aviation (0.6 GtCO2e; 7%) (IPCC, 2023). If we only consider freight transport, then the share of greenhouse gas emissions makes up about 8% of the total, and as much as 11% if warehouses and ports are included (IEA, 2018). GHG emissions from freight transport are growing rapidly due to international supply and transport chains. This growth negatively affects all environmental elements (Petro and Konečný, 2017). Table 1.2 and Figure 1.3 show the share of GHG emissions by transport mode for the year 2018.

International shipping was one of the sectors excluded from the 2015 Paris Agreement (UNFCC, 2015) and despite being one of the most efficient freight options, it contributes for around 3% to global anthropogenic CO_2e emissions (1,076 Mt of GHG emissions in 2018) (Bengue et al., 2024). However, the rate is expected to increase by 90-130% of 2008 levels by 2050 (IMO, 2020), indicating global shipping GHG emissions are heading in the wrong direction unless actions are taken. This is due to the shipping industry being more heavily fossilized than other industries. Without energy transformation, the shipping industry will be less energy efficient along with the age of fleets. On the other hand, international maritime industries involve cross-regional trade and cost transference, which makes it difficult to attribute the abatement responsibilities for different stakeholders.

Table 1.2: Share of GHG emissions by transport mode (2018 data).

Type of mode of transport	
Road:	74.5%
Passenger (includes cars, motorcycles, buses, and taxi)	(45.1%)
Freight (includes trucks and lorries)	(29.4%)
Aviation:	11.6%
Passenger	(9.4%)
Freight	(2.2%)
Shipping	10.6%
Rail	1.0%
Other (mainly transport via pipelines)	2.3%

Source: author's elaboration based on data from the International Energy Agency (IEA) and the International Council on Clean Transportation (ICCT).

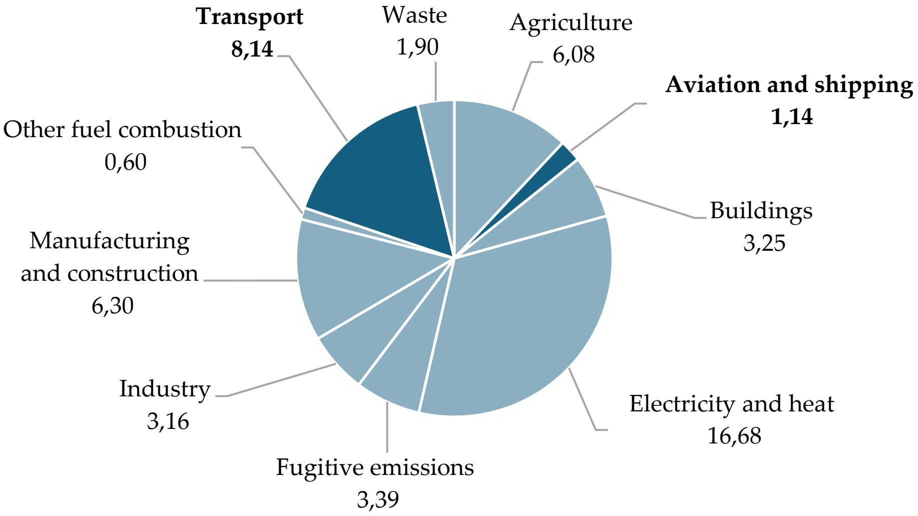


Figure 1.3: Greenhouse gas emissions [in Gt of CO₂e year] by transport mode, 2022.
Source: author's elaboration based on data from www.ourworldindata.org.

Possible options that can contribute to achieve the decarbonization goal in the transport freight sector are various and include efficient intermodal transport (Zhang et al., 2022), modal shift strategies (Nassar et al., 2023), fuel switching, technological interventions, the emergence of more energy-efficient transport technologies (especially in road transport), the emergence of new low or zero emission fuels, operational initiatives, and market-based measures (Serra and Fancello, 2020).

1.2. Problem statement

As described in the previous paragraph, the maritime transport sector is a major source of greenhouse gas emissions, and the pressure to adopt emission reduction policies is steadily increasing. The need to define clear decarbonization strategies can no longer be postponed. Figure 1.4 illustrates the possible stages of a decarbonization strategy for the transport sector. Starting from the awareness of the negative impacts of greenhouse gas emissions, the decarbonization strategy can be summarized in three main steps:

- Quantification of the GHG emissions
- Setting targets for GHG reductions
- Implementation of GHG emission reduction measures

The quantification of greenhouse gas emissions plays a key role in the decarbonisation process. The decarbonisation process, that starts with the measurement of GHG emissions, is fundamental in achieving global greenhouse gas reduction targets and realising sustainable transport chains (Dobers et al., 2019). Standardising methods for the calculation of GHG emissions is crucial in this context, so as the implementation of a carbon accounting framework for effective GHG mitigation in the global freight transport sector. Hence, accurate quantification of CO_2e emission levels is essential for determining the most impactful reduction measures in line with the reduction targets. The emissions generated when cargo is transported must be proportionally allocated to the quantity of goods transported. This process serves two main purposes. 1) Since a consignment often includes a number of shipments belonging to multiple parties, allocation ensures that each party is assigned its fair share of emissions. 2) At the corporate level, companies are increasingly required to report their share of emissions, which is then subject to carbon pricing mechanisms such as carbon taxation or cap-and-trade systems (e.g: EU- ETS). Accurate emission allocation is therefore essential not only to determine the carbon footprint of each stakeholder within the transport chain, but also to implement effective economic reduction measures. Furthermore, measuring and allocating emissions enables the identification of the segments that contribute most significantly to the total emissions.

At this point, it is useful to introduce the polluter-pays principle (PPP), that will be referred to in the next chapters. The PPP was initially introduced as an economic concept to internalise the external costs of pollution and has gradually become a key principle of environmental governance (Zhu and Li, 2025). According to this principle, those responsible for pollution should be held accountable for the associated costs of mitigating it, regardless of the location (Anderson, 2012). The PPP is acknowledged by many international and national laws. At the regional level, for example, it is incorporated into EU environmental policy in Article 191(2) of the Treaty on the Functioning of the European Union. Although it is legally binding for all EU member states, its implementation is often limited by ambiguities, particularly with regard to identifying the actual polluter (Yılmaz Uğur, 2022). Despite its worldwide acceptance, the implementation of this principle in the transport sector is still fragmented and inconsistent (Kukjans et al., 2025). This is due to several regulatory barriers, such as the lack of standardised emissions reporting protocols across countries and sectors (Bahman et al., 2025) or data-related barriers, such as difficulty retrieving primary data, and inconsistent default data among the parties. Moreover, (Beskovnik and Golnar, 2020) highlighted the need for a unified system capable of collecting accurate real-time pollution data from all vehicles in a multimodal transport chain. Regarding the application of the polluter-pays principle in shipping, (Zhu, 2023) concluded that the main issue is identifying polluters and assigning responsibility. This is complicated by different legal regimes and contracts.

The most straightforward action to reduce GHG emissions is to establish specific environmental targets. These targets can be expressed either in absolute or relative terms. To define them, it is essential to understand the current emission levels, past and possible future trends. Relative targets – expressed as a percentage reduction in emissions – are generally the most common.

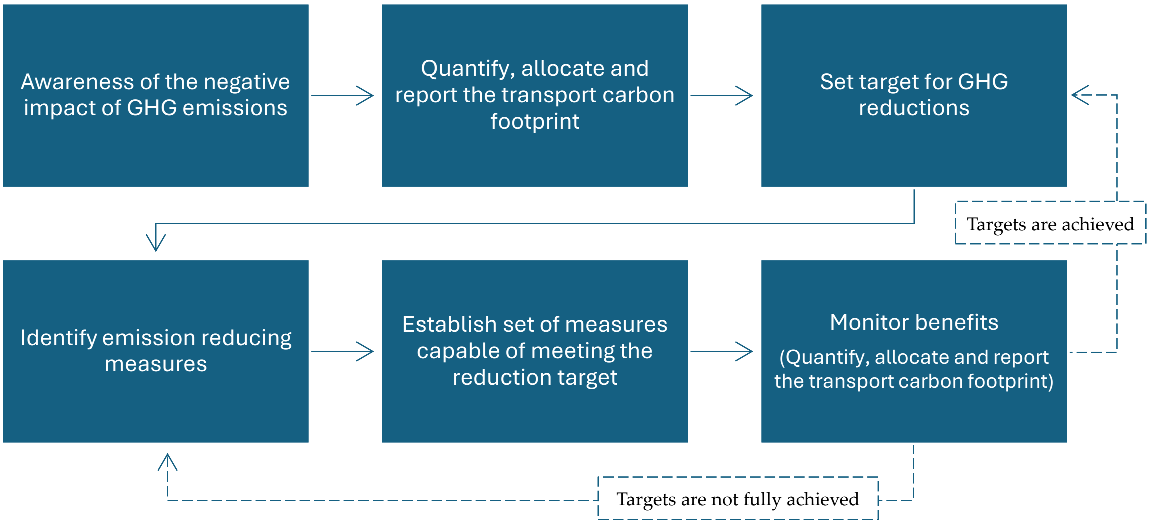


Figure 1.4: Stages in the development of a decarbonization strategy for the transport sector.
Source: authors' elaboration based on (McKinnon and Piecyk, 2012).

At the European level, for example, the Green Deal sets out two important targets for reducing greenhouse gases: a 55% reduction compared to 1990 levels by 2030, and a 90% reduction by 2050. These objectives, set by the Green Deal, outline the trajectory that all EU Member States must follow and form the basis for future legislation and regulatory frameworks. Emission reduction targets can be classified according to their geographical scope (international, regional, national, or local) and/or the sector involved (often both together). Once the targets have been defined, one of the most complex tasks is to measure and monitor emissions in order to assess progress towards these goals. Furthermore, alongside setting general or specific reduction targets, it is crucial to identify the necessary reduction measures, actions and policies. In this context, emission monitoring is useful for evaluating the effectiveness of the adopted reduction measures. If these assessments are carried out continuously, corrective actions can be taken if the measures prove to be inefficient or inadequate in meeting the objectives. Unlike other industrial sectors, where emission sources are fixed, transport emissions are generated by a non-stationary source. While this characteristic is less significant for short-distance land transport, it is crucial for international freight transport. Indeed, emissions could be released across different countries, resulting in fragmented regulations, emission limits and fuel use standards. This complexity is evident in the decision to exclude the international shipping sector from the 2015 Paris Agreement. For this reason, allocating emissions among the various stakeholders involved in freight transport is difficult.

The decarbonization of the maritime sector can be achieved through various measures. These reduction measures can be grouped into three macro-categories: operation measures, technical measures, and market-based measures (Psaraftis, 2012; Tu et al., 2024; Xing et al., 2020). These measures will be described in detail in the following chapters.

1.3. Aim and objectives of the research

The previous paragraph introduced the decarbonisation process within the maritime freight transport sector. Specifically, accurate quantification of greenhouse gas emissions is crucial for two key reasons. Firstly, it provides a baseline that is useful for setting reduction targets. Secondly, it enables the assessment of the effectiveness of the reduction measures that are taken to achieve the environmental targets, by measuring the gap between the latter and the ongoing levels.

Starting from this context, this doctoral thesis will focus on decarbonisation processes in the maritime freight transport sector. The aim is to provide useful and original insights into a possible integration between GHG emissions quantification methodologies and emissions reduction measures, identifying also critical aspects and weaknesses.

To achieve this aim, this research defines five specific objectives (SOs) that will be explored in the next chapters of the thesis. These SOs are listed in the following of this paragraph. The first three specific objectives require a more analytical approach based on qualitative methods.

SO-1. Provide an overview of the International Regulatory context for decarbonising the maritime transport sector and a focus on the European Regulatory Framework, including related climate policies and highlighting critical issues.
  - OO1.1: General overview of the International and European Climate Policies.
  - OO1.2: Review and deep understanding of the European Maritime Regulatory Scheme, in order to identify the climate policies related to the maritime sector.
  - OO1.3: Review of the existing literature on the European maritime Emission Trading System, and the European Monitoring, Reporting, and Verification Regulation, as well as its database.

SO-2. Provide an overview and a critical analysis of the potential greenhouse gas emission reduction measures and policies in the maritime transport sector.
  - OO2.1: Review and analysis of the potential decarbonisation measures and policies in the maritime transport sector.
  - OO2.2: Identification of the features of the measures, followed by a critical classification, carried out based on these characteristics.

SO-3. Provide an overview and a critical classification of the latest available methodologies for quantifying greenhouse gas emissions in intermodal freight transport chains, identifying the most comprehensive ones.
  - OO3.1: Review of the existing literature and analysis of the latest methodologies used for quantifying greenhouse gas emissions in intermodal freight transport chains.
  - OO3.2: Critical classification of the methodologies used for the quantification of greenhouse gas emissions in intermodal freight transport chains.
  - OO3.3: Identification of the most comprehensive quantification methodologies based on the (possible) critical aspects highlighted by the analysis.

The next group of objectives will adopt a more practical and quantitative approach. The aim is to evaluate specific aspects using well-defined case studies. (1) An application of the ISO 14083:2023 standard-based quantification methodology and, (2) the evaluation of the economic impact of the additional voyage costs associated with the maritime EU ETS.

SO-4. Application of the quantification methodology proposed by the ISO 14083 standard to a real case study, in order to identify any weaknesses or critical issues that may arise during its implementation, as well as the integration with the reduction measures.

  - OO4.1: Provide an overview of the ISO 14083 standard methodology and its integration with the GLEC Framework.
  - OO4.2: Definition of a real case study, including the selection of a maritime transport chain and the shipping company.
  - OO4.3: Identification, acquisition and collection of the input data (variables) from the chosen company, that are necessary to perform the case study application.
  - OO4.4: Application of the ISO 14083 standard methodology to the case study.
  - OO4.5: Critical discussion and assessment of the results of the application.

SO-5. Evaluate the economic impact of the inclusion of the shipping sector in the European Emission Trading System by implementing an economic model.

  - OO5.1: Definition of a case study, based on voyage alternatives for deep-sea container transport and alternative reduction measures.
  - OO5.2: Identification and collection of the input data (variables) that are necessary to perform the selected case study.
  - OO5.3: Development of an economic and environmental model.
  - OO5.4: Application of the proposed model to the case study.
  - OO5.5: Discussion and assessment of the results of the application.

By addressing these research questions and objectives, this thesis aspires to contribute in an innovative way to the continuous improvement of the environmental sustainability of maritime freight transport, promoting decarbonization pathways. The findings are expected to give practical insights for shipowners, operators, and legislators, encouraging the adoption of novel technologies and assisting in the global transition to sustainable and zero-emission transport.

1.4. Methodology of the thesis

Building on the previous paragraph, which set out the specific and operational objectives of this thesis, this paragraph aims to illustrate the methodology employed to address these challenges. Several research methods were employed: desk research, descriptive research, direct data collection, qualitative and quantitative methods. Furthermore, a systematic approach was adopted throughout the research.

Qualitative methods where adopted in the first part of the thesis. The use of quantitative methods, in the second part of the thesis, where linked to the two case studies. Data and information used in the first case study have been collected from the selected company, while for the second case study they are retrieved from academic research, technical documentation, and interviews from experts. The data was processed using content analyses and descriptive statistical analyses techniques.

1.4.1. The methodological steps

The methodological framework adopted in this thesis is developed through an in-depth analysis of the decarbonization process within the freight maritime transport sector. It is structured into several phases, each of which is designed to answer to a specific research question. Starting from the main objective, the methodology is applied to the specific objectives.

1) Firstly, an analysis of the European regulatory framework related to decarbonizing the maritime sector was conducted. This part of the research examined the legislative measures regulating emissions in the maritime sector and highlighted the associated implementation challenges.
2) Next, a literature review was conducted on the main international measures promoted by the International Maritime Organization (IMO), together with an overview of the most recent European policies linked to emission reduction in the maritime sector. A critical analysis of these measures categorised them into three main groups: technical, operational, and market-based. Technical measures include adopting more efficient technologies, such as using alternative fuels and improving ship design. Operational measures refer to strategies aimed at optimising daily vessel and port operations, such as route management and speed optimisation. Market-based measures impose carbon market-based rules and encourage shipping companies to comply with regulations set by policymakers.
3) The next step was to analyse the methodologies currently used to quantify greenhouse gas emissions in the maritime transport sector. However, since maritime transport is usually combined with other modes of transport, such as road and/or rail, it is important to use methodologies that assess emissions throughout the entire transport chain. The transport of goods by sea is, in fact, linked to the geographical location of the ports of departure and arrival. In most cases, this means that goods are transported from the origin to the port of departure and from the port of arrival to their final destination by alternative modes of transport. Consequently, this research analyses and evaluates not only methodologies associated with maritime transport, but also those that consider multiple modes of transport and harmonize data and results relating to them. This allows for the accurate, consistent and correct assessment of emissions generated during the various transport stages and, consequently, throughout the entire transport chain. A literature review identified various methodologies used internationally for this

purpose. Based on this analysis, the methodologies were critically evaluated in terms of their ability to integrate various transport modes and accurately and consistently measure emissions. It was found that the most common and comprehensive calculation methodology is the combined use of the ISO 14083 standard and the GLEC Framework. This methodology was therefore chosen for the case study analysis.

4) Having identified the methodology proposed by the ISO 14083 standard as the most suitable one, it was applied to a real-world case study involving a shipping company operating within an intermodal transport chain. This case study enabled the effectiveness of the methodology to be tested in a real-world setting and potential gaps or issues during implementation to be identified. The practical phase involved gathering the necessary data to apply the methodology, such as fuel consumption, distance travel, vessel characteristics, and port operations. The ISO 14083 standard methodology was then used to estimate greenhouse gas emissions throughout the entire transport chain, including maritime and road transport, as well as port operations.
5) The last step of the thesis' methodology focused on the development of a model that could evaluate the economic impact of the extra costs associated to the European Emission Trading System for a deep-sea container voyage. The economic analysis considered various alternatives for deep-sea container voyages and explored the impact of different technical and operational emission reduction measures on the economic costs for shipping companies. The model enabled the simulation of voyage costs, taking into account emissions avoided through the adoption of alternative reduction measures. Furthermore, the economic impact of the EU-ETS was assessed by analysing how the obligation to purchase emission allowances might affect total transport costs, and thus the competitiveness of shipping companies. The analysis also included an evaluation of various scenarios in which the shipping company adopted different measures to reduce their emissions. The results showed that adopting more efficient technologies and optimizing operations can sometimes be economically advantageous by reducing operational costs.

1.5. Structure of the thesis

This PhD thesis is organized in seven Chapters. This section illustrates the structure and the content of each Chapter.

Chapter 1 introduces some general remarks as well as the research setting, the aim of the research, the main objectives and the methodological approach that was employed.

Chapter 2 provides an overview of the Regulatory Framework for decarbonizing the maritime transport sector, investigating in particular the European Climate Policies related to the transport sector and specifically to maritime transport.

Chapter 3 presents an overview and a critical analysis of the potential greenhouse gas emission reduction measures in the maritime transport sector. These measures and policies are then categorized in operational, technical, and market-based measures.

Chapter 4 outlines the most recent methodologies for quantifying greenhouse gas emissions in intermodal freight transport chains. It begins with a review of the existing literature and an overview of the main methodologies. Then, a classification based on critical analysis is presented. Finally, the results are discussed, after which the methodology suggested by the ISO 14083 standard is selected for application to a case study.

Chapter 5 presents an application of the methodology proposed by the ISO 14083 standard and the GLEC Framework to a case study. For the case study, an intermodal Ro-Ro (roll-on/roll-off) maritime transport chain is selected.

Chapter 6 investigates the economic impact of the recent inclusion of the shipping sector in the European Emissions Trading System, using a deep-sea container voyage and a Ro-Ro voyage as two case studies. The Chapter is structured as follows: First, the case studies are defined and some assumptions are provided. Next, the two case studies are presented, the economic and environmental model implemented and applied to the two case studies. Finally the results are described.

The Conclusions are presented in Chapter 7, which is the final chapter. Contributions and practical implications of the research are highlighted and future developments are discussed.

2. Regulatory Framework

Anthropogenic GHG emissions are the main cause of global warming, with approximately 80% of it coming from the energy, industry, transport, and building sectors (IPCC, 2023). The atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are increasing every year (World Meteorological Organization, 2025).

The international shipping industry plays a key role in global trade, facilitating the movement of more than 80% of goods around the world. In the period 2025-2029, total seaborne trade is expected to grow at an annual average of 2.4 per cent and containerized trade by 2.7 per cent (UNCTAD, 2024). The share of GHG emissions from the shipping sector has increased from 2.76% in 2012 to 2.89% in 2018 and is projected to increase to 90-130% of 2008 emissions by 2050 (IMO, 2020). The maritime transport sector must therefore meet the challenges of both decarbonization and the transition from traditional fossil fuels to cleaner energy sources (UNCTAD, 2024). By setting the regulatory path, the International Maritime Organization (IMO) plays a critical role in this context (Notteboom, 2020).

This Chapter is organized as follows: first it will present an overview of the regulatory framework at an international level. Then, the following sections will provide a critical analysis and discussion of the European regulatory framework on greenhouse gas emissions from the maritime transport sector. Indeed, the European Union is one of the first institutions in the world to set stringent emission reduction targets. Therefore, it is considered relevant to the aim of this work.

2.1. International level

At an international level, IMO plays a key role in the decarbonization path of the shipping sector. As a result of the intensive and comprehensive work of the IMO, in recent years there were significant developments in maritime decarbonisation. This culminated with the adoption, in 2018, of the "Initial IMO Strategy on reduction of GHG emissions from ships" (Psaraftis, 2019). This strategy aims to reduce the carbon intensity of maritime transport by 40% by 2030 (compared to 2008 levels), and to cut total greenhouse gas emissions by 50% by 2050 (IMO, 2018). This first version was then revised by the "2023 IMO GHG Strategy" which set stricter environmental targets, such as achieving net-zero GHG emissions by around 2050 and the adoption of zero or near-zero GHG emission technologies, fuels and/or energy sources (IMO, 2023).

Furthermore, the IMO is discussing the adoption of a new strategy: the Net-Zero Framework (NZF). This framework is a key part of the IMO's strategy to decarbonise maritime transport. However, this strategy is currently under review, and its implementation has been suspended until at least the end of 2026. The NZF aims to reduce GHG emissions from ships in line with the 2023 IMO GHG Strategy. It is based on two pillars: the Global Fuel Standard (GFS) and a pricing mechanism for GHG emissions. The GFS imposes progressive limits on GHG emissions per unit of energy in marine fuels, taking into account the entire fuel life cycle. The pricing mechanism establishes a payment system for environmental credits based on the amount of CO_2 emitted, thereby incentivising the adoption of clean technologies and fuels while penalising the most polluting ones.

2.2. Regional level: the EU Climate Policies

In the European Union the transport sector accounts for 20% of anthropogenic GHG emissions (Haasz et al., 2018). To address this issue, the European Commission presented in 2019 the European Green Deal Strategy. This strategy aims to align various EU policies with the European Council's goal of achieving climate neutrality by 2050. The agenda was developed in the context of growing global awareness of the climate emergency, as evidenced by the Paris Agreement and the 2030 Agenda for Sustainable Development Goals of 2015, and the IPCC report "Global Warming of 1.5°C" of 2018. The key measure of the European Greed Deal is the "European Climate Law" adopted in June 2021, which introduced for the first time a binding long-term emissions reduction target. The Climate Law also aligned the 2030 emissions reduction target with the long-term target, raising it from 40 to 55 per cent. To achieve this target, the Commission presented the "Fit for 55" legislative package in July 2021, which includes measures to adapt previous legislation and new initiatives.

The Fit for 55 package revises existing legislation and introduces new rules across various sectors, including energy, transport, buildings, and land use. The package is a key component of the broader European Green Deal. The Fit for 55 includes, among the others, the reform of the Emissions Trading Scheme (ETS), currently the main EU economic instrument for achieving climate targets (Bucak et al., 2025; Vaca-Cabrero et al., 2024). An exhaustive list of the measures included in the Fit for 55 package is presented below:

- EU Emissions Trading System (EU-ETS) reform
- CO_2 emissions standards for cars and vans
- Alternative Fuels Infrastructure Regulation (AFIR)
- ReFuel EU Aviation Regulation
- FuelEU Maritime Regulation
- New EU-ETS for building and road transport fuels
- Social Climate Fund
- Effort Sharing Regulation
- Regulation on Land Use, Forestry and Agriculture
- Carbon Border Adjustment Mechanism (CBAM)
- Renewable Energy Directive (RED)
- Energy Efficiency Directive

Although the European Climate Strategy is extended to various sectors, in the following of the discussion only the transport sector will be considered for a specific focus. Figure 2.1 shows the timeline of the main EU Climate Policies affecting the transport sector, while Table 2.1 illustrates some details and the main targets of each policy.

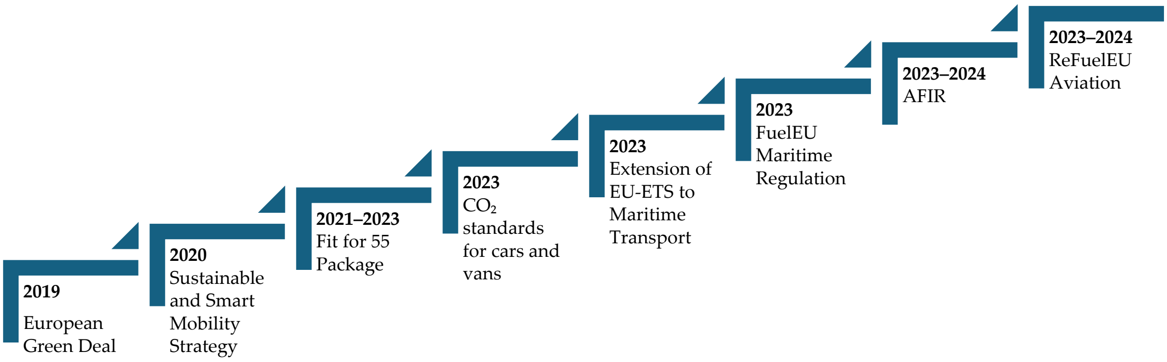


Figure 2.1: Timeline of EU Climate Policies affecting all transport modes, 2019–2025+.
Source: author's elaboration.

The Sustainable and Smart Mobility Strategy, first set of measures dedicated to the transport sector and part of the European Green Deal, was presented in 2021 by the European Commission. This strategy provides a roadmap for the decarbonization of all transport modes and intermodal logistics, and a more efficient smart mobility. According to the Sustainable and Smart Mobility Strategy, rail freight traffic should increase by 50% by 2030 and double by 2050. Additionally, transport by inland waterways and short sea shipping (SSS) should increase by 25% by 2030 and by 50% by 2050. Moreover, it encourages the adoption of zero-emission vehicles, vessels, and airplanes, as well as the use of renewable and low-carbon fuels and the development of related infrastructure, such as airports and ports (EC, 2020a).

Table 2.1: EU Climate Policies related to the transport sector.

EU Climate policy	Adoption/ In force	Transport Sector(s) and target(s)	Source
European Green Deal Strategy	2019+	Communication: Framework strategy for EU climate neutrality by 2050 (all sectors). Sets a 90% emission-reduction goal for transport (all modes).	(EC, 2019)
Sustainable & Smart Mobility Strategy	2020+	Communication: Roadmap for decarbonizing transport modes and smart mobility (all modes + intermodal logistics).	(EC, 2020b)
Fit-for-55 Package	2021+	Legislative Package with the aim of cutting 55% of GHG emissions by 2030 (all transport modes, indirectly rail and inland waterways), supporting the Green Deal goals.	(Erbach et al., 2024)
CO_2 Standards for Cars & Vans	2023/2025	Road Transport. Regulation (EU) 2023/851: Strengthened CO_2 standards for cars and vans. Affects automotive industry and charging infrastructure rollout.	(EU, 2023a)
EU-ETS Extension to Maritime	2023/2024+	Maritime shipping. Regulation (EU) 2023/957: Includes maritime transport emissions into the EU-ETS	(EU, 2023b)
FuelEU Maritime Regulation	2023/2025	Maritime shipping & ports. Regulation (EU) 2023/1805: Sets limits on GHG-intensity of marine fuels and fuels used by ships calling at EU ports, promoting renewable and low-carbon fuels.	(EC, 2023a)
AFIR – Alternative Fuels Infrastructure Regulation	2023/2024	Road, maritime, aviation, inland ports. Reg. (EU) 2023/1804: Mandatory deployment of infrastructure for alternative fuels across transport modes	(EU, 2023c)
ReFuelEU Aviation	2023/2025	Aviation & airports. Regulation (EU) 2023/2405: Mandates progressive sustainable aviation fuels (SAF) blending at EU airports/aviation fuel market	(EU, 2023d)
EU-MRV: Monitoring, Reporting and Verification	2015/2018 *revised in 2023	Maritime shipping & ports. Regulation (EU) 2023/957 & Regulation (EU) 2015/757: Monitoring, reporting and verification of GHG emissions from ships calling at EU ports	(EU, 2023b, 2015)

Source: author's elaboration based on the literature review.

Furthermore, the Greening Freight Transport Package, launched in 2023 by the European Commission, includes various measures under the Fit for 55 Package. The aim is the decarbonisation of freight transport. The main proposals are:

- Proposal for an EU CountEmissions Regulation to establish a unified European framework for calculating emissions from freight and passenger transport operations, using the ISO 14083 standard as the reference for calculation
- Proposal for the revision of the Directive (96/53/EC) on dimensions and weights
- Proposal for a regulation for an improved rail freight capacity management system

With regard to the issue of quantifying and reporting emissions, the proposal for an EU CountEmissions Regulation is of particular interest. Indeed, at the time of writing, there is still no common European framework in place to track the climate impact of transport services (Trio and Lanfranco, 2025). During 2023, the European Commission started to discuss a proposal for a regulation that sets out a single methodology to voluntarily calculate and report transport-related greenhouse gas emissions, referred to as CountEmissionsEU (EC, 2023b). It seeks to ensure that GHG emissions data provided regarding transport services are reliable and accurate, to allow fair comparison between transport services. At the moment (October 2025) trilogue negotiations are taking place. The adoption is still to go. The draft version of the EU Count Regulation states that the ISO 14083 standard should be used as the reference methodology for calculating GHG emissions from the transport sector. This was welcomed by the main stakeholders. In particular, stakeholders from the maritime sector provided feedback in the form of a joint response from the European Community Shipowners' Association (ECSA) and the World Shipping Council (WSC), who maintain that any new harmonised framework should build upon existing methodologies. In the case of maritime transport, this would be the EU Monitoring, Reporting and Verification Regulation n. 2015/757 (EU, 2015)

2.3. The European Maritime Regulatory Scheme

The EU Maritime Regulatory Scheme is a comprehensive set of regulations concerning maritime transport emissions under EU law. It covers the Maritime Emissions Reporting (MRV) system, the FuelEU Maritime Regulation and the EU Emissions Trading Scheme (EU-ETS) policy. This paragraph will further explore the European ETS and the MRV.

2.3.1. Literature review

In recent years, the interest of scholars towards the possible implications of carbon emission trading schemes for the maritime sector is constantly growing. One of the main reasons for this is the inclusion of the shipping sector in the European ETS. Therefore, this section will present and discuss some of the recent work on this topic.

(Kotzampasakis, 2025) revised the legal design or expected effects of the EU-ETS. His findings suggest that the EU-ETS can significantly reduce emissions at a lower overall cost compared to other alternative regulations. However, he points out the uncertainties regarding the risk of carbon leakage, the unfair economic impacts on certain countries (Lynce de Faria, 2024), and on the different shipping segments, as well as its coherence with other domestic and international policies. Indeed, many authors (Christodoulou and Cullinane, 2024; Lagouvardou and Psaraftis, 2022; Park et al., 2024; Peng et al., 2024) underpin the necessity to improve the effectiveness of the EU-ETS in order to prevent carbon leakage. Among others, (Wu et al., 2024), suggest keeping the EUA cost low to reduce carriers' carbon emission expenses and discourage them from evasion strategies, while also expanding the EU-ETS scope by classifying nearby ports as non-transit, which would effectively prevent evasion. Since 2024, the ports of Tanger-Med and Port-Said are already included in this category by the ETS Directive.

Unlike other sectors, international shipping does not benefit from free allocations under the EU-ETS. This forces shipowners to balance abatement costs by adjusting voyage speed and selecting emission reduction technologies in order to maximise profits. According to (Christodoulou et al., 2021), in case the emission allowances are fully auctioned, the increased costs would be disproportional among the maritime segments. This would penalize the Ro-Ro and the Ro-Pax segments due to their high fuel consumption per transport work in relation to oil tankers and container segments. Other authors have hypothesised different carbon quota allocation schemes and investigated their effects on carbon emission reduction (Y. Sun et al., 2022; Y. Sun et al., 2024; Wang et al., 2024).

(Zhou et al., 2025) suggest that, due to the market structure, the overall effectiveness of emission reductions remains limited. Indeed, liner shipping companies have passed the cost of the emission surcharge (EMS) onto their customers, leaving ship profits largely unaffected. The EMS is calculated per TEU, based on individual commercial trades, which typically include multiple origin-destination pairs. This surcharge structure fails to account for variations in distance between od pairs within the same trade. To address this limitation, (Shangguan et al., 2025) propose a carbon emissions allocation policy that uses an optimization method to allocate emissions per TEU for each origin-destination pair. Also (J. Wang et al., 2025) argue that the EU-ETS has led to a restructuring of operational cost frameworks by introducing the EMS as an independent pricing instrument. They state that this has resulted in a shift in market behavior, with competition shifting from conventional freight rate competition to full price (freight rate and EMS) competition, whereby environmental costs are internalized. One of the consequences of the EMS is that the cost of technology becomes the decisive factor in adoption decisions, creating a preference for low-cost, energy-saving technologies over more effective, but costly, solutions.

(Vaca-Cabrero et al., 2024) addressed the economic implications of the EU-ETS on European ports. By analysing various maritime scenarios, the study assesses how the ETS influences shipping routes, port competitiveness, and overall economic activity. A key finding is that the ETS imposes significant additional costs on shipping companies, which could lead to adjustments in routes and a shift in cargo volumes to ports in regions with less stringent environmental regulations. Furthermore, the increase in costs are seen across the entire supply chain, impacting material suppliers, manufacturers, shipowners, charterers, cargo interests and end consumers, who will experience higher commodity and goods prices (Durmuş, 2025).

Carbon prices and fuel prices impact heavily on voyage costs. Rising fuel prices lead to increased voyage costs for liner vessels, which is a significant factor. Furthermore, the EU-ETS can help maintain lower and more stable emissions regardless of carbon price fluctuations; however, higher carbon quotas within the system may lead to increased total emissions despite higher carbon prices (Sun et al., 2025). One of the less costly measures that shipowners can adopt to reduce the ETS cost is speed reduction or slow steaming, in order to conserve fuel as the price increases. In their work, (Park et al., 2024) built a mathematical model that determines the optimal speed for each voyage, in response to the EU-ETS Regulation. (Sun et al., 2025) examined the impact of vessel speed optimization and carbon policies on carbon reduction. The findings suggest that carbon trading mechanisms have a greater environmental impact on voyage costs and emissions than carbon taxes do, by maintaining stable emissions regardless of fuel price volatility. Other researchers investigate the effects of emission reduction strategy of liner shipping companies to comply with maritime carbon trading schemes. (L. Sun et al., 2024; T. Wang et al., 2025) proposed a cost model for container shipping based on fuel consumption, carbon emissions, EUA cost, and total cost of the service. In their work, (Lu et al., 2025) explored the optimal emission reduction mechanism in the context of shipping alliances. The results show that a higher carbon quota price and limited free carbon quotas create economic distortions, forcing shipping companies to choose between high green investment costs and carbon emission expenses. Shipping companies shift economic pressure to shippers by significantly increasing freight rates when green preference fails to translate into actual market demand.

The study by (Bucak et al., 2025) proposes an incentive system to enable shipping companies to rapidly adapt to the EU-ETS and solve potential problems during the process. According to the industry experts interviewed, the EU-ETS should provide two key incentives to encourage long-term profitability within the scheme: “financial incentives for fleet renewal” and “off-price alternative fuels”. (Mao et al., 2024) examine the emission trading mechanism from an international legal perspective. They suggest that China should gradually expand its shipping emissions trading market across the whole country, aligning it with the EU's approach. This would involve improving the country's mechanism for collecting ship energy consumption data, implementing a flexible and adjustable total trading mechanism, and setting a reasonable carbon price safety valve. (Trosvik and Brynolf, 2024) analyse the future transition towards green fuels in the Swedish maritime transport sector. One of the main findings from the application of their model is that when the price of conventional fuels and LNG are assumed to be lower, the price of EUA will have to be higher for renewable fuels to be cost-competitive.

Finally, (Christodoulou and Cullinane, 2024) conducted a qualitative review of the historical development of discussions and actions taken at the global (IMO) and regional (EU) levels. The authors emphasise the importance of the IMO continuing its work to develop a global ETS that promotes a "level playing field" for competition within the sector and eliminates the risk of carbon leakage. However, due to the limited share of global emissions covered by international shipping, the EU-ETS remains a second-best solution for decarbonizing the sector (Kotzampasakis, 2025). The optimal solution would be for the IMO to establish an effective, globally applicable market-based instrument. Such an instrument would also mitigate the risks of carbon leakage and competitive distortions. This solution was approved by the Marine Environment Protection Committee (MEPC 83) in April 2025, under the IMO Net-Zero Framework. It is a market-based system built around performance targets and tiered compliance fees. It therefore functions as a global incentive and funding framework for shipping decarbonization.

2.3.2. EU - Emission Trading System

At a regional level, the European Union has introduced one of the first market-based solutions, implementing the world's first Emissions Trading System (EU-ETS) in 2005, regarded as a key tool for reducing GHG emissions in the EU. It requires polluters to pay for their GHG emissions in the attempt to reduce overall emissions in the EU while generating revenues to finance the green transition (EC, 2005). The EU-ETS is based on the "cap-and-trade" principle. The cap represents the maximum level of emissions that can be generated by the sectors involved in the system. The cap is reduced over time to ensure that all ETS sectors cumulatively contribute to the EU's climate objectives. It covers emissions from installations and operations in the electricity and heat generation sector, the industrial manufacturing sector, and, since 2012, the aviation sector.

Following its inclusion in the "Fit-for-55" and the European Green Deal, the maritime sector was included in the EU-ETS in 2023 through Directive (EU) 2023/959 (Sikora, 2021). Meanwhile, Regulation (EU) 2023/957 included the maritime transport activities in the EU-ETS and for the monitoring, reporting and verification of emissions of additional greenhouse gases and emissions from additional ship types. Shipping companies are thus held liable for GHG emissions after 2024. Therefore, shipping companies will be held liable for GHG emissions after 2024. Furthermore, the regulation establishes the shipping company as the primary responsible party for shipping GHG emissions, deeming it the entity responsible for monitoring and reporting the relevant parameters during the one-year reporting period. The shipping company is also obliged to surrender the allowances (Zhu and Li, 2025). To take account of the introduction of the shipping sector into the EU-ETS, the Union-wide cap was brought to 1,386,051,745 emission allowances (EUA) in 2024 (EC, 2023c). Each year, companies need to surrender the necessary EUA to cover their emissions. One EUA gives the right to emit one tonne of CO_2 (or CO_2e for the shipping sector after 1 January 2026). The individual cap for the maritime sector is set at 78 million for the first year, with linear reduction factors of -4.3% and -4.4% applied from 2023 and 2024 to 2027 respectively. It should be noted that the aviation sector has a separate cap and is subject to free EUAs.

The EU-MRV formed the basis for the inclusion of shipping in the EU-ETS from 2024 (EU, 2015). In the first three years (2024-2026), the EU-ETS applies to ships above 5,000 gross tonnage (GT), regardless of flag. The system covers 100% of emissions from voyages between EU/EEA ports and occurred in EU/EEA port areas, 50% of emissions trat occur from incoming voyages from non-EU to EU/EEA ports and outgoing voyages from EU/EEA to non-EU ports. This cluster of ships represents 55% of all cargo and passenger ships calling at ports in the European Economic Area and covers more than 90% of the CO_2 emissions from shipping in the EU (EC, 2020c).

To ensure a smooth transition, shipping companies only have to surrender allowances for a portion of their emissions during an initial phase-in period:

- 2025: for 40% of their emissions reported in 2024;
- 2026: for 70% of their emissions reported in 2025;
- 2027 onwards: for 100% of their reported emissions.

The allocation of EUA is primarily conducted through the auction process, while the remaining part is allocated for free to the industry sectors that may be vulnerable to carbon leakage risk. In the case of the maritime sector, no free allocation has been decided. The price of the EUA is determined by the spot market logic and is thus defined by the rules of supply and demand.

Figure 2.2 shows the auction price trend (€/tCO_2) of EUA from 2018 to 2024 (EEEX, 2025; ICAP, 2025). From the beginning of 2021, the EUA price rises sharply, reaching a first peak of nearly 95 €/tCO_2 in February 2022, a 70% increase on the 2019 values of about 20-30 €/tCO_2. This volatility complicates the estimation of the economic impacts of the EU-ETS on the maritime sector. In addition, fuel prices have to be considered. (Trosvik and Brynolf, 2024) analysed how fuel costs and EUAs prices can affect the reduction of CO_2 emissions from the maritime sector. Their findings underline that in scenarios characterized by low EUA price signals, the model indicates small reductions (or even increases) in CO_2

emissions. Conversely, in scenarios with higher EUA prices, the most common lowest cost investment options are biofuels and battery electric propulsion. In the latter scenario, investments in renewable fuels are indicated to occur earlier compared to scenarios with lower EUA prices. They also found that renewable fuels are economically competitive if EUAs prices are higher enough to compensates for the lower cost of conventional fuels.

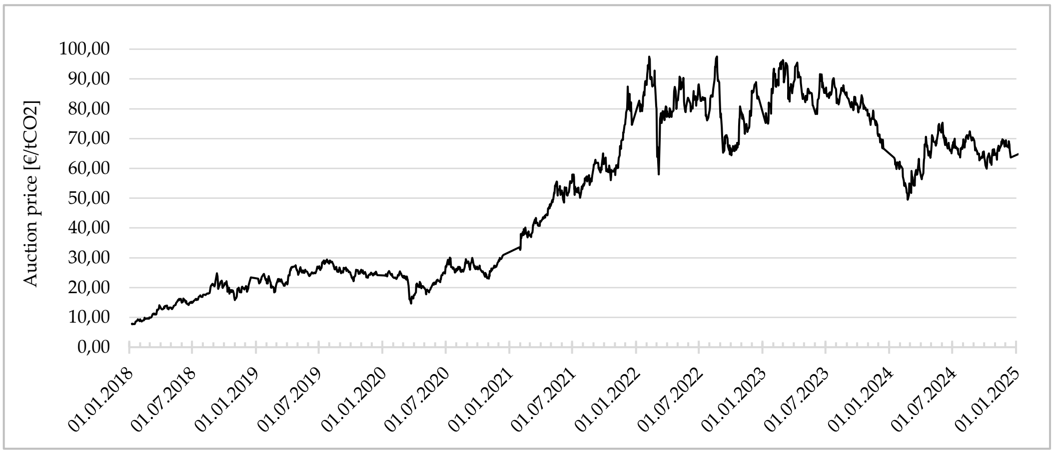


Figure 2.2: EU Allowance Price on the Emission Spot Primary Market Auction, 2018-2024. Source: author's elaboration based on data from (EEEX, 2025; ICAP, 2025).

2.3.3. EU - Monitoring, Reporting, and Verification Regulation[1]

In 2011, considering that no international agreement on the reduction of GHG emissions from international shipping had been approved by Member States through the International Maritime Organisation (IMO), the European Commission proposed to include international maritime emissions in the Community reduction commitment. The document was adopted as the Monitoring, Reporting, and Verification (EU-MRV) Regulation (EU) 2015/757, which entered into force in 2015 (EU, 2015).

In its first version, the EU-MRV Regulation defined a framework for the monitoring, reporting and verification of CO_2 emissions from maritime transport that involved at least one port under the jurisdiction of a Member State. It applied only to ships above 5,000 gross tonnage operating commercial routes, both during navigation and berthing. Data collection started on 1 January 2018 on a per-voyage basis and is managed by the European Maritime Safety Agency (EMSA).

---

[1] This Section is partially based on the following published work by the author:

- Vitiello, D. M., Serra, P., & Fancello, G. (2025). Inclusion of the Maritime Sector in the European ETS: Analysing Future Impacts Using MRV Data. In International Conference on Computational Science and Its Applications (pp. 29-43). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-97651-3_3

This Regulation requires shipping companies to provide data on a company basis and to submit a verified annual emissions report (ER) via THETIS-MRV for each ship calling EU/EEA (European Economic Area) ports during the previous year. The ER includes GHG emissions, fuel consumption, time at sea, distance travelled, and cargo carried for each of their ships on a voyage-by-voyage basis.

In 2023, Regulation (EU) 2023/957 amended Regulation (EU) 2015/757 by adding, from January 2024, other GHG emissions to the CO_2 emissions (namely, methane and Nitrous oxide). CH_4 emissions will be covered due to the increasing use of liquefied natural gas (LNG) as a marine fuel, which can lead to methane leakage from ship engines. Similarly, N_2O will be included to take account of possible future emissions from the introduction of new fuels such as ammonia (Mellin et al., 2020). From January 2025, the EU-MRV Regulation applies also to general cargo ships between 400 and 5,000 gross tonnage, and offshore ships of 5,000 gross tonnage (EU, 2023b). Table 2.2 presents the main characteristics of the EU-MRV Regulations.

Table 2.2: Summary of the main requirement from EU-MRV Regulations.

	Regulation (EU) 2015/757	Regulation (EU) 2023/957
Monitoring, reporting and verification	Carbon dioxide (CO_2)	From January 2024: Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O)
Vessel/company level	Per vessel	Per vessel and company
Application	Ships* above 5,000 GT calling EU/EEA ports for commercial reasons	From January 2025 also includes offshore ships above 400 GT and general cargo ships between 400 and 5,000 GT

NOTE: *Excluding warships, naval auxiliaries, fish catching or processing ships, wooden ships of a primitive build, ships not propelled by mechanical means, government ships used for non-commercial purposes. Source: author's elaboration based on the European Regulations.

In 2016, one year after the introduction of the EU-MRV Regulation, the IMO adopted its own Data Collection System (DCS). From 2019, the DCS requires shipping companies to record and report fuel consumption data (for each type of fuel oil they use) along with travelled distance, for ships exceeding 5,000 gross tonnage (IMO, 2016). The IMO-DCS has been introduced within SEEMP Part II, and since 2023 the recorded data is used to calculate ship's operational carbon intensity (CII). Overall, the two monitor systems are not yet aligned and have some key differences as shown in Table 2.3

Table 2.3: Key differences between EU-MRV and IMO-DCS.

	EU-MRV	IMO-DCS
Type of transport	Only transport of goods and persons	Any activity carried out by ships in the marine environment
Type of voyages	Only voyages to and from EU/EEA ports, including domestic voyages	Only international voyages (no domestic ones)
Emissions in port	Emissions in EU/EEA ports are reported separately	Emissions in port are not reported separately
Type of data aggregation	Requires data per voyage	Requires annual aggregated data
Type of data	Data related to transport work (weight of actual cargo carried or number of passengers)	Data on the deadweight tonnage (the carrying capacity of the ship)
Type of data publication	Publishes data on the performance of individual ships.	Publication of aggregated data

Source: author's elaboration based on (EU, 2023b; Gregor, 2020; IMO, 2016).

2.3.3.1. The EU-MRV database

The EU-MRV Regulation requires shipping companies to provide data both at a company and at a ship level. Data at a ship level are then published on an annual basis by the European Maritime Safety Agency (EMSA) in accordance with Article 21 of Regulation (EU) 2015/757. The typology of the data, referred to singular ships, can be summarized as:

- Ship and verifier details
- Monitoring methods
- Annual monitoring results

The EU-MRV database (EMSA, 2025) covers all maritime voyages, that include a port call at an EU/EEA port, either at the start or at the end of the voyage. It also includes domestic voyages, i.e. voyages between two EU/EEA ports. Only ships above 5,000 GT used for the transport of goods and persons are included. Warships, naval auxiliaries, fish catching or processing ships, wooden ships of a primitive build, ships not propelled by mechanical means, government ships used for non-commercial purposes are excluded.

The MRV data cover all segments of the maritime sector, identifying 15 vessel categories. For the scope of this study, and for a better comprehension of the figures, only the first 10 categories will be considered in the analysis. This cluster represents more than 90% of the total CO_2 emissions. The segments considered are container ships, oil tankers, bulk carriers, Ro-pax ships, chemical tankers, passenger ships, general cargo ships, Ro-ro ships, LNG carriers and vehicle carriers.

CO_2 emissions are reported by separating emissions released during navigation and during port calls (both emissions at berth and emissions released in ports when the ship is not at berth but is moving within a port of call between two voyages). Emissions during navigation are then split in emissions occurred during voyages between EU ports, during voyages departing from an EU/EEA port to a non EU/EEA port, and during voyages arriving in an EU/EEA port from a non EU/EEA port.

The data analysed for this purpose was the most recent one (at the time of writing) and it is referred to the period 2018-2023. Data was downloaded during February 2025.

In order to perform a descriptive statistical analysis of the MRV database, an initial screening was conducted to remove outliers and errors. As reported by (EC, 2025), 0.44% of the total reports contained one or more outliers in 2023, compared to 4% in 2018. Table 2.4 shows the number of recorded ships for the period 2018-2023.

Table 2.4: Number of recorded ships, 2018-2023.

2018	2019	2020	2021	2022	2023
11,428	11,923	11,653	11,962	13,018	12,571

Source: author's elaboration based on EU-MRV data.

The shipping industry includes distinct and diverse maritime segments. Each segment is defined by different characteristics, such as the technical characteristics of the ships, the type of fuel used, the geographical area of interest and the type of service provided, such as long-distance routes (typically container ships) or short sea routes (with Ro-Ro and Ro-Pax ships). Furthermore, certain segments are dedicated to the transport of goods (solid/liquid bulk, containers, vehicles, etc.), others to the transport of passengers (i.e. passenger ships, both leisure and public transport), while others provide a mixed transport of cargo and passengers (Ro-Pax ships).

In order to describe the heterogeneity of the sectors, the MRV data are presented disaggregated for each maritime segment. Figure 2.3 shows the total CO_2 emissions recorded by the MRV system between 2018 and 2023, split for the 10 ship categories analysed. With the exception of LNG carries, all the other segments reduced their emissions over the years, with the container ships, bulk carriers, and general cargo ships reducing their emissions by 20% between 2018 and 2023. In 2023, the share of the container sector in total emissions is 28%, followed by oil tankers (13%) and bulk carriers (12%). Looking at the passenger shipping sector, emissions in 2020 and 2021 were affected by the Covid-19 pandemic.

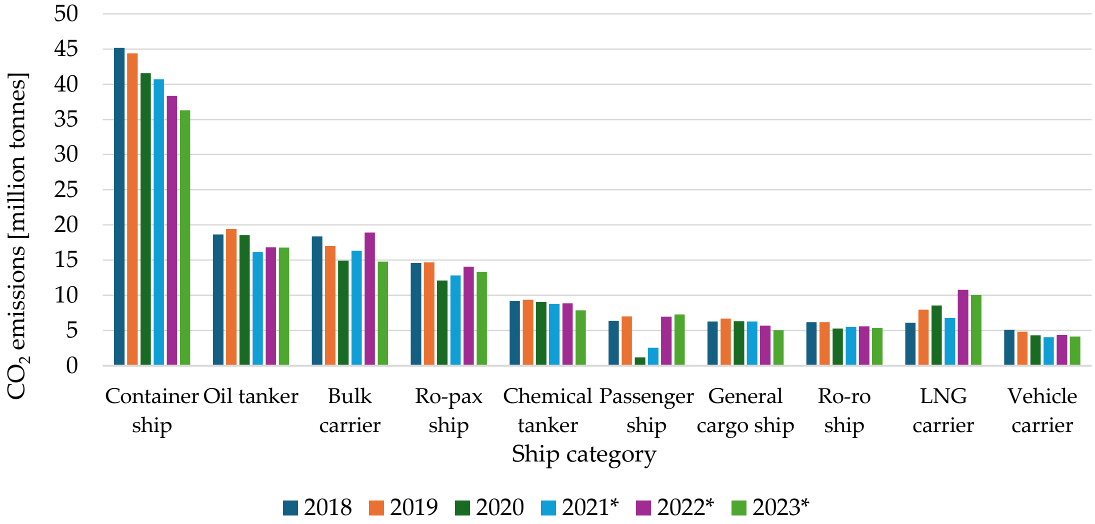


*Figure 2.3. Total CO2 emissions (Mtonnes), top 10 ship categories, 2018-2023, descending 2018 order. Source: authors' elaboration on EU-MRV data. Note: *without UK.*

Figure 2.4 suggest that, although the first three segments on the left are responsible for almost 50% of the total emissions, Ro-Pax and Passenger ships (i.e. cruise ships) are the most polluting when average CO2 emissions per ship are considered. This is due to two main factors: the geographical area of interest and the propulsion characteristics of the engines. Indeed, these types of ships record high percentages of voyages between EU ports. The average emissions from each ship are also related to the time spent on operations.

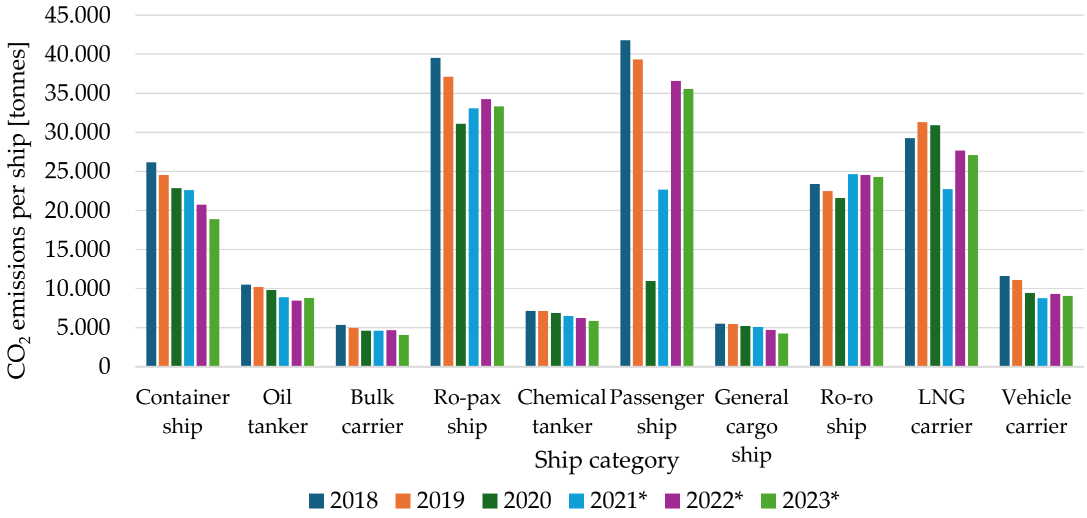


*Figure 2.4. Average CO2 emissions per ship (tonnes), top 10 ship categories, 2018-2023. Source: authors' elaboration on EU-MRV data. Note: * without UK.*

For each segment, the total CO2 emissions are split into emissions from navigation at sea and emissions in the port area (Figure 2.5). In absolute value, oil tankers and container ships were the first emitters in EU ports in 2023.

However, in relative values, passenger ships are the segment with the highest emissions in ports (15% of the total), due to the high consumption during berthing time and the longer stays at the quay. Furthermore, oil tankers and chemical tankers also show higher percentages, possibly related to operations in the port areas.

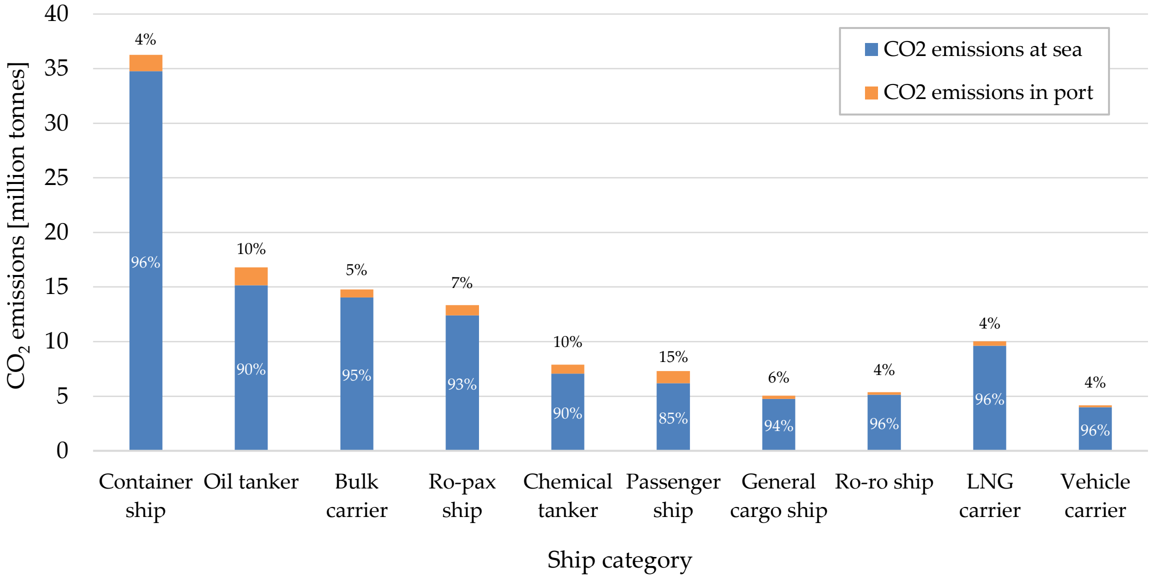


Figure 2.5. CO_2 emissions at sea and in the port area (Mtonnes), top 10 ship categories, 2023.
Source: authors' elaboration on EU-MRV data.

In the EU-MRV system, CO_2 emissions from navigation at sea are divided into emissions from voyages starting or ending in an EU/EEA port and emissions from voyages between EU/EEA ports. From 2024 onwards, this distinction will be essential for the proper functioning of the EU-ETS, as shipping companies will pay the EU allowances for 100% of the emissions from voyages between EU/EEA ports and 50% from voyages to/from EU/EEA ports. Therefore, from an economic perspective, it is important to consider the distinction between the different geographical scopes of the EU-ETS. Furthermore, from an environmental perspective, emissions between EU/EEA ports and in EU/EEA port areas can be geographically allocated to the European area, whereas it's more difficult to allocate the other emissions geographically. Figure 2.6 shows the CO_2 emissions for the different geographical scopes. The Ro-Pax is the segment that emits the most during voyages between EU/EEA ports, followed by container ships. On the other hand, the segment responsible for the highest levels of total emissions from voyages to and from EU/EEA ports is the container ships. This is followed by oil tankers, bulk carriers and LNG carriers.

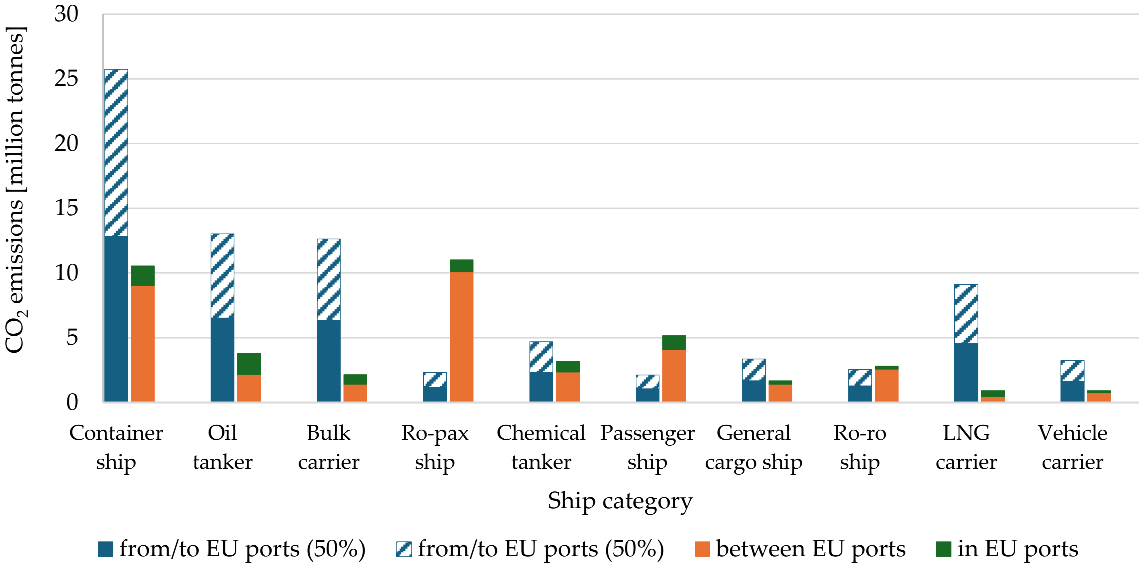


Figure 2.6: CO_2 emissions during voyages from/to EU ports, between EU ports, and in EU port areas (Mtonnes), top 10 ship categories, 2023.
Source: authors' elaboration on EU-MRV data.

According to the scope of the EU-ETS, only 50% of the emissions from voyages from/to EU/EEA ports are covered by EU allowances. Therefore, in this analysis, the EU-ETS emissions are defined as the sum of the emissions covered by the EU-ETS, i.e. 50% of emissions from voyages from/to EU/EEA ports, 100% of emissions from voyages between EU/EEA ports and emissions while in EU/EEA ports. Shipping companies must purchase one EUA for each tonne of ETS emissions. Table 2.5 shows the amount of ETS emissions for all the maritime segments. It is interesting to note that for the Ro-Pax sector, the ETS emissions account for 91% of the overall emissions recorded in the EU-MRV system, while for the containerized sector, the same figure drops to 65%.

The findings underscore the necessity to analyse the various shipping segments independently, given the evident differences between them. Indeed, the shipping sector includes cargo ships, Ro-Pax and cruise passenger ships. Furthermore, within each segment, the technical and operational differences between the ship categories should be taken into account. The impact of the inclusion of the shipping sector in the EU-ETS is not yet evident.

The EU-MRV data analysed refer to the period 2018-2023, which is not yet covered by the EU-ETS. For this reason, further analysis needs to be carried out on data relating to 2024, the first payment year for shipping companies.

Although the sectors with the highest emissions are container ships, oil tankers and bulk carriers, when ETS emissions are taken into account (i.e. 50% of emissions from voyages to/from EU/EEA ports, 100% of emissions from voyages between EU/EEA ports and emissions while in EU/EEA ports), the Ro-Pax sector is the segment that pays the largest percentage of total emissions (91%).

Some sectors, such as the Ro-Pax sector, are characterised by lower emission intensity factors compared to other sectors (e.g. container sector). Furthermore, the Ro-Pax and the Ro-Ro segments could suffer from higher EUA prices. This could lead to a modal shift towards more economic alternatives (e.g. road transport).

Table 2.5: EU-ETS CO_2 emissions, 2023.

Maritime segment	ETS emissions [tonnes]	ETS/MRV [%]
Container ship	23,417,630	65%
Oil tanker	10,287,768	61%
Bulk carrier	8,466,942	57%
Ro-pax ship	12,183,342	91%
Chemical tanker	5,527,094	70%
Passenger ship	6,228,944	85%
General cargo ship	3,362,842	67%
Ro-ro ship	4,088,915	76%
LNG carrier	5,475,003	54%
Vehicle carrier	2,542,473	61%
Gas carrier	1,536,214	60%
Ref. cargo carrier	607,467	57%
Container/ro-ro ship	742,466	69%
Other ship types	1,499,036	65%
Combination carrier	22,066	57%

Source: authors’ elaboration on EU-MRV data.

3. Greenhouse gas emission reduction measures for the shipping sector

The shipping industry is called to reduce its carbon footprint. In this context, the International Maritime Organization (IMO) plays a critical role in setting global standards, with a growing attention towards energy efficiency and reduction of GHG emissions. With the adopted of the "Initial Strategy on the Reduction of GHG Emissions from Ships" in 2018, IMO has set, at a global level, the basis for the implementation of a new regulatory scheme (Psaraftis, 2019). The decarbonization of the maritime sector can be achieved through various measures. These reduction measures can be grouped into three macro-categories: operation measures, technical measures, and market-based measures (Psaraftis, 2012; Tu et al., 2024; Xing et al., 2020). This Chapter will describe the macro-categories, by discussing the principal measures and the related regulations proposed by the IMO.

3.1. Operational measures

Operational measures are usually fleet-related and can be implemented without changing the technology used. They can involve: 1) speed management, and 2) route planning and voyage optimization (Serra and Fancello, 2020).

Speed management is based on the rule of thumb that a ship's fuel consumption, and consequently its GHG emissions, is a cubic function of its speed (Tran and Lam, 2022). Therefore, the adoption of slow steaming (i.e. navigating at a lower ship speed) and speed optimization to reduce fuel consumption and related pollutant emissions are widely adopted measures in the shipping sector. Compared to other operational measures, slow steaming is easier to adopt as it does not require major investments, can be implemented rapidly and produces significant benefits in a short time (Park et al., 2024).

Route planning refers to the practice of organizing the maritime routes in a cost-effective way using real-time data such as weather and currents (weather routing). Voyage optimisation involves optimising time during logistical operations in port, such as reducing port time and improving the ship-port interface, as well as optimising the supply chain and logistics. Other operational measures include cold ironing and maintenance, as well as human factors (Serra and Fancello, 2020; Zis et al., 2020).

To establish the operational efficiency of ships and enforce future optimisation, the IMO has adopted different evaluation tools: the EEOI, the EEXI, and the CII. These will be described in the following sections.

- The Energy Efficiency Operating Indicator

The Energy Efficiency Operating Indicator (EEOI), developed by the IMO in 2009 in order to allow shipowners to measure the fuel efficiency of a ship in operation, is a carbon intensity indicator "CII" and represents the demand for transport work. It can be calculated using equation 3.1.

$$EEOI = \frac{\sum_j (FC_j \cdot EF_j)}{m_{cargo} \cdot D} \tag{3.1}$$

where:

FC_j	is the fuel consumption for the fuel type j
EF_j	is the emission factor for the fuel type j
m_{cargo}	is the amount of cargo transported, in metric tons or work done (number of TEU or passengers) or gross tonnes for passenger ships
D_i	is the distance travelled in nautical miles while laden with transported cargo

- The Energy Efficiency Existing Ship Index & the Carbon Intensity Indicator

As a stimulus to reduce carbon intensity of all ships by 40% by 2030 compared to 2008 baseline, in 2021 IMO adopted a new set of operational measures (IMO, 2021), namely the Energy Efficiency Existing Ship Index (EEXI) to determine their energy efficiency, and their annual operational Carbon Intensity Indicator (CII) and associated CII rating. Carbon intensity links the GHG emissions to the amount of cargo carried over distance travelled. These technical (EEXI) and operational (CII) requirements came into effect on 1 January 2023 as a short-term measure under the Initial IMO GHG Strategy framework. The first annual reporting was completed in 2023, with initial ratings from 2024.

- EEXI: Energy Efficiency Existing Ship Index

All existing ships with a gross tonnage (GT) of 400 or more are required to determine their attained EEXI, which represents the vessel's technical efficiency. A ship's EEXI indicates its energy efficiency in relation to the "required EEXI", which is derived from the

EEDI baseline and an applicable reduction factor set by the IMO for each ship type and size category.

In order to comply, the attained EEXI must be lower than the required value, thereby ensuring that the ship meets the minimum energy efficiency standards. This technology-neutral regulation allows shipowners and operators to select appropriate measures to achieve compliance.

- CII: Carbon Intensity Indicator

All ships of 5,000 GT and above are required to collect and report annual fuel consumption data. Based on this information, each vessel receives a Carbon Intensity Indicator (CII) rating from A to E, where A represents the highest performance and E the lowest. The CII measures the annual reduction in operational carbon intensity needed to ensure continuous improvement. Each ship must document and verify its attained annual operational CII against the required value to determine its rating. Ships rated D or E must include corrective actions in their Ship Energy Efficiency Management Plan (SEEMP), while companies operating A or B-rated vessels may receive incentives. The 2022 guidelines for the development of the SEEMP incorporates best practices for fuel efficient ship operation as well as templates for the development of SEEMPs. It is composed of three parts:

- Part I: a ship management plan to encourage shipping companies to adopt the best practices for improving energy efficiency.
- Part II: a ship fuel oil consumption data collection plan that requires ship operators to include a methodology for Data Collection System (DCS), with the scope of improving data reporting and transparency.
- Part III: ship operational carbon intensity plan, based on the use of a Carbon Intensity Indicator (CII) rating, which links a ship's GHG emissions to the amount of cargo carried over the travelled distance.

The results are recorded in the SEEMP and subject to periodic audits by the Administration or recognized organizations. The CII can be calculated as shown in equation 3.2.

$$CII = \frac{FC_{year} \cdot EF}{Capacity \cdot D} \tag{3.2}$$

where:

FC_{year} is the fuel consumption for one year

EF is the carbon emission factor for each type of fuel used

Capacity is the capacity expressed in GT or DWT

D is the distance travelled in nautical miles while laden with transported cargo for one year

3.2. Technical measures

The technical measures are often (but not always) technological measures that can be used to reduce GHG emissions (Gilbert et al., 2014). They can focus on different aspects. The most traditional one looks at the ship's efficiency, i.e. hydrodynamic resistance, the design of the hull, friction reduction. Technical measures can be taken also to enhance the efficiency of the propulsion system, such as waste heat recovery or wind-assisted ship propulsion (e.g. Flettner rotors, rigid sails) (Metzger, 2022). Carbon capture technologies are also included. Shifts to more efficient technologies are central to any successful emissions reduction effort (Tuladhar et al., 2014).

Although some authors collocate alternative fuels and alternative power sources as separate categories, they can theoretically still be considered technical measures (Halim et al., 2018). The most common alternative fuels are liquefied natural gas (LNG), biofuels (alcohols, hydrocarbons) synthetic fuels (hydrogen, ammonia), biogas and methanol. Among the alternative power sources, wind energy, solar energy, nuclear energy, and fuel cells can be named.

In 2011, IMO adopted amendments to MARPOL Annex VI to mandate technical energy efficiency measures to reduce the amount of CO_2 emissions from international shipping.

- EEDI: Energy Efficiency Design Index

The Energy Efficiency Design Index (EEDI) is an important technical measure that aims at improving the technical efficiency of new built ships, promoting the use of more energy efficient equipment and engines for the design of new ships in order to make them less polluting. The EEDI requires a minimum energy efficiency level per capacity mile (e.g. tonne mile) for different ship type and size segments.

Since 1 January 2013, following a two-year transitional phase, new ship design needs to meet the reference level for their ship type. The level is to be tightened incrementally every five years, and so the EEDI is expected to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase.

The CO_2 reduction level (grams of CO_2 per tonne mile) for the first phase is set to 10% compared to a reference line calculated from the average efficiency for ships built between

2000 and 2010. It is tightened every five years to keep pace with technological developments of new efficiency and reduction measures until 2025 and onwards when a 30% reduction is mandated for applicable ship types.

The EEDI was originally developed for the largest and most energy intensive segments of the world merchant fleet and embraces emissions from new ships covering the following ship types: tankers, bulk carriers, gas carriers, general cargo ships, container ships, refrigerated cargo carriers and combination carriers. In 2014, MEPC adopted amendments to the EEDI regulations to extend the scope to: LNG carriers, Ro-Ro cargo ships (vehicle carriers), Ro-Ro cargo ships; Ro-Ro passenger ships and cruise passenger ships having non-conventional propulsion. These amendments mean that ship types responsible for approximately 85% of the CO_2 emissions from international shipping are incorporated under the international regulatory regime.

$$EEDI = \frac{CO_2 emissions}{Benefit\ Cargo} = \frac{\sum P \cdot C_f \cdot SFC}{Capacity \cdot Speed} \tag{3.3}$$

3.3. Market-based measures

On top of the operational and technical measures, GHG reduction policies can be adopted to reduce GHG emissions from the shipping industry. GHG reduction policies need to be consistent with cost-effective approaches (Lagouvardou et al., 2020). The two most common ones are the “command-and-control” regulations and the “market-based” measures (MBMs) (Helm, 2003; Serra and Fancello, 2020).

Command-and-control measures are a form of environmental regulation that enables decision-makers to regulate the extent to which a company can impact the environment, such as policies that employ fuel efficiency standards or transport and electric generation emission intensity standards (Tuladhar et al., 2014).

Market-based measures (MBMs) are environmental policy instruments that use markets, prices, and other economic variables to provide incentives for polluters to reduce or eliminate negative environmental externalities. Market-based policies are also closely connected to the polluters-pay principle (Schmidtchen et al., 2021). Using market-based instruments to internalise external costs is generally regarded as an efficient way to limit the negative side effects of transport and/or to generate income for the government (CE Delft et al., 2020). They can be classified as quantity or price measures (Weitzman, 1974). For example, “cap-and-trade” programmes are purely quantity measures while carbon taxation is a price measure (Halim et al., 2018). Hybrid schemes that incorporate both measures are also common (Ghaforian Masodzadeh et al., 2022).

IMO's Marine Environment Protection Committee (MEPC) started discussions on MBMs to incentivise emission reductions from the shipping sector in 2006. These discussions where then suspended in 2013 (Kachi et al., 2019; Tanaka and Okada, 2019). In 2017, the European Parliament's intention to include shipping into the EU-ETS from 2023 onwards resulted in an increase in international pressure on the IMO, culminating in the adoption of the "Initial Strategy on the Reduction of GHG Emissions from Ships" in 2018 (Psaraftis, 2019). This strategy sets targets to reduce the carbon intensity of shipping by 40% by 2030 (compared to 2008 levels) and to reduce total GHG emissions by 50% by 2050 (IMO 2018). It also explicitly recognizes the importance of the technological innovation and the global introduction of alternative fuels and/or energy sources in achieving the environmental goals. Emissions Trading Systems (ETSs) are a market-based measure, based on a cap-and-trade principle, where companies can trade carbon permits based on their emissions and their capacity to implement pollution reduction measures (Barthakur, 2021). Emissions Trading Systems can be categorized as either global or regional, depending on their geographical scope. A global ETS has been shown to have certain advantages over a regional ETS, in that it can avoid the risk of carbon leakage and pollution transfer (Cullinane and Yang, 2022). Figure 3.1 depicts the global status of Emissions Trading Systems (cap-and-trade measure) and carbon tax (price measure) systems implemented (or in the process of implementation).

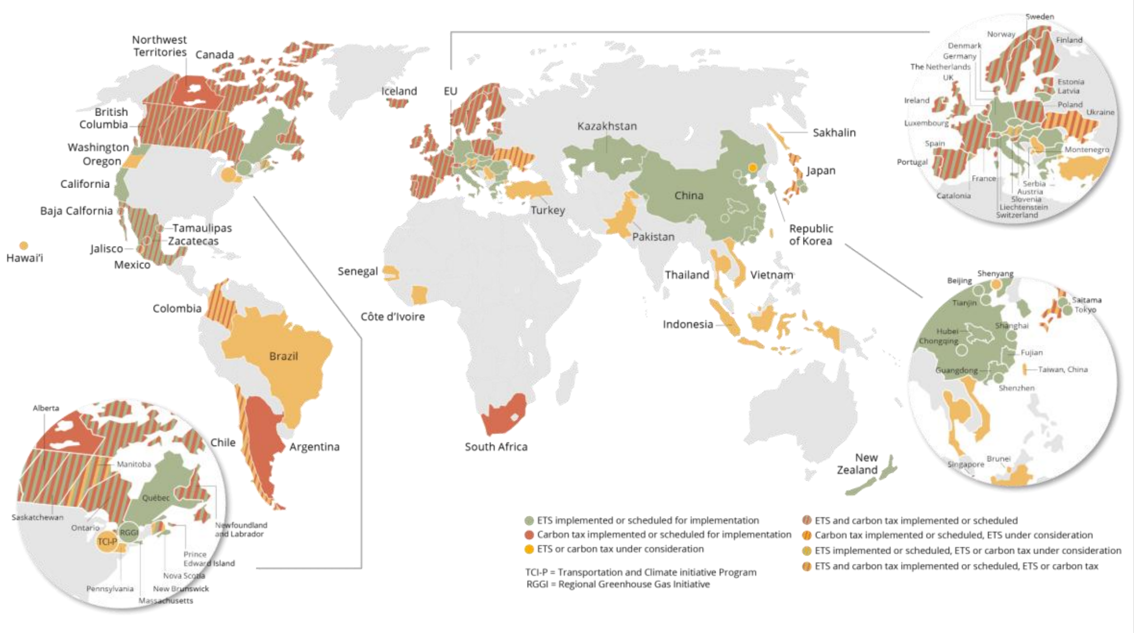


Figure 3.1. Map of global status of Emission Trading System and carbon tax systems implemented (or in the process of implementation).
Source: (World Bank, 2023). Note: Carbon pricing initiatives are considered "scheduled for implementation" once they have been formally adopted through legislation and have an official start date and "under consideration" if the government has announced its intention to work toward implementation.

4. Methodologies for the quantification of greenhouse gas emissions

Quantifying GHG emissions is key to decarbonising the maritime freight transport sector. Although carbon emission calculators and quantification methodologies that allow the environmental footprint of freight transport operations to be estimated are becoming more widespread, their exact measurement is challenging due to the poor quality or limited availability of the necessary input data, and the multitude of possible calculation methods that can result in figures that are highly inaccurate or very misleading.

Since maritime transport is usually combined with other modes of transport, such as road and/or rail, it is strongly recommended to use methodologies that assess emissions throughout the entire freight transport chain. The transport of goods by sea is, in fact, linked to the geographical location of the ports of departure and arrival. Consequently, this research analyses and evaluates not only methodologies associated with maritime freight transport, but also those that consider multiple modes of transport and harmonise data and results relating to them. This allows for the accurate, consistent and correct assessment of emissions generated during the various transport stages and, consequently, throughout the entire transport chain.

This Chapter analyses the existing (and planned) methodologies, standards, regulations, and tools that focus on the evaluation and/or the reporting of GHG emissions derived from freight transport. The aim is to critically classify the methodologies by identifying the best indicators. To do so, a literature review was performed to identify the various methodologies used for this purpose. Based on this analysis, the methodologies were critically evaluated in terms of their ability to integrate various transport modes and accurately and consistently measure emissions.

4.1. Introduction

The correct measurement of GHG emissions is fundamental in achieving global greenhouse gas reduction targets and realising sustainable transport chains (Dobers et al., 2019). Standardising methodologies for the calculation of GHG emissions is crucial in this context, so as the implementation of a carbon accounting framework for effective GHG mitigation in the global freight transport sector. Hence, accurate quantification of CO_2e emission levels is essential for determining the most impactful reduction measures in line with the reduction targets.

In the last twenty years, the necessity for a comprehensive and transparent standardized methodology for calculating and reporting GHG emissions produced by transport chains has been increasingly acknowledged (Ehrler et al., 2018; Fancello et al., 2023; Kellner and Schneiderbauer, 2019; Wild, 2021). For this reason, much effort was put to provide a common methodology for the quantification of GHG emissions from freight transport operations. The result is a mix of state-supported standards, standards self-developed by associations, recommendations by research bodies, regional approaches, and standards for individual modes of transport, (Kellner and Schneiderbauer, 2019).

The importance of good performance in the logistics industry in contributing to a low-carbon economy is widely recognized. However, compared to other sectors, the transport and logistics sector has been relatively slow to respond to environmental policies (Oberhofer and Dieplinger, 2014). This could be attributed, in part, to the indirect contact between transport companies and end-users, as well as to the sectors' fragmentation and its low reactivity to changes.

Many authors have assessed the comparability between existing methodologies. (Ehrler et al., 2013) began analysing the compatibility between calculation methods and identifying the missing steps required to achieve a fully aligned standard for the calculation of CO_2 emissions. Moreover, (Auvinen et al., 2014) presented an overview of prioritised gaps and ambiguities in existing standardisation approaches related to the global methodological harmonisation of logistics-related carbon footprint emissions along complex supply chains.

Building on this, the EN 16258 standard has been considered a possible starting point for a global standardisation approach. (Davydenko et al., 2014) analysed this standard, highlighting gaps and ambiguities that render comparisons of supply chains difficult. Prior the release of the first version of the GLEC Framework, the existing methodologies were not based on consistent conversion factors from fuel to emissions. (Lewis, 2016) argued that this issue needed to be addressed in order to establish a clear approach by mode, fuel and global region for well-to-wheel CO_2e emissions. Further efforts have focused on refining emission calculation frameworks. (Ehrler et al., 2018) identified gaps that need to be addressed to ensure accurate emission calculations using the GLEC Framework v1.0, while (Davydenko et al., 2019) designed a procedure based on data input for harmonising different methodologies and ensuring the comparability of carbon footprint computations between different calculation tools. In that period, (Hülemeyer and Schoeder, 2019) compared the EN 16258 standard and the first version of the GLEC Framework, identifying similarities and inconsistencies between the two. In the same context, the study conducted by (Kellner and Schneiderbauer, 2019) aimed to harmonize the process of GHG declarations for transport chains by identifying, among all allocation units specified by the EN 16258, the one that best describes a shipment's contribution to GHG emissions. Building on the these foundations, (Wild, 2021) suggested recommendations for developing a global standard for all transport modes based on the EN 16258 standard for freight and logistics transportation.

In the field of road transport, (McKinnon and Piecyk, 2009) examined various methods of carbon auditing road freight transport, while (Petro and Konečný, 2017) created a calculator of external costs based on road transport carbon emissions. Similarly, (Kellner, 2016) proposed new EN 16258 allocation rules for emissions from road freight transport operations to single shipments, suggesting the use of *distance* as the only allocation unit. In line with previous studies, (Kellner, 2022) analysed the accuracy and fairness of EN 16258 allocation rules, investigating the incentive power of different allocation schemes to promote GHG-minimal operation in road freight networks. Moreover, (Agavanakis et al., 2023) developed a cloud-based data hub that is capable of collecting and sharing primary data regarding the vehicle type, the road trip, and the load transported.

(Hörandner et al., 2023a) conducted a literature review on emission factors along multimodal transport chains and their effects on emission calculation results, while (Hörandner et al., 2023b) presented an overview of emission calculations in inland navigation.

Looking at transport chains, some authors have focused also on the methodologies used in logistic hubs. In their research, (Dobers et al., 2019) described the motivations and barriers currently experienced by shippers and logistics service providers when computing emissions from logistics hubs. Later, (Dobers et al., 2023) provided an overview of relevant indicators that can be used for measuring the sustainability in logistic hubs and specifically in ports, helping decision making on their roadmap towards climate neutrality. Moreover, (Barbieri et al., 2024) proposed a methodology for calculating the environmental impact of logistics sites based on carbon footprint assessment.

Some studies (Fancello et al., 2023; Gallo, 2022; Olivari et al., 2025) compared results obtained using some of the most commonly used online calculation tools (e.g.: EcoTransIT World, CarbonCare, GLEC Framework, TK'Blue, GreenRouter) based on transport case studies. The results obtained show slight differences between the selected tools and highlight that the final figures primarily depend on the quality of the data provided for the calculation. An interesting study, conducted by (Schramm and Lehner, 2024) analysed forty-two Online Carbon Emission Calculators (OCECs) and tested those that met all the selection criteria (six). A benchmark case study revealed that, despite using identical input data, results from different OCECs varied widely. These discrepancies were mostly unexplained due to limited transparency in calculation methods and data sources. The study confirmed that a better understanding of the context of transport operations leads to more accurate emission estimates. However, many OCECs lacked detailed transport input options, rendering their results unreliable. The six OCECs were then evaluated based on the transparency of their routing, data sources and calculation methods. While each tool excelled in at least one area, only one OCEC met all five criteria completely.

Limitations of existing methodologies where assessed by (du Plessis et al., 2022) who argue that one of the limitations is that they are based on general principles, which makes it challenging to apply them to specific transport chains, such as, for example, the fresh fruit distribution. Scientific literature still requires further advancement in the field of decision-making models pertaining to greenhouse gas emissions produced by logistic activities (Dehdari et al., 2023).

In the following section, the different types of methods will be presented and classified.

4.2. Classification of the methodologies

Before going into detail for each methodology, it is first worth introducing the classification groups, based on their methodological category. This was achieved through a critical analysis of the existing methodologies. The research identified the following six groups:

- Commercial tools
- Frameworks
- Initiatives
- Programs
- Research Projects
- Standards

The main characteristics for each group will be presented. Table 4.1 provides an overview of the methodologies, specifying the geographical scope and modes of transport considered. In the following of this paragraph, these items will be presented in detail.

Table 4.1: Classification groups of the transport sector's GHG emissions methodologies.

Methodological category	Name	Coverage	Modes of Transport	Reference
Commercial Tools	BigMile	World	Multimodal	(bigmile.eu)
	CarbonCare	World	Multimodal	(carboncare.org)
	EcoTransIT World	World	Multimodal	(ecotransit.org)
	GreenRouter	World	Multimodal (except IWT)	(greenrouter.it)
	HBEFA 4.2	Europe	Road	(HBEFA, 2022)
	TK'Blue Agency	World	Multimodal	(tkblueagency.com)
Initiatives	CCWG	World	Sea - container shipping	(CCWG, 2015)
	EEEG GHG Guidance	Europe	Hub - Container terminals	(EEEG, 2017)
	EEEG GHG Guidance	Europe	Hub - Dry Bulk terminals	(EEEG, 2023)
Methods	GLEC Framework	World	Multimodal	(SFC, 2025)
	IATA RP 1678/1725	World	Air	(IATA, 2022a, 2022b)
	ICAO Calculator	World	Air	(icao.int)
Programs	Green Freight Asia	Asia	Multimodal	(greenfreightasia.org)
	Green Freight Europe	Europe	Multimodal	(europeanshippers.eu)
	SmartWay Transport	North America	Multimodal	(epa.gov)
Research Projects	STREAM - CE Delft	World	Multimodal	(CE Delft, 2020)
	Green Efforts	Europe	Hub - Port terminals	(Froese et al., 2014)
	IML Guide	World	Hub - Logistic sites	(Dobers et al., 2023)
Standards	EN16258 (former)	Europe	Multimodal	(EN, 2016)
	ISO14083	World	Multimodal	(ISO, 2023)

Source: author's elaboration based on the literature review.

4.2.1. Commercial tools

In recent years, many tools for calculating and reporting GHG emissions have emerged. These tools are often based on methodologies and guidelines proposed by international institutions.

A general challenge about emission values and calculations in literature results from the fact that the various available calculation tools apply different indicators and often have different application scopes, making the results hardly comparable with one another (GLEC, 2016). In the following, some of the most important will be presented.

4.2.1.1. BigMile

BigMile is a software platform that collects and combines data from the day-to-day operations of shippers, logistics services providers, and carriers.

4.2.1.2. Carbon Care

Carbon Care is a commercial CO_2 emission calculation platform comparable to EcoTransIT or BigMile. It estimates GHGs for all modes of transport, for transhipping/warehousing and for cooling chains.

4.2.1.3. EcoTransIT World

The EcoTransIT World Initiative (EWI) is an independent, industry-driven, platform for carriers, logistics service providers, and shippers. In 2003 it launched an online tool, the EcoTransIT World (Ecological Transport Information Tool for Worldwide Transports), with the aim of continuously developing and harmonising the emission calculation methodology for the global freight transport sector. It is developed by IFEU Heidelberg, INFRAS Berne and IVE mbH Hannover. The EcoTransIT World tool is globally recognized as one of the most established calculation tools.

4.2.1.4. GreenRouter

GreenRouter (Carbon accounting and reduction strategies) is a platform created in 2016 with the aim of analyzing and reducing the overall impact of emission generated by companies.

This tool requires the following inputs: information regarding the type of transport, type of trip, time frame, type of freight unit used, type of goods and characteristics (such as temperature-controlled travel, weight of goods and point of departure and arrival). Also logistics site emissions are taken into account. In this case, the tool requires geographic data, size and type of activity for the logistics site, as well as consumption data broken down into electrical, fuel, refrigerant, water and steam/heat categories. If the user is unable to provide the distances travelled when transporting goods, the tool extimates them using an external routing system. GreenRouter includes all major modes of transport except inland waterway transport. Emission intensity factors can be provided by customers and carriers using this tool. Where this information is unavailable, the values provided by GreenRouter can be used instead. These values are based on data from other users (GLEC and other sources).

As an output of the emission calculation, GreenRouter provides the following: distance; total emissions; emission intensity; and total emissions divided by scope and by transport mode. GreenRouter complies with the GLEC Framework v.3.1, ISO 14083 and IML guidelines.

4.2.1.5. Handbook of Emission Factors - HBEFA 4.2.

The Handbook of Emission Factors (HBEFA 4.2) is a database application providing emission factors for road vehicle categories (passenger cars, light duty vehicles, heavy duty vehicles, buses, and motorcycles). HBEFA was originally developed on behalf of the Environmental Protection Agencies of Germany (UBA), Switzerland (FOEN/BAFU), and Austria (Umweltbundesamt). In the meantime, further countries and the JRC (Joint Research Centre of the European Commission) are supporting HBEFA. The handbook is developed and provided by INFRAS.

4.2.1.6. TK'Blue

TK'Blue Agency was launched at the end of 2011, after the adoption of a new CSR strategy from the European Commission. It offers professionals innovative solutions to measure, analyze and optimize the environmental and societal impact of transport operations, also supporting clients in choosing the best logistics provider. The information provided is organized into five levels: by transportation methodology, by origin, by destination, by carrier, and finally by month. This tool requests as input data: weight of the cargo, delivery distance, type of vehicle including its category, whether the transport is considered as fully loaded or not and the performance level attributed to the carrier (low medium and high).

4.2.2. Framework

Frameworks are structured reference systems that define fundamental principles, scope boundaries, and conceptual rules for addressing complex methodological domains. They establish a shared foundation that ensures consistency and comparability across different applications and stakeholders. They are intended to guide the development and application of methods, tools, and standards within a coherent system. As such, frameworks play a central role in harmonizing practices while allowing flexibility in implementation.

4.2.2.1. GHG Protocol Framework

The GHG Protocol arose when the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) recognized the need for an international standard for corporate GHG accounting and reporting in the late 1990s. The GHG Protocol establishes comprehensive global standardized frameworks to measure and manage GHG emissions from private and public sector operations (governments, cities, industry associations, private companies, NGOs, businesses and other organizations), value chains and mitigation actions. The GHG Protocol is now widely accepted and used as a reference at a global level, especially following the agreements of the COP in Paris in December 2015. The standard covers the seven major gases greenhouse effect covered by the Kyoto protocol.

According to the indications of the GHG Protocol, emissions relating to an organization are attributable to three areas: Scope 1 (direct emissions deriving from owned sources o controlled by the organization), Scope 2 (indirect emissions such as deriving from the use of electricity, heat and steam), Scope 3 (indirect emissions deriving from the organization's activities that take place from sources neither owned nor controlled by it).

4.2.2.2. GLEC Framework

One of the most complete methods is the GLEC Framework, developed by the Global Logistics Emissions Council (GLEC), led by the Smart Freight Centre. It aims at standardizing the calculation of GHG emission related to freight transport. Furthermore, it harmonizes numerous other existing methodologies, and it cover all freight transport modes (air, inland waterways, rail, road, sea, pipelines, cable cars) and hub operations (ports or warehouses) along the transport chain. It is aligned with the IPCC Guidance and the Science based target initiative SBTi. It is considered the industry benchmark for calculating and reporting greenhouse gas emissions in multimodal logistics, by transforming operational data into comparable KPIs to guide reduction plans.

The first version of the GLEC Framework was released in 2016, while the second version in 2019. During September 2023, in full alignment with the new ISO 14083 standard, an updated version of the GLEC Framework was published (third release). Figure 4.1 shows the timeline of the main standards for the calculation of GHG emissions and the three releases of the GLEC Framework.

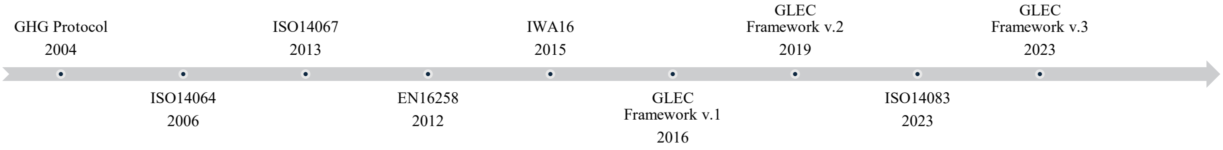


Figure 4.1. Timeline of the main standards for the calculation of GHG emissions. Source: author's elaboration.

4.2.3. Initiatives

Initiatives refer to organized and often collaborative efforts aimed at promoting, coordinating, or advancing particular methodological approaches. They are frequently led by public institutions, international organizations, research consortia, or professional communities. Initiatives may focus on awareness-raising, knowledge sharing, capacity building, or policy alignment. They often serve as catalysts for broader adoption of methodologies across sectors. Outcomes may include guidelines, networks, or supporting resources rather than concrete tools.

4.2.3.1. Clean Cargo Working Group (CCWG)

The Clean Cargo Working Group (CCWG) was established in 2003 as a Business for Social Responsibility (BSR) initiative, bringing together ocean containerised cargo shippers, forwarders and carriers who are interested in making the container shipping sector more sustainable. Since 2022, the CCWG has been integrated into the Smart Freight Centre programme, collaborating on the implementation of the GLEC Framework.

4.2.3.2. EU Ports European Economic Interest Group (EEEG)

The EU Ports European Economic Interest Group (EEEG) provides container terminal operators and dry bulk terminal operators with a guidance for GHG emission footprinting. The aim is to give first instructions on the elements to be included and excluded in reporting GHG emissions, as part of terminal-level carbon footprinting and analyses.

4.2.3.3. IPCC Guidance

Created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), the Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change. The objective of the IPCC is to provide governments at all levels with scientific information that they can use to develop climate policies. IPCC reports are also a key input into international climate change negotiations. Through its assessments, the IPCC identifies the strength of scientific agreement in different areas and indicates where further research is needed. The IPCC does not conduct its own research. The Good Practice

Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC Guidance) is a report on good practice in GHG inventory management. It provides good practice guidance to assist countries in producing inventories, reducing uncertainties as far as practicable.

4.2.4. Programs

Programs support the implementation of methodologies over a sustained period of time. They typically encompass a set of activities, resources, and governance mechanisms, such as training, funding, or technical assistance. Programs are often institutional or non-profit. Their objective is not only methodological application but also long-term capacity building. As such, programs often integrate multiple methods or tools within a unified structure.

4.2.4.1. Green Freight Asia

Green Freight Asia (GFA) is a non-profit association of industry players, which collaborates with industry companies, NGOs, and governments to improve energy efficiency, fuel efficiency, reduce CO_2e emissions, and to lower operational costs across the entire supply chain. Following the guidelines and requirements of the GHG Protocol methodology, GFA promotes a Measurement, Reporting, and Verification Programme to help companies to keep track of their emissions.

4.2.4.2. Green Freight Europe

Green Freight Europe (GFE), launched during 2012, is the leading industry programme supporting carriers, shippers and logistics service providers in improving the environmental performance of freight transport across Europe. It includes a platform for the monitoring and reporting of carbon emissions, based on existing standards. The programme also promotes collaboration between carriers and shippers in driving improvement actions and monitoring progress.

4.2.4.3. SmartWay Transport

The SmartWay Transport program aims to improve the fuel efficiency of the transportation supply chain industry and reduce its GHG emissions and air pollution. It's developed jointly by the EPA (US Environmental Protection Agency's) and Charter Partners (represented by industry stakeholders, environmental groups, American Trucking Associations, and Business for Social Responsibility)

4.2.5. Research Projects

Research projects aim at developing, testing, refining, or validating methodologies. They are usually conducted by academic institutions, research organizations, or interdisciplinary teams. Their scope is typically defined by specific research questions or hypotheses. The results may help in the implementation of future methodologies or policy decisions.

4.2.5.1. STREAM - CE Delft

The emission factors from the STREAM (Study on Transport Emissions for All Modes) studies are frequently used by policymakers, industry, researchers and consultants for policy exploration and development on issues relating to modal shift, vehicle fleet renewal, (carbon) footprinting and other such matters. STREAM Freight Transport 2020, updates the 2016 version, providing a comprehensive review of the emission factors of freight transport modes for the year 2018. This update was needed because European vehicle standards, fleet renewal, government policies and technological progress mean that transport emissions have changed since 2014, the reference year adopted in STREAM 2016. The aim of STREAM is to provide an up-to-date and accessible review of emission factors for key freight transport modes for use in (policy) analysis, intermodal comparison and (carbon) footprinting studies.

4.2.5.2. Green Effort

The GREEN EFFORTS Research Project (Green and Effective Operations at Terminals and in Ports), co-funded by the European Commission, ended in 2014. The aim was "to make terminals and ports a better place to work and to live with", as carbon footprint mitigation was the objective specified by the European Commission. The project developed a methodology for sea and inland navigation terminals characterised by a top-down approach from total terminal emissions to product level, hence using only real data, no default data, and by integrating the management of energy-efficiency and mitigation of emissions.

4.2.5.3. IML Guide

The IML Guide for greenhouse gas emissions accounting at logistics hubs is developed by the Fraunhofer Institute for Material Flow and Logistics IML. This guide provides advice on how to carbon audit logistics hubs with a view to performing logistics chains calculation. Therefore, it outlines requirements and options set by the ISO 14083 standard. The guide illustrates, in detail, the methodology for the evaluation of GHG emissions at logistic hubs and how to report them at a company level.

4.2.6. Standards

Standards are formally defined norms, guidelines, or specifications established by recognized standardization bodies or authoritative organizations. Their purpose is to ensure consistency, quality, interoperability, and comparability across implementations. Standards are typically developed through consensus-driven processes involving multiple stakeholders. They provide a common reference framework that supports widespread adoption and compliance. Unlike methods or tools, standards are often normative and may be referenced in regulation or certification processes.

4.2.6.1. ISO 14064 standard

The ISO 14064 is an international standard that provides private and public organizations a set of tools to quantify, monitor, report and verify of greenhouse gas emissions and their respective "removals" at the level of enterprise.

Contains multiple meeting points with the GHG Protocol, such as the focus on the whole organization instead than on the single product. ISO 14064 refers to the division between direct and indirect emissions, going beyond the concept of Scope, classifying the emissions into categories and introducing criteria for the significance of the emissions.

4.2.6.2. ISO 14083 standard

The ISO 14083, “Quantification and reporting of greenhouse gas emissions arising from operations of transport chains”, was released in March 2023 by the International Standard Organization (ISO). ISO 14083 provides, for the first time, requirements and guidance for quantifying, verifying, monitoring, and reporting of GHG emissions along the entire transport chains for passengers and freight. It covers all modes of transport and includes the operational GHG emissions from hubs. It is aligned with the ISO families 14040 and 14060.

4.2.6.3. EN 16258 standard

EN 16258 standard, published by the European Committee for Standardization (CEN) in 2012, presents a "Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and/or passengers)".

It was replaced by the ISO 14083 standard in 2023. Until then, the EN 16258 standard, constituted the only official international, though European, standard for emission calculation of transport operations. It specifies general principles, definitions, system boundaries, calculation methods, allocation rules and data recommendations, with the objective to promote standardised, accurate, credible and verifiable declarations, regarding energy consumption and GHG emissions related to any transport service quantified.

Many studies have focused on the EN 16258 as a starting point for a global standard for emission calculation and declaration (Auvinen et al., 2014; Davydenko et al., 2014; Kellner, 2016; Kirschstein and Bierwirth, 2018).

4.2.6.4. Publicly Available Specification (PAS) 2050

The Publicly Available Specification (PAS) 2050 is an internationally applicable standard, developed in 2008 (and revised in 2011) by the British Standards Institution (BSI), to assess the life cycle greenhouse gas emissions of goods and services (BSI, 2011).

4.3. Carbon Emissions Reporting

Implementing these methodologies often leads to the creation of a report. Reporting GHG emissions is as important as quantifying them. It is the tool through which organisations communicate their efforts and results in reducing GHG emissions. The purpose of GHG emission reporting is therefore to provide transparent and accurate information. Reporting also helps stakeholders, including investors, customers, and regulators, understand an organisation's environmental impact and sustainability performance. This can be done from a business point of view and by providing clients with this emissions data for their own reporting purposes. There are different levels of reporting. ISO 14083 standard provides two options: 1) Reporting at the organizational level, 2) Reporting at the level of transport or hub services (ISO, 2023).

- **Reporting at the organizational level**: The aim of reporting at an organisational level is to reflect the GHG emissions resulting from transport and hub operations. This reporting is suitable for organisations that either operate all transport services they use or purchase a significant amount of transportation services and wish to report on the associated GHG emissions for their entire transport chain(s). Depending on practical issues, the report shall take the form of either a single long report, or a short report complemented with other information made available separately.
- **Reporting at the level of transport or hub services**: The transport or hub service level reporting is designed for service providers who want to report on the GHG emissions associated with a specific set of transport or hub services provided to a service user. The requirement for reporting at this level is a more focused analysis of emissions associated with the specific set of services provided, that are identified in one or more TCE(s).

When reporting is done from a corporate perspective, then it's called Corporate Carbon Emissions Reporting (CCER). CCER functions within a complex landscape of international frameworks, each characterized by its own specific focus and scope. Reporting can be mandatory or voluntary, creating regulatory fragmentation across regions and contributing to reporting heterogeneity (McDonald et al., 2024). Among the most widely recognized programs are the Global Reporting Initiative (GRI), the Carbon Disclosure Project (CDP), the European Sustainability Reporting Standards (ESRS) – specifically ESRS E1 on climate change – and the Task Force on Climate-Related Financial Disclosures (TFCD) (Traub et al., 2025). These frameworks collectively seek to improve transparency and comparability in corporate carbon accounting by promoting the disclosure of Scope 1, 2, and 3 GHG emissions, typically based on the GHG Protocol. An overview of these programs is presented in Table 4.2.

Starting from 2024, large companies in the EU with more than 250 employees are required to report their carbon emissions under the CSRD (Corporate Sustainability Reporting Directive). The CSRD is the European directive that requires companies to report on sustainability in accordance with the ESRS and its specific technical standards, which define how this reporting should be carried out. The ESRS E1, in particular, focuses on climate change.

Table 4.2: Comparison of the main corporate carbon emissions reporting programs

Criteria	GRI 305	CDP	ESRS (E1)	TCFD
Materiality approach	Impact on environment	Primarily environmental	Financial & Environmental impact	Primarily financial
Scope of reporting	GHG emissions	Climate data, emissions, strategies	GHG emissions, reduction targets	Climate-related financial risk and governance
Emission coverage	Scope 1, 2, 3	Scope 1, 2, 3 (encouraged)	Scope 1, 2, 3 (mandatory)	Scope 1, 2, 3 - when relevant
Regulatory status	Voluntary	Voluntary, widely used	Mandatory in the EU	Voluntary, growing adoption
Alignment with GHG Protocol	Yes	Yes	Yes	Encourages alignment
Stakeholders focus	General public and regulators	Investors, supply chains, stakeholders	Regulators, investors, stakeholders	Investors, financial institutions

Source: author's elaboration based on (Traub et al., 2025)

4.4. Conclusions

This chapter analysed existing and planned methodologies, standards, regulations and tools focusing on the evaluation and/or reporting of greenhouse gas emissions from freight transport. Based on a review of the literature, the methodologies were classified according to their ability to accurately and consistently measure emissions across various transport modes. The analysis revealed that the methodology proposed by the ISO 14083 standard, when used in conjunction with the GLEC Framework, is the only multimodal methodology recognised as an international standard.

For this reason, it has been chosen for an application to a real case study. The aim is to understand how the proposed methodology functions, analyse the main outcomes, and identify potential weaknesses. This will be done in the next Chapter.

5. Quantifying greenhouse gas emissions using the ISO 14083 standard: a numerical application to a Ro-Ro Maritime Transport Chain[2]

The analysis conducted in the previous Chapter revealed that the methodology proposed by the ISO 14083 standard, in conjunction with the GLEC Framework, offers the most comprehensive approach to quantifying greenhouse gas emissions from freight transport chains. Furthermore, as the ISO 14083 standard was released for the first time in 2023, literature on it is limited. For these reasons, this methodology was chosen for an application to a real case study.

The objective of this application is to understand how the proposed methodology works, to analyse the main results and to identify potential weaknesses by evaluating the greenhouse gas emissions generated during the delivery of a consignment and the related GHG emission intensity.

This Chapter will present the application. Section 5.1 will introduce the case study, while section 5.2 will illustrate the ISO 14083-based methodology. Section 5.3 will present the case study and the input data. The application of the methodology and the numerical results will be shown in sections 5.4 and 5.5. Finally, section 5.6 will conclude the Chapter.

---

[2] This chapter is partially based on the following published work by the author:

- Vitiello, D. M., Serra, P., & Fancello, G., (2025). Assessing greenhouse gas emissions arising from intermodal freight transport chains using the ISO14083 standard. Transportation Research Procedia, 90, 464-471. https://doi.org/10.1016/j.trpro.2025.06.119
- Fancello, G., Vitiello, D. M., & Serra, P. (2023). Evaluating the environmental sustainability of an intermodal freight logistic chain using the GLEC Framework. In International Conference on Computational Science and Its Applications (pp. 563-576). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-37123-3_39

5.1. Introduction to the application

Compared to other maritime segments, knowledge of how to quantify and allocate greenhouse gas emissions in the Ro-Ro sector is still limited, particularly with regard to its integration with other modes of transport. Indeed, the Ro-Ro sector is characterized by many challenges in calculating the emission intensity due to a wide scatter in the ship type (vehicle/car carrier, Ro-Pax, Ro-Ro cargo, Con-Ro), speed, type of service (short sea shipping, deep sea, regular services, etc.), and operational status (laden with cargo vs. ballast/repositioning). Both the IMO and the EU have struggled to find ways to accurately report the GHG emission intensity of this segment (ECG and SFC, 2023). Therefore, the chosen case study for this application is a Ro-Ro maritime freight transport chain.

A maritime transport chain (MTC) refers to the movement of cargo, as well as any related support, involving two destinations and using both maritime (sea) and land transportation. (Lam, 2011) defines MTC as "the connected series of activities of shipping services concerned with planning, coordinating, and controlling (containerized) cargoes from the point of origin to the point of destination". MTC are shaped by chain-choice decision makers – such as suppliers, exporters, cargo packing companies, freight forwarders, agents, shippers, logistics providers, warehousing companies, ports, carriers, and customers – who collaborate to achieve mutually beneficial outcomes. These stakeholders are vertically connected through customer–supplier relationships (Tongzon et al., 2009). These complex networks integrate sea and land operations, involving storage, distribution, customs clearance and communication. When considering only the distribution of cargo, it is referred to as a maritime transport network or chain. A MTC is created when carriers, ports and shippers are involved in the movement of cargo (Talley, 2014). Figure 5.1 shows a schematic representation of an MTC. At the origin location, shippers deliver cargo to land carriers – by truck or rail – to reach the departure port, where it is transferred to a shipping line for sea transport to the destination port. There, the cargo moves from the vessel to a land carrier for final inland delivery.

Figure 5.1: Example of a maritime transport chain.
Source: author's elaboration.

5.2. The ISO 14083-based methodological approach

This section introduces the methodology provided by the ISO 14083 standard. This standard was developed through a collaboration between the Smart Freight Centre and the ISO. Building on the second version of the GLEC Framework, developed by the Smart Freight Centre, the ISO Working Group created the ISO 14083 standard. Following the release of the latter, the GLEC Framework was revised to comply in turn with the ISO 14083 standard.

The main difference between the ISO 14083 standard and the GLEC Framework is that the former is a standard, that presents a more structured detailed methodology and more guidance for dealing with uncertainties, whereas the latter acts as a practical guide to help companies implement it.

The aim of this paragraph is to provide an overview of the methodology by illustrating the main features of the calculation process. This methodology will then be applied to a case study in the next section. The rest of the section is divided as follows. First, an overview of the classification of greenhouse gas emissions is given to explain which gases are included, what measurement unit is used, and how they are classified. Next, the basis of the GLEC Framework will be discussed, followed by a detailed presentation of the methodology proposed by the ISO 14083 standard.

5.2.1. Classification of GHG emissions

The greenhouse gases covered by the ISO 14083 standard and the GLEC Framework are those defined and targeted by the Kyoto Protocol. These gases are listed in Annex A and include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). In particular, CO_2 comprises the majority of GHG emissions for logistics activities. For this reason, GHG emissions are expressed in a common standard unit, based on the global warming potential (GWP), called CO_2-equivalent (CO_2e or CO_2eq or CO_2-e).

The GHG Protocol classifies greenhouse gas emissions into three categories, called Scopes. This classification was initially adopted by the GLEC Framework (v.1.0 & v.2.0). The Scopes are:

- Scope 1: direct emissions from assets that are owned or controlled directly by the reporting company (e.g.: combustion of fuel).
- Scope 2: indirect emissions from the production and distribution of electricity, heat, and steam purchased by the reporting company.

- Scope 3: indirect emissions from assets or activities that are not owned or controlled by the reporting company, but for which the company is directly responsible. It also covers the production and distribution of fuels burned in Scope 1.

The ISO 14083 introduces a different categorization, moving from a concept based on the purpose (scope) of the use, to one based on the nature of the use. Accordingly, the updated version of the GLEC Framework (v.3.x) adopted the new classification aligned with the ISO 14083 standard. In detail, the GHG emissions are divided into:

- Direct emissions: emissions related to energy use,
- Indirect emissions: emissions related to the provision of the used energy.

Furthermore, as required from the GHG Protocol, both the ISO 14083 standard and the GLEC Framework, take into account the entire fuel/energy life cycle, known as Well-to-Wheel (WtW), when calculating GHG transport chain emissions. WtW emissions include:

- Well-to-Tank (WtT) emissions, related to the provision of the energy used for transport activity or hub operations. They include all the processes between the energy source (Well) and the various stages of refining, storage and delivery up to the point of use (Tank);
- Tank-to-Wheel (TtW) emissions. They are related to the energy use of the transport operations – hub and transport activity – also referred to as "Tank-to-Wake" where appropriate.

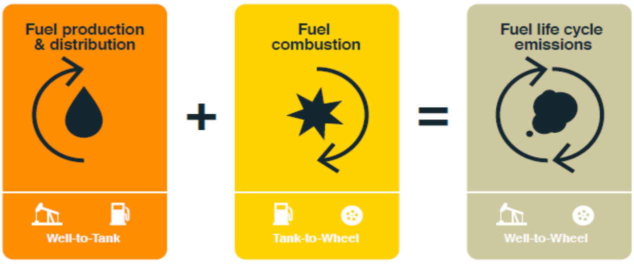


Figure 5.2: Schematization of the fuel/energy life cycle emissions.
Source: SFC (2025).

Figure 5.2 provides a schematization of the fuel/energy life cycle emissions, while Table 5.1 summarizes the changes in the emission classification between the GHG Protocol, the second and third release of the GLEC Framework, and the ISO 14083 standard.

Table 5.1: Classification of GHG emissions: comparison between different methodologies.

GHG Protocol & GLEC Framework (v.2.0)	ISO 14083 standard & GLEC Framework (v.3.x)
Scope 1: direct emissions (company)	Direct emissions: energy use, TtW (Tank-to-Wheel)
Scope 2: indirect emissions (electricity)	Indirect emissions: energy provision, WtT (Well-to-Tank)
Scope 3: indirect emissions (supply chain)	

Source: author's elaboration.

5.2.2. The GLEC Framework

The GLEC Framework was developed by the Global Logistics Emissions Council (GLEC), a voluntary and independent partnership of companies, green freight programs and industry associations, supported by researchers and experts, led by the Smart Freight Centre. It aims at standardizing the calculation of GHG emission related to freight transport, specifically developed for transport chains, including all transport modes.

This tool has recently been updated in 2023 following the publication of the ISO14083 standard, which implements the European EN16258 standard. The standard defines the methodology for calculating energy consumption and greenhouse gas emissions caused by transport. The tool is already widely used. Measuring the environmental impacts of logistics processes objectively requires a single methodology to ensure comparability and classification. Operators in the sector could take the next step towards promoting more environmentally sustainable choices by adopting self-declared environmental declarations. This would benefit the entire sector.

Table 5.2: Timeline of the different versions of the GLEC Framework.

Versions	Date	Content
v.1.0	2016	First release
v.2.0	2019	Second release
v.3.0	September 2023	Update after ISO 14083
v.3.1	October 2023	Update of the v.3.0

Source: author's elaboration.

The carbon accounting methods used to develop the GLEC Framework are various. Among the others, it is aligned with the following norms: ISO 14083, GHG Protocol, IPCC Guidance, and SBTi. Furthermore, it harmonizes numerous other existing methodologies. Table 5.3 provides the methodologies used for the considered transport modes.

Table 5.3: Overview of harmonized carbon accounting methods in the GLEC Framework v.3.1.

Transport mode	Carbon accounting method	Source
Air	International Air Transport Association: Recommended Practice 1678 for Cargo CO_2 Emissions Measurement Methodology, 2022 update	(IATA, 2022a)
	International Air Transport Association: Recommended Practice 1726 Passenger CO_2 Calculation Methodology, 2022 update	(IATA, 2022b)
	United States Environmental Protection Agency: SmartWay Air Carriers: Tools and Resources, 2024 update	(US EPA, 2024a)
Cable cars	ISO 14083:2023	(ISO, 2023)
Hubs	Guide for Greenhouse Gas Emissions Accounting at Logistics Hubs v.2	(Dobers et al., 2023)
	EU Ports European Economic Interest Group: Guidance for Greenhouse Gas Emission Footprinting for Container Terminals	(EEEG, 2017)
	EU Ports European Economic Interest Group: Guidance for Greenhouse Gas Emission Footprinting for Dry Bulk Terminals	(EEEG, 2023)
Inland waterways	United States Environmental Protection Agency: SmartWay Barge Carrier: Tools and Resources, 2024 update	(US EPA, 2023)
	GHG Emissions Factors for Inland Waterways Transport	(SFC and STC-NESTRA, 2018)
	International Maritime Organization: Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI) (2009)	(IMO, 2009)
Pipelines	ISO 14083:2023	(ISO, 2023)
Rail	EcoTransIT: Methodology and Data Update 2024	(EcoTransIT, 2024)
	United States Environmental Protection Agency: SmartWay Rail Carrier Tools and Resources (2024)	(US EPA, 2024b)
Road	Handbook of Emission Factors - HBEFA 4.2	(HBEFA, 2022)
	United States Environmental Protection Agency: SmartWay Truck Carrier Partner Resources: Technical Documentation	(US EPA, 2024c)
Sea	Clean Cargo Working Group Carbon Emissions Accounting Methodology	(CCWG, 2015)
	International Maritime Organization: Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI) 2009	(IMO, 2009)

Source: adaptation from (SFC, 2025).

5.2.3. The ISO 14083 methodology

This section is based on the methodology set out in the ISO 14083 standard. Its purpose is to provide a summary of the relevant information and the calculation methodology. It is therefore not intended to be exhaustive. Further detailed information can be found in the full version of the ISO 14083 standard.

The ISO 14083 standard "Greenhouse gases - Quantification and reporting of greenhouse gas emissions arising from transport chain operations" was released in March 2023 by the International Standard Organization (ISO). This standard provides, for the first time, requirements and guidance for quantifying, verifying, monitoring, and reporting of GHG emissions along the entire transport chains for passengers[3] and freight. It covers all modes of transport and includes the operational GHG emissions from hubs.

Freight transport chains (TC) are composed by different transport chain elements (TCE) that, when considered together, constitute the movement of freight from an origin to a destination. Within the transport chain elements, freight is carried by a single vehicle (including all modes of transport) or transits through a single hub.

Figure 5.3 provides an illustrative example of a freight transport chain from the point where freight leaves its last point of production or transformation (point A) to the point where freight reaches its first non-transport related operation (point B). This transport chain consists of five transport chain elements (TCEs), the GHG emissions of which are calculated separately. The first and last TCEs (TCE 1, TCE 5) represent road services (C) covering pre- and on carriage; TCE 2 to TCE 4 represent a rail freight service (D) composed of road/rail terminal operations (TCE 2, TCE 4) and main carriage by rail transport (TCE 3). The approach used in the ISO 14083 is aligned with the United Nations Framework Convention on Climate Change (UNFCCC), the GHG Protocol, and the GLEC Framework.

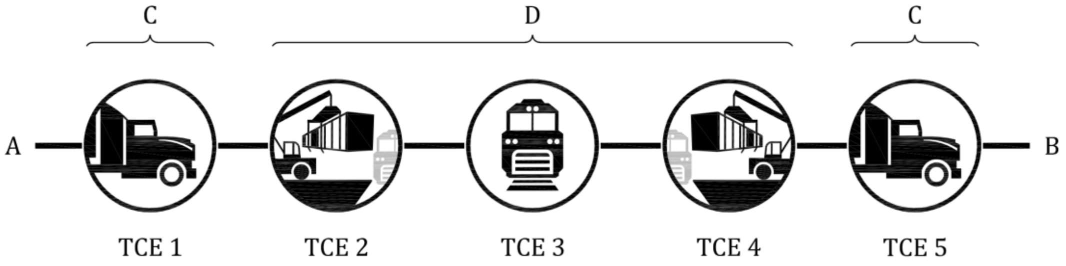


Figure 5.3: Illustrative example of a multi-element freight transport chain.
Source: (ISO, 2023).

It is also complementary to several existing standards. It is aligned with the ISO 14064 series and ISO 14067. It contributes to the carbon footprint of products (see ISO 14067) and

---

[3] Note that, from now on, in this document only freight transport chains will be considered. Further information on passenger transport chains can be found in the ISO 14083 standard.

the life cycle assessment in accordance with the ISO 14040 family of standards and ISO 14044. Figure 5.4 shows the relationship of this document to other International Standards, using the example of a freight transport chain.

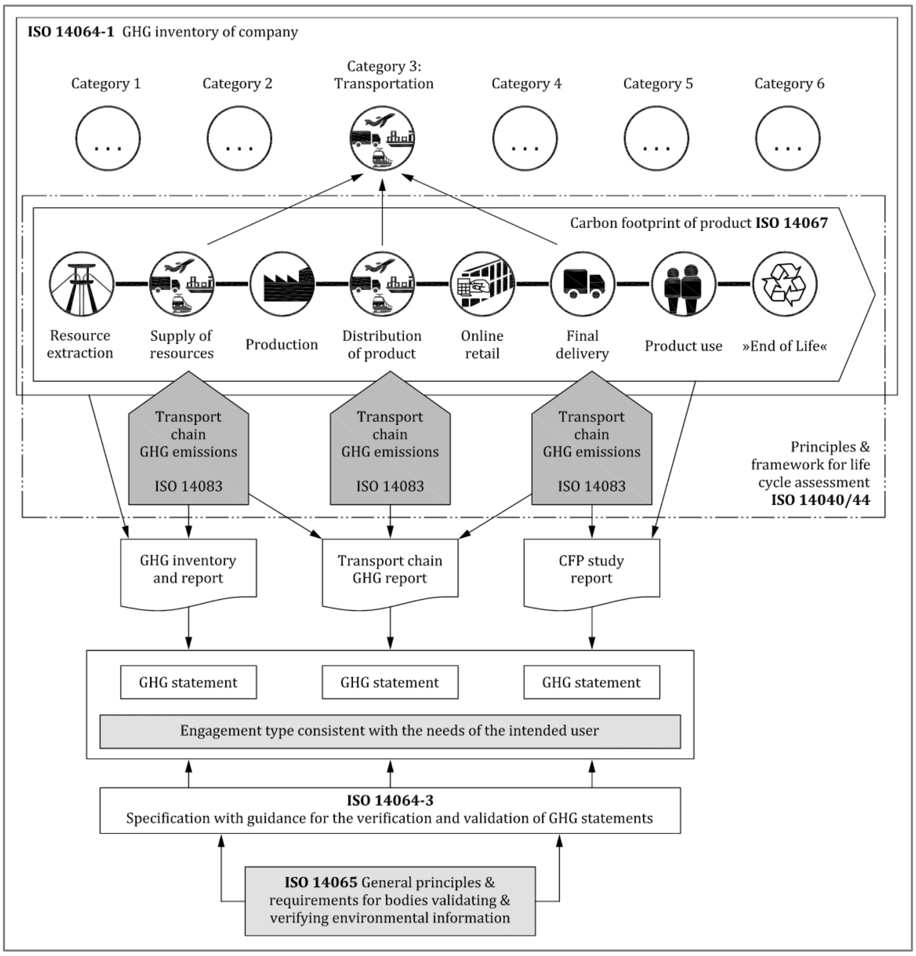


Figure 5.4: Relationship between the ISO 14040 family of standards and the ISO 14060 family of standards, using the example of a freight transport chain. Source: (ISO, 2023).

5.2.3.1. Terms and Definitions

This paragraph will introduce the main terms and definitions related to the ISO 14083 methodology used in the document. All definitions are derived from (ISO, 2023).

- **Allocation**: partitioning GHG activity or GHG emissions related to transport operations and hub operations with multiple functionalities, between groups of entities (freight) carried or transferred that benefit from the same functionality. Allocation may be implemented when multiple functionalities are fulfilled by the same vehicle or hub, but the carried freight does not benefit equally from it.
- **Consignment**: separately identifiable amount of freight transported from one consignor to one consignee via one or more modes of transport.

- **GHG emission factors**: coefficient relating GHG activity data with the GHG emission.
- **GHG emission intensity**: coefficient relating specific GHG activity data with the GHG emission. It can be expressed as:
  - mass of CO_2e per tonne-kilometre (or equivalent units) for freight transportation
  - mass of CO_2e per tonne (or equivalent units) for freight hub throughput
- **Hub**: location where freight is transferred from one vehicle or mode of transportation to another before, after or between different elements of a transport chain. Hubs include, but are not limited to, rail/road terminals, cross-docking sites, airport terminals, terminals at seaports and distribution centres.
- **Hub activity**: quantity of freight (outbound), including the mass of the initial packaging, and excluding any additional transport packaging, pallets or containers used for the transport operations. In specific circumstances (post/parcels or containerized transport), alternative units for the quantity of freight may be used.
- **Hub operations category (HOC)**: group of hub operations that share similar characteristics, in a defined time period (up to one year). Some factors to take into consideration are: number and type of hub operations (handling, (un-)loading, (de-)boarding, transport on-site), nature and consistency of the hub operations, inbound/outbound transport mode and intermodal change, nature of handled freight. A hub may perform different hub operations that form part of different HOCs.
- **Shipment**: a set of one or more freight items (available to be) transported together from the original shipper to the ultimate consignee.
- **Throughput**: quantity of freight handled, sorted, cross-docked or transferred within and between modes at a hub.
- **Transport activity**: quantity of freight multiplied by the transport (activity) distance. The quantity of freight shall be the actual freight mass, expressed in metric tons (also referred as tonne or t), including the mass of the initial packaging, and excluding any additional transport packaging, pallets or containers used for the transport operations. In specific circumstances (post/parcels or containerized transport) alternatives to the standard unit can be used.
- **Transport chain (TC)**: sequence of elements related to freight that, when taken together, constitutes its movement from an origin to a destination. Where there are two or more elements, in many cases, one of them implies that the freight uses a hub.
- **Transport chain element (TCE)**: section of a transport chain within which the freight is carried by a single vehicle or transits through a single hub. Each TCE shall

be related to a corresponding transport operation or hub operation. Figure 5.5 illustrates a multi-element freight transport chain. Once the last point of production or transformation is left, the freight (E: shipment; F: consignment) is transported from point A, where the consignor entrusts the goods to point B, when the freight reaches its intended destination. Point B is also defined as the first point at which no operations related to the transportation of the goods take place. In this example, the intermodal transport is carried out by two road transport elements (C) and a maritime shipping service (D). Land/sea terminal operations are also included.

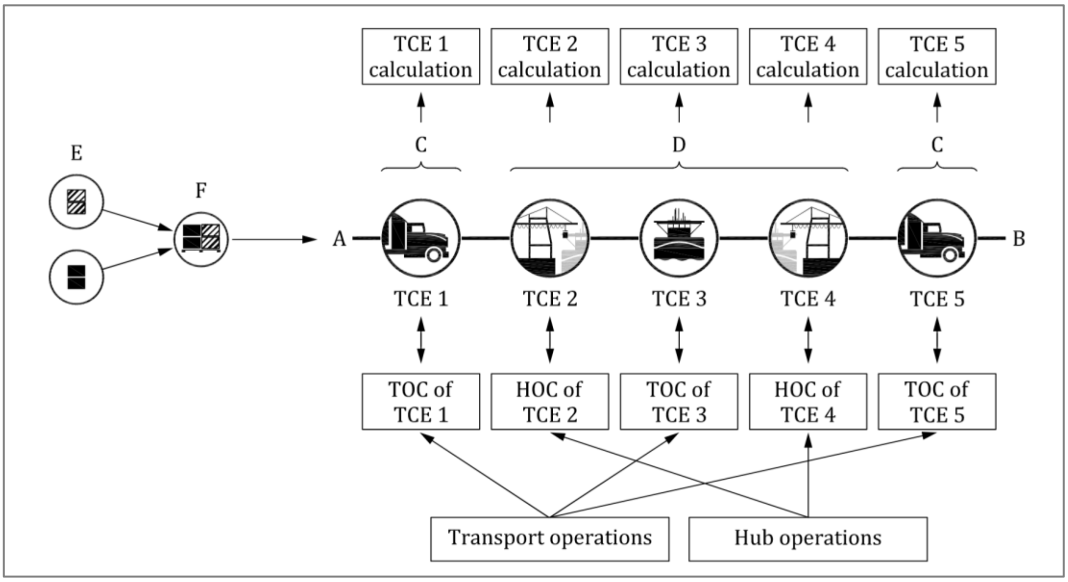


Figure 5.5: Relationship between TCEs and TOCs/HOCs for a multi-element freight transport chain. Source: (ISO, 2023), pag.20.

- **Transport operations category (TOC)**: group of transport operations that share similar characteristics, in a defined time period (up to one year). Some factors to take into consideration are number and type of vehicles, nature of the vehicle operations, nature and maintenance conditions of the freight. A single TOC can include transport operations with vehicles using different energy carriers for propulsion. The TOC should consider entire round trips, including both loaded and empty trips. Furthermore, also the relocation of containers, roll cages or pallets must be included when assigning GHG emissions.

5.2.3.2. GHG emission intensity

The quantity of GHG emissions is one of the KPIs (Key Performance Index) used to assess the environmental sustainability, and in particular the carbon footprint, of the transport sector and its various transport modes. Therefore, it is useful for comparing or rating transport alternatives.

However, this parameter only provides an overall image of the situation. Indeed, it does not address the efficiency of the chosen transport mode or transport chain.

For these reasons, GHG emission intensity is the most commonly used KPI for comparing and rating the environmental impact of different transport modes. In the case of freight transportation, it quantifies the amount of GHG emissions generated during the transport of one tonne of freight (or equivalent units) over the distance of one kilometre (expressed in tonnes of CO_2 equivalent per tonne-kilometre, or tCO_2e/t-km). For freight hub operations, it is expressed as the mass of CO_2e per tonne (or equivalent units). Emission intensity can be calculated:

- As a global indicator of the transport chain (TC)
- For each transport phase (TCE)
- As an environmental indicator of the single shipments

5.2.3.3. The calculation steps

The calculation of GHG emissions from transport operations begins with the identification of the transport chain (TC). The total GHG emissions of a TC are calculated as the sum of the GHG emissions from all processes related to the individual transport chain elements (TCEs). To do so, the ISO 14083 standard recommends a bottom-up approach (see Figure 5.6).

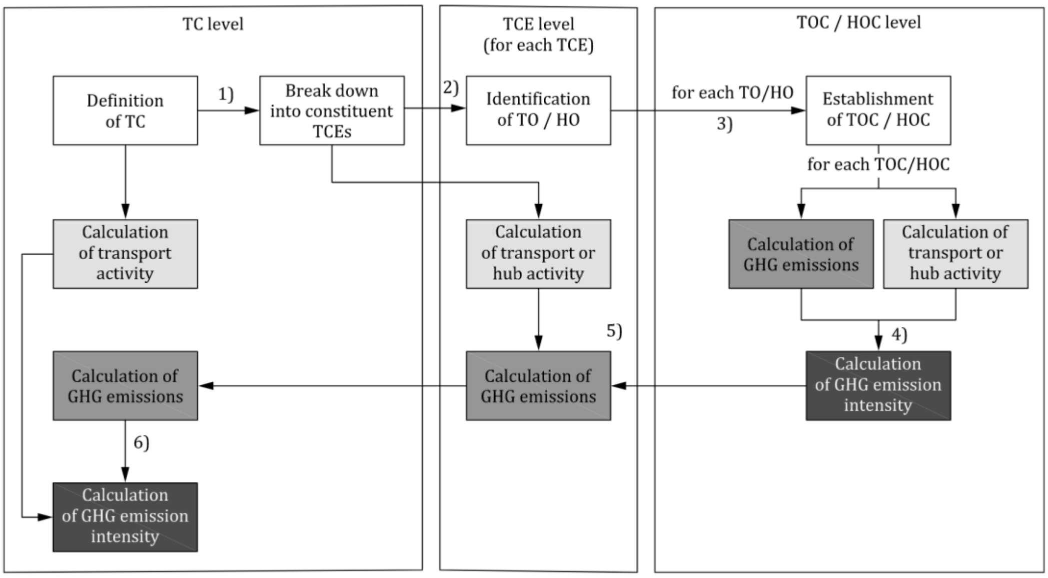


Figure 5.6: Bottom-up approach for calculating transport chains' emissions. Source: (ISO, 2023).

The following steps provide the general procedure for the calculation of the GHG emissions of a TC consisting of *n* TCEs. For each step, the main features will be analysed.

1) The transport chain is broken down into TCEs (TC level);
2) For each TCE, a transport or hub operation (TO/HO) is identified (TCE level);
3) For each TO/HO, a TOC/HOC is established (TOC/HOC level);
4) For each TOC/HOC, one or more GHG emission intensities are selected (TOC/HOC level);
5) The GHG emissions of each TCE are calculated (TCE level);
6) The GHG emissions and the GHG emission intensity of the TC are calculated (TC level).

5.2.3.4. STEP 1: The transport chain is broken down into TCEs (TC level)

Once the transport chain (TC) has been identified and defined, it is broken down into its constituent elements, the transport chain elements (TCEs). Each TCE shall be related to a corresponding transport operation or hub operation.

5.2.3.5. STEP 2: For each TCE, a TO/HO is identified (TCE level)

For each transport chain element (TCE), a related transport operation (TO) or hub operation (TO) is identified.

5.2.3.6. STEP 3: For each TO/HO, a TOC/HOC is established (TOC/HOC level)

For each transport operation (TO) or hub operation (HO), a transport operation category (TOC) or hub operation category (HOC) is established. The chosen characteristics of a TOC/HOC can be based on different factors (mode of transport, number and type of vehicles, type of journey, type of freight, etc.).

5.2.3.7. STEP 4: Selection of emission intensities (TOC/HOC level)

In this phase it is necessary to identify or calculate an emission intensity value for each transport operation category (TOC) or hub operation category (HOC). As stated before, the GHG emission intensity is a coefficient based on the ratio between the GHG emissions and the transport or hub activity data.

The transport activity for freight transportation can be expressed in tonne-kilometres (t-km), while the hub operation activity can be measured in tonnes of outbound freight (t). Consequently, both the mass of the shipment and the covered distance are required. In addition to mass, which should always be included in the analysis, other metrics, such as volume or item, can be used occasionally. This issue will be further detailed in the next sections. With regard to the transport activity distance, the ISO 14083 considers three possible alternatives: the shortest feasible distance (SFD), the great circle distance (GCD) and the actual distance corrected by a Distance Adjustment factor (DAF). The latter is used only when the transport operator does not have access to the SFD or the GCD.

Due to the complexity of retrieving GHG and transport activity data from all the different sources, the ISO 14083 allows different methods to be used to calculate GHG emission intensity based on different data categories (see Table 5.4). The categories are:

- primary data: direct measurement or calculation based on direct measurements (e.g. emission factor or activity data);
- secondary data, divided in two categories:
  - default data: from a published source or a database;
  - modelled data: modelled using primary data and/or relevant GHG emission parameters.

Table 5.4: GHG emission intensity data categories.

Approach	Primary data	Default data	Modelled Data
Definition	Real, shipment-specific data	Based on industry-average emission factors	Combines primary data with vehicle/fleet models to estimate emissions
Prons	Highly accurate	Easy to use	Balances accuracy and practicality
Cons	Difficult to obtain	Less accurate	Requires advanced modelling tools

Source: author's elaboration based on literature review.

Although GHG emission intensities may be collected from contracted operators that used primary o modelled data in their calculations, the use of primary data must always be prioritized, when possible. In the case of calculation of the GHG emission intensity with primary data, these steps must be followed for each TOC/HOC:

1. calculate the GHG emissions: identify and quantify the GHG activity data from all sources (fuel consumed, refrigerant leakage, etc.) and convert them to GHG emissions;
2. calculate the related transport of hub activity;
3. calculate the GHG emission intensity.

5.2.3.7.1. *Calculation of the GHG emissions*

The calculation of the GHG emissions is based on the conversion of GHG activity data into GHG emissions. This is done using emission factors. This can be done at a TOC level or at a HOC level, with or without allocation. In the following of this section, the general case, with no allocation involved, will be presented, for both TOC and HOC levels.

- *GHG emissions at a TOC level (no allocation)*

$$G_{TOC} = \sum\nolimits_{i} G_{j_V,TOC} \tag{5.1}$$

$$G_{j_V,TOC} = \sum\nolimits_{i} G_{j_V,TOC,A_i} \tag{5.2}$$

$$G_{j_V,TOC,A_i} = Q_{TOC,A_i} \cdot \varepsilon_{j_V,A_i} \tag{5.3}$$

where:

G_{TOC}	is the total GHG emissions for the TOC
$G_{j_V,TOC}$	is the VO/VEP GHG emissions of the TOC
G_{j_V,TOC,A_i}	is the VO/VEP GHG emissions, of the TOC, for each GHG activity type A_i
Q_{TOC,A_i}	is the quantity of GHG activity type A_i for the TOC
ε_{j_V,A_i}	is the VO/VEP GHG emission factor for GHG activity type A_i
j_V	is either the vehicle operation (VO) or the vehicle energy provision (VEP)
A_i	GHG activity type (e.g.: combustion of fuel, consumption of energy, refrigerant leakage, methane slip, etc.)

- *GHG emissions at a HOC level (no allocation)*

$$G_{HOC} = \sum\nolimits_{i} G_{j_H,HOC} \tag{5.4}$$

$$G_{j_H,HOC} = \sum\nolimits_{i} G_{j_H,HOC,A_i} \tag{5.5}$$

$$G_{j_H,HOC,A_i} = Q_{HOC,A_i} \cdot \varepsilon_{j_H,A_i} \tag{5.6}$$

where:

G_{HOC}	is the total GHG emissions for the HOC
$G_{j_H,HOC}$	is the HEO/HEEP GHG emissions of the HOC
G_{j_H,HOC,A_i}	is the HEO/HEEP GHG emissions, of the HOC, for each GHG activity type A_i
Q_{HOC,A_i}	is the quantity of GHG activity type A_i for the HOC
ε_{j_H,A_i}	is the HEO/HEEP GHG emission factor for GHG activity type A_i
j_H	is either the hub equipment operation (HEO) or the hub equipment energy provision (HEEP)
A_i	GHG activity type (e.g.: combustion of fuel, consumption of energy, refrigerant leakage, methane slip, etc.)

5.2.3.7.2. *Calculation of the related transport activity*

The transport activity differs between TOC and HOC. In the first case, it is calculated as the product of the transport activity distance and the mass of the freight. In the latter case, it is represented by the mass of freight passing through the hub.

- *Transport activity at a TOC level (general case)*

For each TOC, the freight transport activity (T_{TOC}) must be evaluated. To do so, the transport activity distance and the quantity of freight of each consignment must be known. The transport activity distance needs to be either the shortest feasible distance (SFD) or the great circle distance (GCD), while the quantity of freight is expressed by its mass.

$$T_{TOC} = \sum_{1}^{c} M_i \cdot s_{ci} \qquad (5.7)$$

where:

T_{TOC}	is the freight transport activity of the TOC
M_i	is the mass (or appropriate unit) of an individual consignment i in the TOC
s_{ci}	is the transport activity distance of an individual consignment i in the TOC
c	is the number of consignments in the TOC

- *Transport activity at a HOC level (general case)*

The freight hub activity (T_{HOC}) corresponds to the freight throughput (outbound), measured with an appropriate unit (in general mass, but not always).

5.2.3.7.3. *Calculation of GHG emission intensity*

- *GHG emission intensity at a TOC level (general case)*

$$g_{j_V,TOC} = \frac{G_{j_V,TOC}}{T_{TOC}} \qquad (5.8)$$

where:

$g_{j_V,TOC}$	is the GHG emission intensity for activity type j_V for the TOC
$G_{j_V,TOC}$	is the total GHG emission for activity type j_V for the TOC
T_{TOC}	is the transport activity of the TOC
j_V	is either the vehicle operation (VO) or the vehicle energy provision (VEP)

- *GHG emission intensity at a HOC level (general case)*

$$g_{j_H,HOC} = \frac{G_{j_H,HOC}}{T_{HOC}} \tag{5.9}$$

where:

$g_{j_H,HOC}$	is the GHG emission intensity for activity type j_H for the HOC
$G_{j_H,HOC}$	is the total GHG emission for activity type j_H for the HOC
T_{HOC}	is the transport activity of the HOC
j_H	is either the hub equipment operation (HEO) or the hub equipment energy provision (HEEP)

5.2.3.8. STEP 5: The GHG emissions of each TCE are calculated (TCE level)

In this step, the GHG emissions of each TCE are calculated, both for a transport TCE and a hub TCE.

- *GHG emissions for a transport TCE (general case)*

GHG emissions of a transport TCE are evaluated by multiplying the corresponding GHG emission intensity ($g_{j_V,TOC}$), calculated in the previous step, by the transport activity. The transport activity is evaluated similarly to the one calculated for a TOC (see 5.7). GHG emissions of a transport TCE shall be calculated using equations 5.10 and 5.11.

$$G_{j_V,TCE} = g_{j_V,TOC} \cdot T_{TCE} \cdot \delta \tag{5.10}$$

where:

$G_{j_V,TCE}$	is the total GHG emission for activity type j_V for the TCE
$g_{j_V,TOC}$	is the GHG emission intensity for activity type j_V for the TOC
T_{TCE}	is the transport activity for the TCE
j_V	is either the vehicle operation (VO) or the vehicle energy provision (VEP)
δ	is the DAF between the transport distance type used for the transport activity of the TCE and the transport distance type used for the GHG emission intensity of the TOC

$$G_{TCE} = G_{VO,TCE} + G_{VEP,TCE} \tag{5.11}$$

where:

G_{TCE}	is the GHG emission of the TCE
$G_{VO,TCE}$	is the vehicle operation GHG emissions of the TCE
$G_{VEP,TCE}$	is the vehicle energy provision GHG emissions of the TCE

- *GHG emissions for a hub TCE (general case)*

GHG emissions of a hub TCE are evaluated by multiplying the corresponding GHG emission intensity ($g_{j_H,HOC}$), calculated in the previous step, by the transport activity. The transport activity is evaluated similarly to the one calculated for a HOC (see 5.8). GHG emissions of a hub TCE shall be calculated using equations 5.12 and 5.13.

$$G_{j_H,TCE} = g_{j_H,HOC} \cdot H_{TCE} \tag{5.12}$$

where:

$G_{j_H,TCE}$	is the total GHG emission for activity type j_H for the TCE
$g_{j_H,TCE}$	is the GHG emission intensity for activity type j_H for the HOC
H_{TCE}	is the hub activity for the TCE
j_H	is either the hub equipment operation (HEO) or the hub equipment energy provision (HEEP)

$$G_{TCE} = G_{HEO,TCE} + G_{HEEP,TCE} \tag{5.13}$$

where:

G_{TCE}	is the GHG emission of the TCE
$G_{HEO,TCE}$	is the vehicle operation GHG emissions of the TCE
$G_{HEEP,TCE}$	is the vehicle energy provision GHG emissions of the TCE

5.2.3.9. STEP 6: GHG emissions and GHG emission intensity of the TC (TC level)

In the last step, the GHG emissions and the GHG emission intensity of each transport chain element must be determined. First, the total transport chain GHG emissions are evaluated by adding up the GHG emissions of all the transport chain elements (obtained in the previous step). Then, the transport chain GHG emission intensity is calculated by multiplying its GHG emissions by the sum of the transport activity of all the transport chain elements of the transport chain.

5.2.3.9.1. Calculation of the GHG emissions

The GHG emissions of a TC are calculated using equations 5.14 - 5.19.

$$G_{VO,TC} = \sum\nolimits_i G_{VO,TCE_i} \tag{5.14}$$

$$G_{HEO,TC} = \sum\nolimits_i G_{HEO,TCE_i} \tag{5.15}$$

$$G_{VEP,TC} = \sum\nolimits_i G_{VEP,TCE_i} \tag{5.16}$$

$$G_{HEEP,TC} = \sum\nolimits_i G_{HEEP,TCE_i} \tag{5.17}$$

$$G_{T,TC} = G_{VO,TC} + G_{HEO,TC} + G_{VEP,TC} + G_{HEEP,TC} \tag{5.18}$$

$$G_{O,TC} = G_{VO,TC} + G_{HEO,TC} \tag{5.19}$$

where:

$G_{VO,TC}$	is the vehicle operation GHG emissions of the transport chain
$G_{VO,TCEi}$	is the vehicle operation GHG emissions allocated to each relevant TCE_i
$G_{HEO,TC}$	is the hub equipment operation GHG emissions of the transport chain
$G_{HEO,TCEi}$	is the hub equipment operation GHG emissions allocated to each relevant TCE_i
$G_{VEP,TC}$	is the vehicle energy provision GHG emissions of the transport chain
$G_{VEP,TCEi}$	is the vehicle energy provision GHG emissions allocated to each TCE_i
$G_{HEEP,TC}$	is the hub equipment energy provision GHG emissions of the transport chain
$G_{HEEP,TCE}$	is the hub equipment energy provision GHG emissions allocated to each TCE_i
$G_{T,TC}$	is the total (operation and provision) GHG emissions of the transport chain
$G_{VO,TC}$	is the operation GHG emissions of the transport chain

The above results may be obtained from a mix of GHG activity data of different categories (primary data, modelled data and default values).

5.2.3.9.2. Calculation of transport activity

The transport activity of a transport chain (T_{TC}) shall be calculated by adding the transport activity of all transport TCEs that compose this transport chain. The unit of transport activity shall the same for all TCEs within the transport chain. For freight transport, this shall be the tonne kilometre (unless one of the specific alternatives is used, such as item, TEU, etc.). The hub activities are not included in this calculation.

5.2.3.9.3. Calculation of the GHG emission intensities

The GHG emissions for the transport chain can be converted into GHG emission intensities (g_T or g_O), by dividing the GHG emissions by the transport activity. The hub activities are not included in this calculation, whereas the GHG emissions cover all TCEs, including hubs. GHG emission intensity is a KPI that is frequently employed to assess the environmental efficiency of a transport chain or the performance of a logistics operator.

5.3. Case study

The chosen case study considers the transport of a quantity of freight (consignment), transported with a semi-trailer (freight unit), from the initial customer O (point of origin) to the final customer D (point of destination). The service includes a maritime freight transport chain, operated combining road and maritime transport. For this numerical application, a service operated by an intermodal company was selected. The chosen company provides its customers with integrated logistics solutions, using its network of warehouses, terminals and road transport services for the collection and delivery of goods. It also offers regular short sea shipping services, operated by Ro-Ro ships. By managing the entire transport chain, the company guarantees an end-to-end service.

Figure 5.7 provides a comprehensive schematic overview of the maritime transport chain considered for this application. As the company is the only operator of the selected maritime route, details of the journey's origins or destinations cannot be provided, for commercial competition reasons. However, it can be stated that the entire journey takes place within the Italian territory, including the ports of departure and arrival, as well as the initial and final destinations. The maritime transport chain is divided into five transport chain elements. TCE1 and TCE5 represent the road transport phases performed with a semi-trailer, TCE3 the Ro-Ro maritime service, while TCE2 and TCE4 include the hub operations that take place in the port terminals.

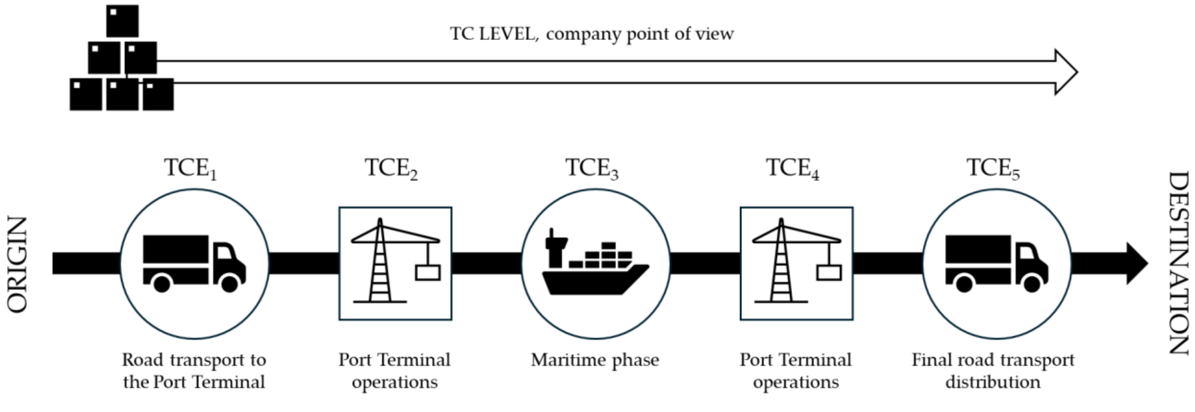


Figure 5.7: Maritime freight door-to-door transport chain, TC level.
Source: author's elaboration.

5.3.1. Input data

Based on the GLEC guidelines, a first preparatory planning phase was carried out, including the selection and collection of primary data (strongly recommend) from the company. Primary data is defined as "the quantified value of a process or activity from direct measurement or calculation based on direct measurement" (ISO, 2023; SFC, 2025). If this is not possible, secondary data - either modelled or default data - can be used. Emission intensities based on default data can be used to compare the environmental impacts of different transport modes when choosing the best intermodal solution to transport goods from an origin to a destination. For the selected transport chain, the company provided the following data:

- fuel consumption
- distance between ports
- distance from the initial origin to the port of departure
- distance from the port of departure to the port of destination
- and volumes of goods transported.

The specifications of the input data are shown in Table 5.5, while Source: input data collected from the company.

Table 5.6 presents the emission factors used in the calculations (based on data provided by the GLEC Framework).

Table 5.5: Input data collected from the company.

Data	TOC-HOC	Unit	Value
Actual distance by road (full) TCE_1	TOC-road	[km]	146
Actual distance by road (full) TCE_5	TOC-road	[km]	248
Empty running (% of total)	TOC-road	[%]	23
Average fuel consumption	TOC-road	[km/l]	2.86
Quantity of fuel (diesel)	TOC-road	[kg]	148.6
Mass of the consignment (cargo)	TOC-road	[t]	21
Gross mass of the semi-trailer	TOC-road	[t]	35
Annual fuel (diesel) consumption	HOC-port	[l]	289,386
Annual throughput	HOC-port	[t]	2,922,954
Actual distance by sea	TOC-sea	[km]	542
Quantity of HFO (VLSFO)	TOC-sea	[kg]	28,943
Quantity of MDO (ULSFO)	TOC-sea	[kg]	2,710
Mass of the consignment (overall laden)	TOC-sea	[t]	4,305
Mass of the consignment (cargo)	TOC-sea	[t]	2,583
Mass of the shipment - overall laden	TOC-sea	[t]	35
Mass of the shipment (cargo)	TOC-sea	[t]	21
Distance Adjustment Factor (DAF)	All	[-]	1.05

Source: input data collected from the company.

Table 5.6: Emission factors related to the type of fuels considered.

Type of fuel	(WtT) [$kgCO_2e/kg$]	(TtW) [$kgCO_2e/kg$]	(WtW) [$kgCO_2e/kg$]
Diesel	0.97	3.22	4.19
HFO (VLSFO)	0.68	3.16	3.84
MDO (ULSFO)	0.75	3.26	4.01

Source: (SFC, 2025).

5.4. Application

In this Section, the ISO 14083-based methodology (see Section 5.2) is applied to the case study. The following steps summarize the calculation process used in the application:

1) The transport chain is broken down into TCEs (TC level);
2) For each TCE, a transport or hub operation (TO/HO) is identified (TCE level);
3) For each TO/HO, a TOC/HOC is established (TOC/HOC level);
4) For each TOC/HOC, one or more GHG emission intensities are selected (TOC/HOC level);
5) The GHG emissions of each TCE are calculated (TCE level);
6) The GHG emissions and the GHG emission intensity of the TC are calculated (TC level).

At the transport chain level, the quantity of GHG emissions and the GHG emission intensity will refer to the quantity of freight (consignment) transported from the origin to the destination.

5.4.1. Steps 1-3: Identification of TCEs, TO/HO and TOC/HOC

The first three steps refer to the identification of the Transport Chain Element, the Transport/Hub Operation and Transport/Hub Operation Category. This section will illustrate these three steps. Following the first Step of the methodology, the analysed transport chain is split up into five TCEs, one for each transport phase or hub operation. The five TCEs are:

- **Transport chain element 1 (TCE_1):** During the first transport phase the goods are collected from a single customer (origin) and transported to the port terminal by road transport. This quantity of freight is referred to as the consignment. The vehicle selected for transportation is an articulated truck, loaded as a full truckload (FTL).
- **Transport chain element 2 (TCE_2):** Port operations take place in the port terminal. The freight is transferred from the port yard to the Ro-Ro ship. In this case, only the unaccompanied semi-trailer is loaded onto the Ro-Ro ship.
- **Transport chain element 3 (TCE_3):** The second transport phase consists of the maritime transport between the two selected ports. The Ro-Ro ship, loaded only with unaccompanied semi-trailers, departs from the port of origin (A) and arrives at the port of destination (B).
- **Transport chain element 4 (TCE_4):** Once the ship arrives at the port terminal (B), the semi-trailer is unloaded and transferred to the port yard, from where it will continue its journey.
- **Transport chain element 5 (TCE_5):** The final phase involves the last-mile direct delivery, by road transport, to the end destination (final client). Therefore, the semi-trailer is coupled with a road tractor to form an articulated truck (FTL).

In the second Step of the methodology, a transport or hub operation (TO/HO) must be assigned to each of the five identified TCEs. A TO consists of operations of a vehicle in order to transport freight, while a HO consists of operations in order to transfer freight through a hub. Therefore, TCE$_1$, TCE$_3$, and TCE$_5$ are referred to a transport operation while TCE$_2$ and TCE$_4$ to a hub operation.

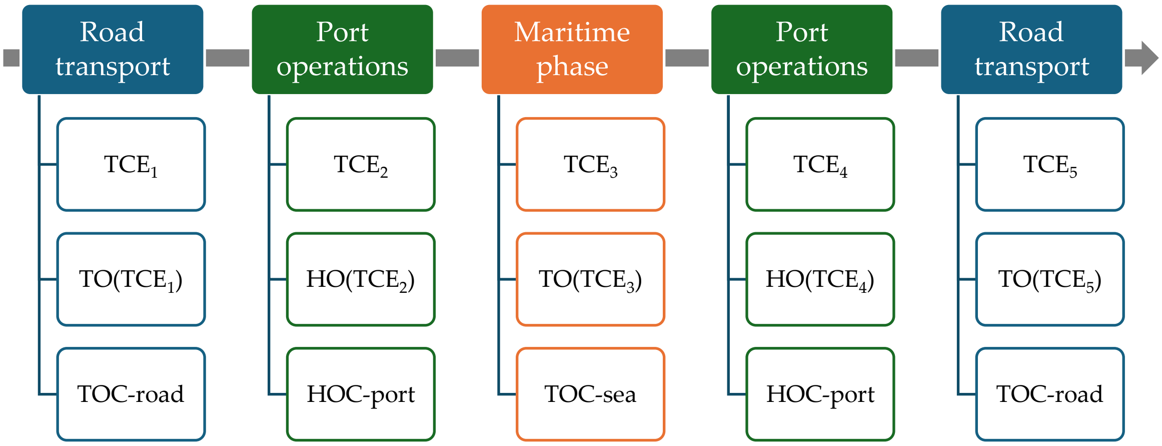


Figure 5.8: Graphic representation of the first 3 steps of the ISO 14083 standard methodology. Source: author's elaboration.

Following the third Step of the methodology, transport or hub operation categories (TOC/HOC) must be assigned to a TO(TCE$_i$) or a HO(TCE$_i$). A TOC/HOC consists of transport/ hub operations that share similar characteristics, over a period of time[4]. Due to the similar characteristics of the articulated truck in the transport phases, TO(TCE$_1$) and TO(TCE$_5$) share the same TOC (TOC-road). For an analogue reason, HO(TCE$_2$) and HO(TCE$_4$) share the same HOC (HOC-port). Finally, the TO(TCE$_3$) is characterized by the TOC-sea. The graphic representation of the first three steps of the methodology is shown in Figure 5.8.

5.4.2. Steps 4-6: Calculations

Once the transport chain categories and the hub operation categories are defined (Step 3), it is possible to calculate, for each TOC/HOC, the GHG emission intensity, then the GHG emissions for each TCE and finally the GHG emissions and the GHG emission intensity of the transport chain. To do so, Steps 4-5-6 will be followed.

Figure 5.9: Graphical representation of the paths 4-5-6 of the ISO 14083 standard methodology.

---

[4] NOTE: The ISO14083 standard and the GLEC Framework propose the establishment of GHG. emissions and relative intensity factors over a specified period, typically one calendar year. In this way annual variabilities (seasonal variability, demand fluctuations, interruptions, etc.) are included in the model (SFC, 2025). However, for the aim of this application, the time period of one year will not be considered. Instead, the analysis will be assessed at a transport chain level.

Source: author's elaboration. shows the graphical representation of the next steps of the methodology.

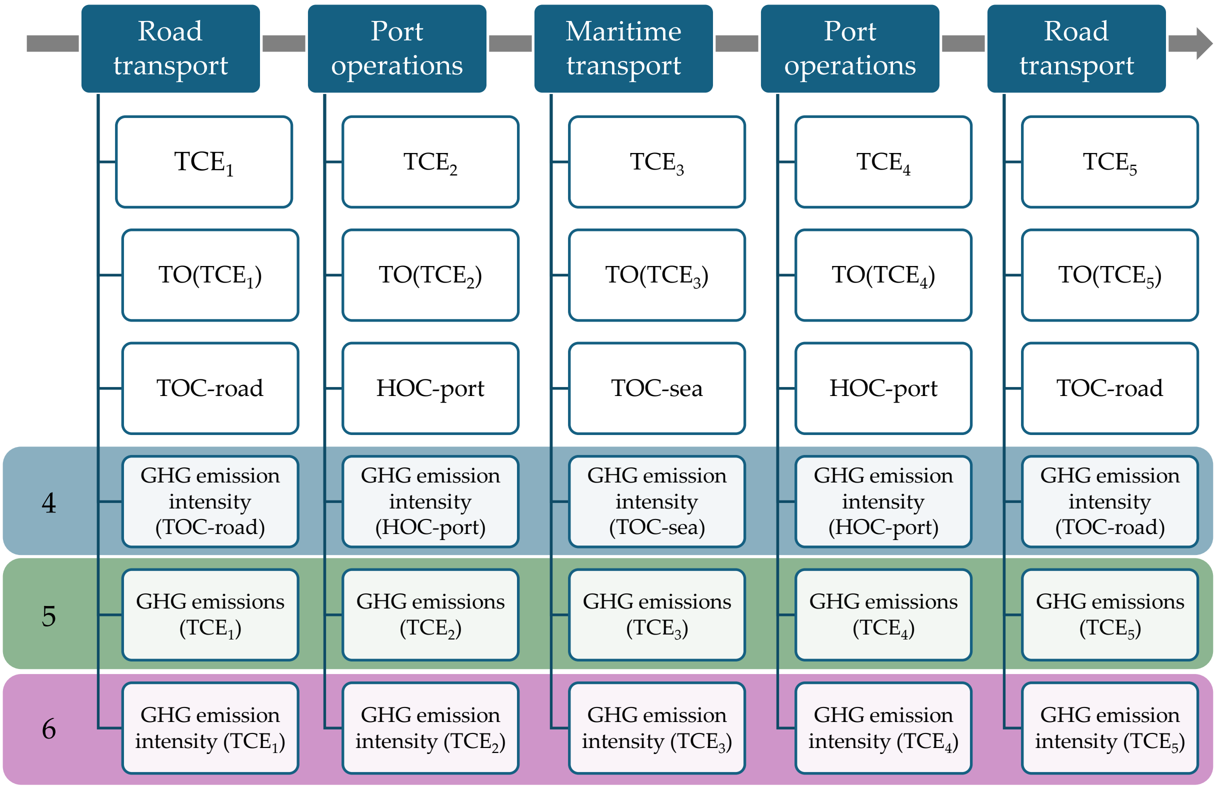


Figure 5.9: Graphical representation of the paths 4-5-6 of the ISO 14083 standard methodology. Source: author's elaboration.

5.4.2.1. Road transport: planning and calculation of emissions (TOC-road)

During the road transport (first and last leg), the same type of truck was used. Therefore, one transport operation category (TOC-road) can be defined for both legs.

When planning and calculating emissions from road transport, the ISO 14083 standard and the GLEC Framework take into account the SmartWay Road Carrier Tool, particularly useful in the event of a lack of specific data regarding transport means and activities. The data, provided by the company and referred to the road phase, include the actual distances travelled by the articulated truck (tractor & semi-trailer) while laden, the average fuel consumption including both laden and empty journeys, the gross mass of the semi-trailer, and the consignment mass. To allocate the emissions derived from empty running, the company provided a percentage of the average empty running. The quantity of fuel (diesel) was also derived from the company data. Table 5.7 shows the intermediate results of the calculations referred to the TOC-road.

GHG emissions are evaluated by multiplying the quantity of fuel by the relevant emission factor. Transport activity is derived from the consignment's mass and the corrected distance. These figures are then used to calculate the GHG emission intensity (step 4). At this point (step 5) the emissions are then allocated to TCE n.1 and n.5.

Table 5.7: Intermediate results of the calculations for the TOC-road.

Steps	Unit	VEP (WtT)	VO (TtW)	Total (WtW)
STEP 4 (TOC level)				
1. GHG emissions	[$kgCO_2e$]	144.2	478.7	622.8
2. transport activity	[t-km]	7,880	7,880	7,880
3. GHG emissions intensity	[$kgCO_2e$/t-km]	0.018	0.061	0.079
STEP 5 (TCE level)				
TCE_1	[$kgCO_2e$]	53.4	177.4	230.8
TCE_5	[$kgCO_2e$]	90.8	301.3	392.0

5.4.2.2. Port operations: planning and calculation of emissions (HOC-port)

The company provided the data relating to port operations, as they also managed the operations taking place in the port terminals under consideration. The only available data was the annual aggregated fuel consumption of the vehicle fleet covering both port terminals. Due to the lack of detailed data, the IML methodology, the Annex H of the ISO 14083 standard, and the GLEC guidance were used to allocate the amount of GHG emissions to the correct activity data, following the principles of extrapolation and proportionality. Therefore, given that the two port terminals are mainly operated by diesel-powered vehicles, this assumption was deemed acceptable.

As the main activity of the port terminals is freight transshipment, the assessment was carried out based on the total annual fuel consumption of all vehicles operating in both terminals and the cumulative annual tonnes throughput leaving the centre, i.e. outbound freight. Table 5.8 shows the intermediate results of the calculations referred to the HOC-port.

Table 5.8: Intermediate results of the calculations for the HOC-port.

HOC-port	Unit	HEEP (WtT)	HO (TtW)	Total (WtW)
STEP 4 (TOC level) – ANNUAL DATA RELATED TO THE TWO TERMINALS				
1. GHG emissions	[$kgCO_2e$]	232,985	773,413	1,006,398
2. hub activity	[t]	2,922,954	2,922,954	2,922,954
3. GHG emissions intensity	[$kgCO_2e/t$]	0.08	0.26	0.34
STEP 5 (TCE level) – EMISSIONS ALLOCATED TO THE SINGLE CONSIGNMENT				
HOC_2	[$kgCO_2e$]	1.7	5.6	7.2
HOC_4	[$kgCO_2e$]	1.7	5.6	7.2

5.4.2.3. Maritime transport: planning and calculation of emissions (TOC-sea)

A Transport Operation Category was defined for the maritime transport phase, which consists of a single leg. The service operated by the company is a regular short sea shipping route performed by a Ro-Ro vessel. The vessel uses heavy fuel oil (HFO), combined with scrubbers, as the main fuel during navigation and marine diesel oil (MDO) during port approach, manoeuvring, and berthing. According to the ISO 14083-based methodology, GHG emissions generated during mooring phase must also be included in the TO (they are not accounted within hub-related emissions). Fuel consumption data provided from the company refer to the total amount of HFO and MDO consumed during the maritime leg, including a proportionally allocated share corresponding to the fuel used during berthing operations. Additional required inputs include the actual distance between the two ports (then corrected by applying a DAF), and the total mass of the consignment (both gross load and cargo).

With regard to the determination of the transport activity used to calculate the GHG emission intensity of Ro-Ro maritime transport, it is important to keep in mind the distinction between consignment and shipment, as defined by ISO 14083. Indeed, while a consignment includes the quantity of goods transported throughout the logistics chain by the carrier, a shipment refers to the amount of freight dispatched by the shipper. For example, during the road transport phases, the actual cargo is considered simultaneously a shipment (from the shipper's perspective) and a consignment (from the carrier's perspective).

However, this correspondence does not apply to Ro-Ro maritime transport. Indeed, as specified by the GLEC Framework, in this case the consignment represents the total freight transported by the maritime carrier, while the shipment identifies the specific quantity of cargo considered. Therefore, when referring to Ro-Ro maritime transport, the allocation unit must correspond to the gross load of the freight (e.g., the combined mass of the semitrailer – or the truck – and its cargo), since this constitutes the actual load transported by the vessel. Emissions must subsequently be reallocated to the goods within the truck by the cargo owner, using an emission intensity that considers only the quantity of cargo inside the semitrailer. This feature introduces a degree of complexity when reporting GHG emission intensities, particularly when the carrier and the shipper (or the logistic service provider) are distinct entities, as this would produce different GHG emission intensities for the same transport chain element.

At the moment, no specific guidelines are currently available that use alternative units to gross tonnes for measuring the quantity of maritime Ro-Ro freight. Therefore, in this case study, mass is used to represent the transported quantity of goods. A further discussion and more considerations will be provided in the discussion section of this Chapter. Table 5.9 presents the intermediate results of the computational steps, for both the consignment (total amount) and the shipment (allocated quota).

Table 5.9: Intermediate results of the calculations for the TOC-sea.

TOC-sea	Unit	VEP (WtT)	VO (TtW)	Total (WtW)
STEP 4 (TOC level) – DATA REFERED TO THE CARRIER'S PERSPECTIVE (consignment)				
1. GHG emissions	[$kgCO_2e$]	21,714	100,294	122,007
2. transport activity (gross load)	[t-km]	n.d.	n.d.	2,222,200
3. GHG emissions intensity	[$kgCO_2e$/t-km]	0.010	0.045	0.055
STEP 5 (TCE level)				
TCE_3 (consignment-total)	[$kgCO_2e$]	21,714	100,294	122,007
TCE_3 (shipment-allocated)	[$kgCO_2e$]	177	815	992

Table 5.10 provides detailed data, distinguished by the point of view. It is worth noting that, in the case of containerised transport, where the TEU is used as the basic unit of load, the emission intensity expressed as CO_2 equivalent per tonne-kilometre would yield identical results. This simplifies calculations and, more importantly, reduces the complexity and risk of errors when exchanging data between carriers and shippers.

Table 5.10: TOC-sea. Emission KPIs based on consignment & shipment and gross load & cargo.

Point of view (type of load)	GHG emissions [WtW-kgCO$_2$e]	Transport activity [t-km]	GHG emission intensity [WtW-kgCO$_2$e/t-km]
consignment (gross load)	122,007	2,222,200	0.055
consignment (net mass cargo)	122,007	1,333,320	0.092
shipment (gross load)	992	18,067	0.055
shipment (net mass cargo)	992	10,840	0.092

5.4.2.4. TC level

Finally, step 6 of the methodology involves calculating the global KPIs for the transport chain. The total Well-to-Wheel GHG emissions are evaluated as the sum of all the emissions form the different TCEs. They consist of the Well-to-Tank emissions and the Tank-to-Wheel (and/or Wake) emissions, expressed in kgCO$_2$e. In this case study, the latter accounts for 80% of the total emissions. Transport activity is calculated at an aggregated level, based on the sum of the transport activities of the TCEs related to a TOC, and expressed in tonne-kilometre. Last, the GHG emission intensity is obtained by dividing the emissions by the transport activity. These values represent the total emission intensity of the transport chain, including the emissions released during operations in the hubs. Table 5.11 summarizes the results of the calculations for the transport chain for the single freight unit (only the mass of the cargo is considered).

Table 5.11: Step 6, summary of the results for the transport chain (cargo mass-single freight unit).

STEP 6 (TC level)	Unit	Well-to-Tank	Tank-to-Wheel	Well-to-Wheel
1. GHG emissions	[kgCO$_2$e]	324	1,305	1,629
2. transport activity*	[t-km]	18,720	18,720	18,720
3. GHG emissions intensity	[kgCO$_2$e/t-km]	0.017	0.070	0.087

NOTE: *Only the net mass of the cargo (single freight unit) is considered.

5.5. Numerical results

The numerical results of the application, presented in Table 5.12, show that the total GHG emissions of the analysed transport chain are approximately 1,629 WtW-kgCO$_2$e. Of this total, 992 WtW-kgCO$_2$e arise from the maritime phase (61%), 623 WtW-kgCO$_2$e from the road phases (38%) and the remaining 14 WtW-kgCO$_2$e from the port terminal operations (1%). Looking at the GHG emission intensity of the hole transport chain, it equals 0.087 WtW-kgCO$_2$e/t-km. For the road phase the value is 0.079 WtW-kgCO$_2$e/t-km while for the maritime phase it's 0.092 WtW-kgCO$_2$e/t-km. The hub GHG emission intensity is equal to 0.344 WtW-kgCO$_2$e/t.

Table 5.12: GHG emissions, transport activity, and emission intensities (cargo-single freight unit).

	GHG emissions [WtW-kgCO$_2$e]	Transport (hub) activity [t-km] or [(t)]	GHG emission intensity [WtW-kgCO$_2$e/t-km] or [(…/t)]
TCE$_1$	231	2,920	0.079
TCE$_2$	7.23	(21)	(0.344)
TCE$_3$	992	10,840	0.092
TCE$_4$	7.23	(21)	(0.344)
TCE$_5$	392	4,960	0.079
TOTAL TC	1,629	18,720	0.087

The measures of the GHG emission intensity, as well as the transport/hub activity, refer to the quantity of cargo transported, measured in tonnes. In the next paragraph, a discussion of the possible alternative metrics for the maritime Ro-Ro segment will be performed.

5.6. Discussion

It is important to note that quantifying GHG emissions is not the ultimate goal in the decarbonization process, but rather the starting point for analysing the current situation, defining reduction strategies, and identifying the causes and possible alternative solutions. In the context of (maritime) freight transport, carbon emission reporting is essential for accurately determining the source of emissions and the *polluters*[5] (among the stakeholders involved in the transport chain) and allocating the correct quantity of GHG emissions to the transported freight (using the best unit). According to (Kellner and Schneiderbauer, 2019), the allocation principle should reflect the causal relationship between the transport process and GHG generation by allocating GHG emissions according to the "polluter-pays principle". The authors emphasise that, otherwise, there is a risk of ineffective measures being taken to reduce transport-related GHG emissions. Furthermore, the proposed

---

[5] In this case, the term *polluter* is used in its wider meaning, including also an entity that is responsible of emitting greenhouse gases.

allocation rule should align with a broad set of fairness criteria, as allocation principles perceived as arbitrary or unfair will reduce acceptance and compromise transport cooperation.

In maritime transport, total GHG emissions must be allocated to the transported cargo, and therefore, to the related transport activity. Compared with other modes of transport, the maritime sector is characterized by a significant heterogeneity across its different segments, characterized by the type of cargo handled (dry bulk, liquid bulk, container, Ro-Ro, Ro-Pax, etc.). As a result, different allocation units may be used for emission allocation. The ISO 14083 methodology allows the use of alternatives to mass-based units; for example, containerized transport is encouraged to use TEUs (tonnes should still be considered). Looking more in depth into the differences in perspective between the carrier and the shipper reveals that the amount of GHG emissions allocated to a consignment remains unchanged when the evaluation is done based on either gross load tonnage or cargo tonnage. The same applies at the shipment level, since emissions are proportional to the amount of freight in relation to the total. The value of transport activity varies depending on the quantity of freight considered. It is higher when calculations are based on the gross load (the carrier's perspective) and lower when only the cargo is considered (the shipper's perspective). Consequently, emission intensity, which is obtained by dividing total emissions by transport activity, is lower in the former case, regardless of whether the carrier's or shipper's viewpoint is adopted.

Table 5.13: Main information regarding the ship, the voyage and the cargo transported.

	Information	Unit	Value
Ship and voyage	Total GHG emissions, single voyage	[kgCO$_2$e]	122,007
	Distance (adjusted), single voyage	[km]	516
	Ship's full capacity (lane meters)	[m]	2,200
	Ship's actual load (lane meters)	[m]	1,845
	Ship's actual load (n. of semitrailers)	[-]	123
Cargo	Length of a semitrailer	[m]	13.6
	Occupancy space of a semitrailer	[m]	15
	Mass of the full semitrailer (gross - overall)	[t]	35
	Mass of the full semitrailer (net - cargo)	[t]	21
	Mass of the empty semitrailer (tare)	[t]	14

This section will discuss an alternative GHG emission intensity metric for pure Ro-Ro maritime transport. The starting point will be the case study presented in the previous paragraphs. Different hypotheses related to the characteristics of the ship's load will be considered, and the emission intensity will be calculated first using the ISO 14083 methodology, and then using an alternative metric based on lane metres or vehicles rather than tonnes. Table 5.13 summarizes the main information regarding the ship, the voyage and the cargo transported, while Table 5.14 presents the considered alternatives.

Table 5.14: The three considered alternatives, referred to the load characteristics of the ship.

	Unit	Alternative 0	Alternative 1	Alternative 2
% of full semitrailers	[%]	100%	0%	61%
% of empty semitrailers	[%]	0%	100%	39%
n. of full semitrailers	[-]	123	0	75
n. of empty semitrailers	[-]	0	123	48
Ship's load (lane meters)	[m]	1,673	1,673	1,673
Ship's load (gross load)	[t]	4,305	1,722	3,297
Ship's load (net mass cargo)	[t]	2,583	0	1,575

Alternative 0 refers to the case study scenario in which it was assumed that the ship's cargo consisted of 123 semitrailers, all of the same type, length and weight. No further information about the load factor of the singular semitrailer was available. Alternative 1 considers the opposite scenario, that is that all the semitrailers are empty. Although this scenario does not reflect reality, it is useful for introducing the new metric. Alternative 2 refers to an intermediate scenario. Indeed, it considers that about 60% of the semitrailers are fully loaded (75 semitrailers) while the remaining 40% are completely empty (48 semitrailers).

At this stage, the GHG emission intensities can be calculated using the ISO 14083 methodology (based on the transport activity measured in t-km), both from the point of view of the carrier and the shipper. Table 5.15 and Figure 5.10 illustrate the GHG emission intensities for the former case.

Table 5.15: GHG emission intensity [WtW-gCO$_2$e/t-km] based on the ISO 14083 methodology.

Perspective	Type of load	Alternative 0	Alternative 1	Alternative 2
Carrier	Gross load (overall)	55	137	72
Shipper	Net load (only cargo)	92	n.a.	150

In particular, it is interesting to note that from the point of view of the carrier, the intensity grows from a minimum of 55 WtW-gCO$_2$e/t-km to a maximum of 137 WtW-gCO$_2$e/t-km; that means that, when the share of empty semitrailers grows, then the quantity of transported freight decreases until all the semitrailers are empty and the quantity of freight equals the tare of the semitrailers.

According to the ISO 14083 methodology, once the emission intensity has been evaluated from the carrier's perspective, the shipper should convert it into its own emission intensity by referring to the actual quantity of cargo (the net load of the semitrailer) and multiplying the carrier's emission intensity by the ratio of the ship's total gross load to the net load of the semitrailer for which the intensity has been calculated.

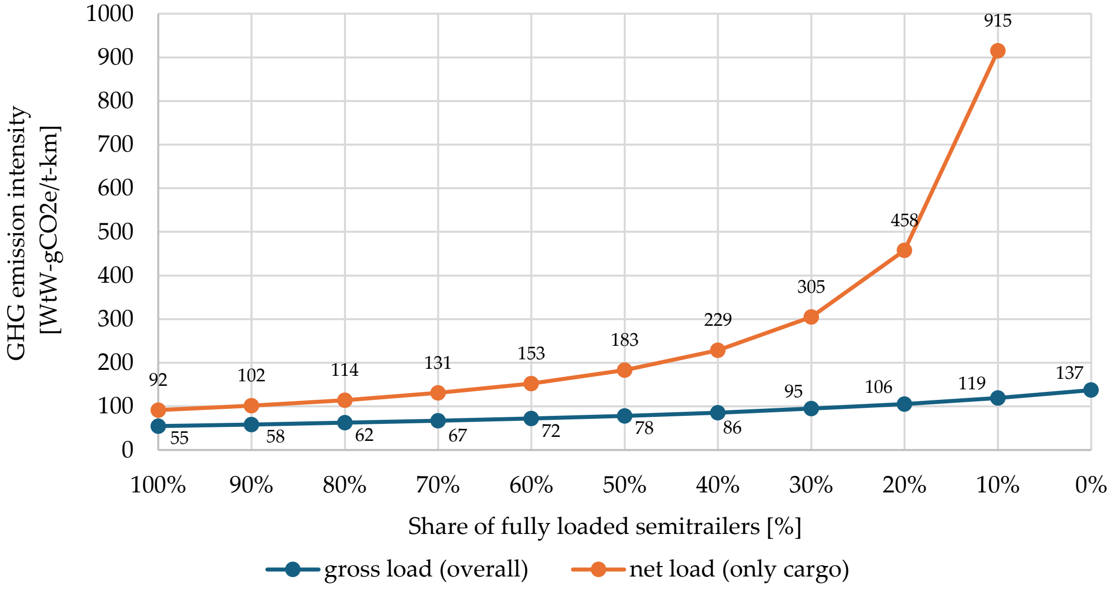


Figure 5.10: Plot of the GHG emission intensity for different shares of fully loaded semitrailers.

In this case too, the shipper's emission intensity increases when the share of the loaded semitrailers decreases, but at a faster rate. Furthermore, in the limit case of 100% empty semitrailers, the emission intensity becomes theoretically infinite, as no actual cargo is loaded on the ship and therefore the total GHG emissions can't be allocated.

In order to solve this misalignment, this research suggests the use of alternative metrics, based on length or vehicles, rather than tonnes. Table 5.16 shows the numerical examples.

Table 5.16: GHG emission intensities based on the new metric.

Perspective	Type of load	Unit	Alternative 0	Alternative 1	Alternative 2
All	Lane meters	[WtW-gCO$_2$e/LM-km]	141	141	141
All	Vehicles	[WtW-gCO$_2$e/H-VEU-km]	1,922	1,922	1,922

NOTE: LMO stands for Lane Meters while HVE for Heavy Vehicle Equivalent

The first emission intensity uses the length (measures in lane meters - LM) of the semitrailer, or of the vehicle in general, instead of the tonnes of gross/net freight, while the second metric uses a new unit called Heavy-Vehicle Equivalent Unit (H-VEU). One H-VEU represents a standard semitrailer measuring 13.6 metres. As with the TEU, this unit enables different vehicles to be converted into it. Similar units are already in use in the sector, such as for example the "Cargo Equivalent Unit" proposed by the European Association of Vehicle Logistics (ECG) for the car carrier segment (ECG and SFC, 2023), and the "Standard Passenger Equivalent Unit" adopted by the ISO 14083 methodology for the Ro-Pax segment (ISO, 2023). However, there is no specific unit defined for the pure Ro-Ro segment (particularly for the transport of semitrailers associated to short sea shipping). Therefore, this unit is intended to be applied on pure Ro-Ro ships.

It is easy to notice from Table 5.16 that in all the chosen alternatives (and for any share of loaded semitrailers) the emission intensities do not change. This is a key factor in simplifying the allocation calculations, in particular in the case of at intermodal freight transport chains, where Ro-Ro transport is combined with other transport modes. Furthermore, another advantage of these alternative metrics, is the relationship with the ship's capacity measured in lane meters or number of semitrailers. In this way, the load factor of the ship can be evaluated, and therefore the environmental efficiency.

5.7. Conclusion

The aim of this first application was to implement the methodology proposed by the ISO 14083 standard in order to quantify the GHG emissions derived from a chosen Ro-Ro maritime transport chain. It is important to notice that, prior to the release of this standard, there was no other international standard for quantifying and reporting GHGs emitted from transport chain operations. As this is a recent methodology, this application was firstly necessary to understand how the proposed method works.

In this Chapter, the ISO 14083 standard's methodology was examined through an analysis of a real case. First the overall GHG emissions and the GHG emission intensities associated to an intermodal freight maritime transport chain involving two modes of transport (sea and road transport) and two transfer hubs (port terminals) where evaluated employing the bottom-up approach. Then, a discussion on alternative allocation metrics was performed.

The preliminary findings demonstrate the method's potentiality to integrate several transport phases of a transport chain. Another notable advantage is that the results are comparable between different modes of transport. However, one of the model's main limitations is that the quality of the primary data (e.g. distances, consumption and commodity characteristics) has a significant impact on the results, and primary data are often difficult to obtain, as logistics operators often lack the necessary tools to record it in a timely manner.

Furthermore, the results of the case study highlighted a critical issue in the GHG emission intensity metric recommended by the ISO 14083 standard. The emission intensity is indeed calculated based on the quantity of goods transported in tonnes. However, this is not always appropriate for pure Ro-Ro maritime transport, particularly when combined with other modes of transport. This highlights the need for alternative metrics. In order to solve this misalignment, this research suggests the use of two alternative metrics. The first emission intensity uses the length (measures in lane meters - LM) of the semitrailer, or of the vehicle in general, instead of the tonnes of gross/net freight. The second metric uses a new unit called Heavy-Vehicle Equivalent Unit (H-VEU). One H-VEU represents a standard semitrailer measuring 13.6 metres, and it enables different vehicles in length to be converted into it. This unit is intended to be applied only on pure Ro-Ro ships.

The key factor in the use of these alternative metrics is that they simplify the allocation of the GHG emissions to the cargo, in particular in the case of at intermodal freight transport chains, where Ro-Ro transport is combined with other transport modes. Furthermore, another advantage of these alternative metrics, is the relationship with the ship’s capacity measured in lane meters or number of semitrailers. In this way, the load factor of the ship can be evaluated, and therefore its environmental efficiency.

One of the limitations of this preliminary application, is the adoption a simplified approach to the method. In fact, it only considered a single trip of a semi-trailer, excluding other transport modes or multiple trips. Therefore, future studies will need to consider more complex transport chains. There are also limitations linked to the suggested alternative metrics. Indeed, more applications should be performed to evaluate the robustness of the metrics and also to calibrate with real data the H-VEU unit.

6. Assessing the extra-costs related to the European Emission Trading System: an application with two case studies

In response to the extra-costs imposed by the maritime European Emissions Trading Scheme, based on the polluter-pay principle, shipping companies can adopt various strategies to comply with this policy and reduce their GHG emissions (Cariou et al., 2024; L. Sun et al., 2024; T. Wang et al., 2025; Zhen et al., 2020). The alternative measures include, among the others, fuel switching, the use of scrubbers and liquefied natural gas (LNG), or the adoption of slow steaming and speed optimisation strategies.

This Chapter aims to assess the impact of these additional costs on the total cost of single voyages. This will be achieved by using a mathematical model to evaluate environmental and economic impacts and the associated costs of the EU-ETS and overall voyage expenditures, enabling a comprehensive comparative assessment of economic and environmental impacts.

The model will be applied at two different case studies. The first one analyses a containerized voyage between a European port and a non-European port, while the second one will focus on a Ro-Ro voyage between two Italian ports.

The rest of the Chapter is organized as follows. Section 6.1 provides an introduction to the applications. Section 6.2 presents the methodology. Section 6.3 describes the first case study, illustrates the application of the mathematical model and presents the numerical results, while Section 6.4 does the same thing with the second case study. Section 6.5 presents a discussion of the results of the two case studies and finally Section 6.6 concludes the Chapter.

6.1. Introduction to the selected application

The EU-ETS requires polluters to pay for their greenhouse gas emissions with the aim of reducing overall emissions in the EU and generating revenue to finance the green transition (EC, 2024a). Since 2012, the system has covered emissions from installations and operations in the electricity and heat generation sector, the industrial manufacturing sector, and the aviation sector. Following its inclusion in the "Fit for 55" package and the European Green Deal, the maritime sector has also been covered by the EU-ETS since 2024 (EC, 2023a; Sikora, 2021). Including the maritime sector in the EU-ETS is the first regional attempt to impose an emissions reduction pathway on shipping companies. This followed the adoption of the EU Monitoring, Reporting and Verification (EU-MRV) Regulation, which formed the basis for the sector's inclusion (EU, 2015). Since 2018, the EU-MRV system has collected information related to CO_2 emissions from ships in the European Economic Area (EEA).

The maritime EU-ETS is based on the "cap-and-trade" principle. The cap represents the maximum level of emissions that can be generated by the sectors involved in the system. This cap is reduced over time to ensure that all sectors in the ETS cumulatively contribute to the EU's climate targets. Each year, companies must surrender the necessary allowances (EUAs) to cover their emissions. One EUA entitles the holder to emit one tonne of CO_2e. Unlike other sectors, the transport sector does not receive free EUAs, but the number of EUAs surrendered is regulated by a phase-in period that progressively increases the carbon quota (see Table 6.1). From the 1st of January 2026, CH_4 and N_2O will also be included in the maritime EU-ETS.

Table 6.1: Share of emissions that must be covered by the surrendering of EUA.

Year	Share of emissions that must be covered by the surrendering of EUA
2025	40% of their emissions reported in 2024
2026	70% of their emissions reported in 2025
2027 onwards	100% of their reported emissions in the previous year

Source: author's elaboration based on EC (2024a).

6.2. Methodology: the mathematical model

The methodological framework used in these applications is based on a mathematical model. This model will be structured in four steps: 1) Estimation of the ship's fuel consumption; 2) Evaluation of the GHG emissions; 3) Calculation of the EU-ETS cost; 4) Calculation of the total voyage costs. The variables used in this application are set in Table 6.2.

Table 6.2: Notation of the variables used in this application.

Variables	Meaning	Unit
FC_i	Total ship's fuel consumption	t
$FC_i^{s,in}$	Ship's fuel consumption during navigation at sea inside ECAs for vessel type *i*	t
$FC_i^{s,out}$	Ship's fuel consumption during navigation at sea outside ECAs for vessel type *i*	t
FC_i^{p}	Ship's fuel consumption in port inside ECAs for vessel type *i*	t
D_i^{in}	Distance sailed during navigation inside ECAs by the vessel type *i*	nm
D_i^{out}	Distance sailed during navigation outside ECAs by the vessel type *i*	nm
V_i^{in}	Speed during navigation inside ECAs for vessel type *i*	kn
V_i^{out}	Speed during navigation outside ECAs for vessel type *i*	kn
$T_i^{s,in}$	Navigation time at sea inside ECAs for vessel type *i*	h
$T_i^{s,out}$	Navigation time at sea outside ECAs for vessel type *i*	h
T_i^{p}	In-port time for vessel type *i*	h
$SFOC_{i,j}$	Specific fuel oil consumption of the chosen fuel *j* for vessel type *i*	t/kWh
$\Delta_{payload,i}$	Payload displacement of the vessel type *i*	t
$\Delta_{LW,i}$	Lightweight displacement of the vessel type *i*	t
Ac_i	Admiralty constant of vessel type *i*	$kW/(kn^3t^{2/3})$
E_T	Total GHG emissions	gCO_2e
$E_{x,j}$	Emissions of greenhouse gas *x*, combusted fuel *j*, by ship type *i*	gCO_2e
$EF_{x,j}$	Emission factor of greenhouse gas *x* by combusted fuel *j*	g_{gas}/g_{fuel}
C_{ETS}	EU-ETS cost	€
$CF_{i,j}$	Fuel cost for a voyage of vessel type *i* using fuel *j*	€
PF_j	Price of fuel *j*	$€/t_{fuel}$
δ	Share of emissions included in the EU-ETS	%
θ	Voyage regulatory weight	-
μ	Cost of the EU allowance	$€/tCO_2e$

6.2.1. Estimation of the ship's fuel consumption

The total ship's fuel consumption (FC_i) includes fuel consumption during navigation at sea $\left(FC_{i,j}^{s}\right)$ and during in-port stage $\left(FC_{i,j}^{p}\right)$. In order to take into account navigation inside and outside ECA zones, ship's fuel consumption can be calculated as:

$$FC_i = \sum_j FC_{i,j}^{s} + FC_{i,j}^{p} = \sum_j \left(FC_{i,j}^{s,in} + FC_{i,j}^{s,out}\right) + FC_{i,j}^{p} \tag{6.1}$$

i. Ship fuel consumption during navigation at sea

According to the admiralty formula (Barrass, 2004), the ship's fuel consumption at sea can be evaluated using equation 6.2 and 6.3.

$$FC_{i,j}^{s,in} = \frac{D_i^{in}}{V_i^{in}} \cdot SFOC_{i,j} \cdot \frac{\left(\Delta_{payload,i} + \Delta_{LW,i}\right)^{2/3} \cdot \left(V_i^{in}\right)^3}{Ac_i} \tag{6.2}$$

$$FC_{i,j}^{s,out} = \frac{D_i^{out}}{V_i^{out}} \cdot SFOC_{i,j} \cdot \frac{\left(\Delta_{payload,i} + \Delta_{LW,i}\right)^{2/3} \cdot (V_i^{out})^3}{Ac_i} \tag{6.3}$$

6.2.1.1. Ship fuel consumption in port

The in-port stage begins when the ship enters the port area and ends when it leaves. During this time, the ship's fuel consumption can be defined by equation 6.4, where *S* is the sailing time inside the port area, *W* is the waiting time, *M* is the manoeuvring time at the terminal and *B* is the berthing time (i.e. the operational time for loading and unloading) (Cariou et al., 2019; Park and Suh, 2019). *S, W* and *M* depend on port characteristics such as location, traffic and congestion, while *B* is proportional to port productivity (TEU/h) and the number of scheduled TEUs to be loaded and unloaded. $FCh_{i,j}$, expressed in t/h, represents the ship *i* fuel *j* consumption per hour for each port phase.

$$FC_{i,j}^{p} = S \cdot FCh_{i,j}^{S} + W \cdot FCh_{i,j}^{W} + M \cdot FCh_{i,j}^{M} + B \cdot FCh_{i,j}^{B} \tag{6.4}$$

6.2.2. Evaluation of the GHG emissions

This section describes the methodology used for evaluating the amount of GHG emissions. GHG emissions are directly proportional to fuel consumption (Park et al., 2024; Psaraftis and Kontovas, 2013). Therefore, the model takes as input the ship's fuel consumption at sea and in port.

According to the EU-MRV Maritime Regulation, shipping companies are required to monitor their Tank-to-Wake (TtW) GHG emissions both on a per-voyage basis and on an annual basis (EU, 2015). The GHGs covered by the regulation are CO_2, CH_4 and N_2O. The

EU-ETS covers CH_4 and N_2O only from 1 January 2026 onwards. The emissions can be evaluated using the following methods (EC, 2024b).

- Calculation-based approach: the emissions are calculated by multiplying the quantity of fuel (actual fuel consumption for each voyage, determined by direct measurements) by an emission factor.
- Measurement-based approach: direct measurements (on board of the ship) of GHG emissions are used.

In this application, the evaluation of the GHG emissions will follow a calculation-based approach. The emissions are therefore quantified as shown in equation 5. CH4 and N2O emissions are expressed in CO_2e, based on their global warming potential (GWP100). The values, set by (IPCC, 2023), are: GWPCO2 = 1, GWPCH4 = 27, and GWPN2O = 273. In the case of CH4 emissions, also the methane slippage must be considered (EC, 2023d). Fuel consumption will be estimated using the methodology presented in the previous paragraph while Table 6.3 shows the emission factors ($EF_{x,j}$) for different marine fuels.

$$E_{x,j} = \left\{\left[\left(FC_j - \frac{FC_j \cdot C_j}{100}\right) \cdot EF_{x,j}\right] + \frac{FC_j \cdot C_j}{100}\right\} \cdot GWP_x \tag{6.5}$$

At this point, the total emissions can be calculated, by adding together all the GHG emissions related to each type of fuel and each type of considered greenhouse gas, as shown in equation 6.

$$E_T = \sum_x \sum_j E_{x,j} \tag{6.6}$$

Table 6.3: Carbon content, TtW emission factors for different marine fuels, slippage coefficient.

Type of fuel	Carbon content [m/m]	Tank-to-Wake emission factors [g_{gas}/g_{fuel}]			% mass fuel j
		CO_2	CH_4	N_2O	C_j
HFO	0.849[b]	3.114[c]	0.00005[c]	0.00018[c]	-
VLSFO	0.86[a]	3.151[c]	0.00005[c]	0.00018[c]	-
MDO/MGO	0.875[b]	3.206[c]	0.00005[c]	0.00018[c]	-
LNG-Otto (LPDF, slow-speed)	0.750[b]	2.750[c]	0[cd]	0.00011[c]	1.7
LNG-Diesel (HPDF, slow-speed)	0.750[b]	2.750[c]	0[cd]	0.00011[c]	0.2

Source: [a](Herdzik, 2021); [b](Kim et al., 2023; L. Sun et al., 2024) based on ISO 8217; [c](EC, 2023d, 2023a; IMO, 2024).

6.2.3. Calculation of the EU-ETS cost

As stated previously, the EU-ETS is a market-based measure that relies on the purchase and use of EU Emission Allowances (EUAs) by shipping companies for each reported tonne of CO_2e emitted under the scope of the EU-ETS (EC, 2020c; EU, 2015; Vitiello et al., 2026). The EUA cost can be defined as equation 6.7, where δ is the share of emissions that must be covered by the surrendering of EUA, θ is a regulatory weight (if the voyage is between non-EEA ports, the factor is 0; if it is within the EEA, 1; and if only one of the ports is an EEA port, it is 0.5), μ is the cost of the EU allowance, and E_T represents the related GHG emissions (EC, 2024b).

$$C_{ETS} = \delta\theta\mu E_T \tag{6.7}$$

6.2.4. Calculation of the total voyage costs

This section provides the approach to estimate the entire voyage cost, including both navigation at sea and in-port phase. The proposed methodology is based on the methodology established by (Van Hassel et al., 2016), with updated values for 2022 provided by (Pruyn and van Hassel, 2022; van Hassel et al., 2022). This existing model enables the calculation of vessel-related costs from the owner's perspective. It consists of three modules: the maritime model, the port model, and the hinterland model. In this application, only the first two will be used. The maritime cost model includes operational costs, voyage costs and capital costs. The input data required are the characteristics of the voyage, that is, the distance between ports, the vessel's speed and the navigation time. The port model evaluates the total port cost, comprising port shipping cost, port authority cost and third-party cost.

6.3. Case study n.1: application to a containerized voyage

The mathematical model is applied to a container route between the ports of Shanghai and Rotterdam. Two alternative routes are considered: one passing through the Suez Canal, and the other via the Cape of Good Hope. Doing so allows to consider the impact of rerouting due to global disruptions (e.g., geopolitical tensions, Red Sea crisis, etc.).

Furthermore, the adoption of alternative measures is included in the study. The chosen measures are: 1) fuel switching, thus employing different fuels (notably diesel gas oil (MDO) in ECAs and heavy fuel oil (HFO) outside); 2) installing scrubbers in combination with HFO; 3) using liquefied natural gas (LNG); and 4) slow steaming and speed optimization. It should be borne in mind that each strategy entails a consequent variation in the total costs in order to be implemented. The different chosen scenarios are schematized in Table 6.4.

Table 6.4: Chosen scenarios used in the case study.

Scenario	Ports (o-d)	Route	Fuel
A.1	Shanghai-Rotterdam	via Suez Canal	VLSFO (outside ECA) & MDO (inside ECA)
A.2	Shanghai-Rotterdam	via Cape Good Hope	VLSFO (outside ECA) & MDO (inside ECA)
B.1	Shanghai-Rotterdam	via Suez Canal	HFO & scrubber (inside and outside ECA)
B.2	Shanghai-Rotterdam	via Cape Good Hope	HFO & scrubber (inside and outside ECA)
C.1	Shanghai-Rotterdam	via Suez Canal	LNG (inside and outside ECA)
C.2	Shanghai-Rotterdam	via Cape Good Hope	LNG (inside and outside ECA)

6.3.1. The alternative measures

6.3.1.1. Emission Control Areas

With regard to air pollution, the IMO MARPOL Annex VI (Regulations for the Prevention of Air Pollution from Ships) establishes requirements to regulate pollutant emissions from ships, including the limitation of nitrogen oxides (NO_x) and sulphur oxides (SO_x) by introducing Emission Control Areas (ECAs) (IMO, 2008).

There are currently five ECAs. These ECAs cover the Baltic Sea, the North Sea, North America, the US Caribbean Sea Areas, and the Mediterranean Sea (effective since May 2025). As of 2015, ships are required to use fuel with a 0.1% Sulphur content limit while operating in these ECAs. As of the 1st of January 2020, a revision of the MARPOL Annex VI required globally that Sulphur content of marine fuel oil used on board of all ships shall not exceed 0.5%, reducing it from a permitted 3,5%. However, this implementation has not changed the requirements applicable in the ECAs.

Until now, only few articles have considered the case of the Med SECA. Analysis by (Fagerholt et al., 2015) of ship routing and speed optimization considered the Indonesia-Northern Europe route and concluded that a Med SECA would not change the shipowners' decisions towards the Med Sea route instead of the Cape of Good Hope. The study by (Chen et al., 2025) considers the container trade between the Far East and Europe and concludes that vessels up to 5,000 TEU are more likely to be rerouted than larger vessels, most of which are already SECA-compliant. In their work, (Cariou et al., 2024) measured the impact of the future Mediterranean SECA at trade and country levels. They concluded that implementing a future Med SECA would not have a neutral effect. Their findings show that trade in goods highly sensitive to maritime transport costs (e.g.: food products, live animals, vegetables and plastics) would be more affected, with several countries facing a reduction in trade value.

6.3.1.2. Fuel switching

For ships that operate both within and outside ECAs, such as deep-sea vessels, fuel switching is a straightforward and widely used method for complying with the sulphur limits. This involves the ship burning fuel with a lower sulphur content within ECAs (e.g., Marine Gas Oil (MGO with 0.10% sulphur content), while using heavy fuel oil (HFO with 0.50% sulphur content, also called Very Low Sulphur Fuel Oil - VLSFO) outside.

To perform fuel switching, ships require two sets of segregated fuel tanks: one for HFO and one for MGO. For older vessels, this would involve retrofitting with corresponding investment costs depending on the ship type. However, these costs would be lower than those of the other emission reduction options analysed in this application (Fagerholt & Psaraftis, 2015). With regard to this option, we consider no initial investment cost. Therefore, the price difference between HFO and MGO is a critical element.

6.3.1.3. Installing scrubbers

In order to comply with global and regional sulphur limits, an alternative to switching fuels is to continue to use cheaper fuels, (e.g., HFO) also inside ECAs by installing an exhaust emission scrubber device which removes up to 90–99% of SO_x from exhaust gases by passing HFO exhaust gases through a buffering solution that captures and binds pollutants (Reynolds, 2011). However, due to the high cost of installation, this solution is usually not considered cost-effective for deep-sea vessels, given the limited time they spend in ECAs (Carr and Corbett, 2015). The initial investment cost of installing scrubbers on new ships, or the retrofitting cost on existing ships are difficult to define. They depend on technical aspects, on the type of ship and on the difference in price between HFO and MGO. (Lindstad et al., 2017) found that the investment cost of an open loop scrubber starts at around 1.5 million USD (2.25 million USD in case of hybrid scrubbers), with an additional cost of 70,000 USD per 1,000 kW of engine installed. (Hazar et al., 2025) suggests using the values shown in Table 6.5. The average lifespan of a typical scrubber is estimated to be 12 years in the case of retrofitting, and 15 years in the case of newbuild (Åström et al., 2018; Jiang et al., 2014).

Table 6.5: Investment cost per type of scrubber, expressed in USD/kW.

Type of scrubber	Open loop	Closed loop	Hybrid	Dry
Investment cost [USD/kW]	163.5	377.14	522.19	680.55

Based on (Hazar et al., 2023; Hermansson et al., 2024; Reynolds, 2011; Wu and Lin, 2021).

6.3.1.4. Use of LNG

An effective alternative measure is to replace LNG for traditional fuels (Acciaro, 2014). LNG is characterised by lower levels of sulphur and carbon, which reduces SO_2 and CO_2 emissions, as well as those of many other substances, such as NO_x. However, particular attention must be given to the risk of CH_4 spills, which can occur when a percentage of LNG remains unburned. As with scrubbers, traditional ships require modifications and significant investment to retrofit them to store and burn LNG. According to (Mohseni et al., 2019), the average investment cost for LNG propulsion retrofit of a ULCV is 18,000,000 USD with a lifetime of 27 years.

6.3.1.5. Slow steaming and speed optimization

Using slow steaming to cut energy consumption stands out among all operational solutions due to its immediate and obvious results (Wan et al., 2018). This is due to the exponential (at least cubic) relationship between fuel consumption and vessel speed, while GHG emissions are proportional to the amount of fuel burned, with the proportionality constant known as the emission factor (Psaraftis and Kontovas, 2013; Zhang et al., 2025). This means that even a slight reduction in speed can lead to a substantial decrease in fuel consumption and GHG emissions, reducing them by 20%-40%. Using extremely slow steaming can achieve a reduction of more than 60% (Pelić et al., 2023). Consequently, operational speed optimisation has gained interest among shipping companies, establishing itself as a cost-efficient method of reducing costs and GHG emissions (Goicoechea and Abadie, 2021; Zhen et al., 2020). Furthermore, the resulting cost savings are substantial enough to encourage shippers to adopt these measures independently of government intervention (Sun et al., 2025).

An effect of slow steaming is that shipping companies could decide to differentiate speed between ECAs and non-ECAs, in order to use less of the more expensive fuel (MDO). On some shipping routes, this might result in a decrease in total cost, and a considerable increase in the total amount of fuel consumed and GHG emissions (Doudnikoff and Lacoste, 2014; Fagerholt et al., 2015), with a consequent increase in the EU-ETS cost related to the extra emissions.

6.3.2. Input data

The mathematical model uses technical and cost information about the selected container ship as input data. The values are presented in Table 6.7. In addition to information about the ship, information about the different routes is also needed. Table 6.6 presents the distances travelled inside and outside the ECAs (Mediterranean and North Sea ECAs), both for the scenario 1 and 2.

Table 6.6: Distances travelled inside/outside ECAs for the different considered routes.

Route	Inside North Sea-ECA [mn]	Inside Med-ECA [mn]	Outside ECA [mn]	Total [mn]
1. via Suez Canal	403	1,937	8,250	10,590
2. via Cape Good Hope	402	0	13,447	13,849

Table 6.7: Information about the selected container ship and the related costs.

Ship and cost information	Value
Selected container ship capacity (TEU)	23,964
Installed engine power (kW)	66,650
Design speed of the selected container ship (kn)	23.2
Operational speed on the selected routes (kn)	20
Payload factor (%)	80
Running fixed cost (USD/day)[a]	8,200
Capital cost (USD/day)[a]	54,851
Suez Canal cost (USD)[b]	934,000
Closed loop scrubber retrofitting cost (USD/year)[c]	590,000
LNG retrofitting cost (USD/year)[d]	670,000

Source: [a]Chain Cost Model (Van Hassel et al., 2016); [b]official website; [c]based on a total cost of 7,000,000USD on 12 years; [d]based on a total cost of 18,000,000USD on 27 years.

6.3.3. Application

Table 6.8 shows the SFOC values used in the calculations and the average cost for each type of fuel considered. Table 6.9 shows the quantity of fuel consumed, and the related cost, calculated for each scenario.

Table 6.8: Specific Fuel Oil Consumption (SFOC) values [g/kWh] and prices for different fuels.

	HFO	VLSFO	MDO	LNG
SFOC[1] [g/kWh]	175[a]	169	165	148 LNG + 0.8 MDO (pilot)[b]
Fuel cost[2] [USD/t]	473	550	752	747

NOTE: [a]In case of use in conjunction with a scrubber system, it must be incremented with an additional 2% (den Boer and Hoen, 2015). [b]LNG-Otto/LPDF, slow-speed engine. The LNG engines require a small amount of pilot fuel injected (MDO). Source: [1]author's elaboration based on (IMO, 2020; Pavlenko et al., 2020); [2]Average values, period January-September 2025, retrieved from https://shipandbunker.com/prices

Table 6.9: Fuel consumption and cost for the different scenarios.

	Scenario A.1	Scenario A.2	Scenario B.1	Scenario B.2	Scenario C.1	Scenario C.2
Fuel consumption [t]	4,072	5,385	4,152	5,399	3,489	4,563
Fuel cost [USD]	2,413,159	2,991,629	1,963,966	2,553,672	2,606,586	3,408,744

Then, for each scenario, the quantity (expressed in tonnes of carbon dioxide equivalent) of the different considered gases are evaluated and presented in Table 6.10.

Table 6.10: Total GHG emissions in the different scenarios.

	Scenario A.1	Scenario A.2	Scenario B.1	Scenario B.2	Scenario C.1	Scenario C.2
CO_2 emissions [t]	12,879	16,783	12,930	16,812	9,433	12,336
CH_4 emissions [t]	5.5	7.3	5.6	7.3	59	78
N_2O emissions [t]	200	265	204	265	103	135
GHG emissions [t]	13,084	17,249	13,139	17,085	9,595	12,548

Table 6.11: EU-ETS cost for the period 2026-onwards (100% share on 50% of total emissions).

	Scenario A.1	Scenario A.2	Scenario B.1	Scenario B.2	Scenario C.1	Scenario C.2
CO_2 cost [USD]	450,751	594,184	452,543	588,424	330,146	431,746
CH_4cost [USD]	192	254	196	255	2,076	2,715
N_2O cost [USD]	7,004	9,262	7,141	9,286	3,605	4,715
EU-ETS cost [USD]	457,947	603,701	459,880	597,965	335,827	439,176

The cost of the EU ETS is calculated separately for each greenhouse gas. Considering a voyage between a non-EU port to an EU port, only 50% of the emissions will be counted.

EUA cost is fixed at $70\ \$/tCO_2e$[6]. According to the EU, the proportion of emissions included in the ETS follows this transitional phase: 40% in 2024, 70% in 2025, and 100% from 2026 onwards. Table 6.11 shows the related ETS costs for the period from 2026 onwards.

6.3.4. Numerical results

Finally, the total cost is calculated based on the sum of the fuel cost, the EU-ETS cost, and the other costs. Table 6.12 and Figure 6.1 summarise the results. The proportion of EU-ETS costs in the total costs ranges from 6% to 12%. Lower values are seen for Scenario C (LNG-powered) due to the lower carbon intensity per distance. The highest values are recorded for the options using traditional fuels when the Good Hope Cape Route is taken. Despite the lower impact of the EU-ETS, Scenario C incurs the highest total costs compared to the other options. This is partly because of the higher operating costs associated with the use of this technology.

Table 6.12: Fuel cost, EU-ETS cost, other costs and total costs, associated to different scenarios

	Scenario A.1	Scenario A.2	Scenario B.1	Scenario B.2	Scenario C.1	Scenario C.2
Fuel cost [USD]	2,413,159	2,991,629	1,963,966	2,553,672	2,606,586	3,408,744
EU-ETS cost [USD]	457,947	603,701	459,880	597,965	335,827	439,176
Other costs [USD]	2,557,094	1,740,819	2,592,756	2,047,673	2,597,592	2,053,996
Total costs [USD]	5,428,200	5,336,149	5,016,602	5,199,310	5,540,005	5,901,916

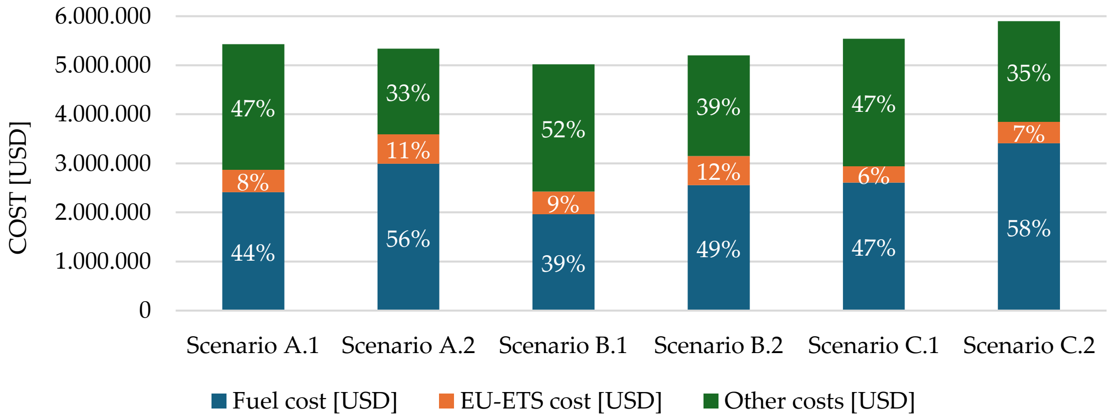


Figure 6.1: Percentage breakdown of fuel cost, EU-ETS cost and other costs as a proportion of total voyage costs for different scenarios.

---

[6] The average value for October 2025, obtained from https://tradingeconomics.com/commodity/

6.4. Case study n.2: application to a Ro-Ro voyage

The mathematical model is now applied to a regular Ro-Ro maritime service between the Italians ports of Cagliari and Genoa. The service runs three times a week from each port. One single voyage will be analysed in this case study.

6.4.1. Input data

The mathematical model uses technical and cost information about the selected Ro-Ro ship as input data. The information about the ship is presented in Table 6.13 and are partially based on the results of a study that involved also *Confindustria Sud Sardegna*. The distance between the ports of Cagliari and Genoa is 353 mn. The navigation time at sea is about 21h. The hole journey falls within the Mediterranean ECA.

Table 6.13: Information about the selected Ro-Ro ship and the related costs

Ship and cost information	Value
Selected Ro-Ro ship capacity (lane meters of cargo)	2,500
Design speed of the selected container ship (kn)	21
Operational speed on the selected routes (kn)	17
Payload factor (%)	70
Running fixed cost (€/journey)	9,000
Capital cost (€/journey)	18,250

6.4.2. Application

Table 6.14 shows the quantity of fuel consumed (HFO), and the related cost. The SFOC values used in the calculations and the average cost for each type of fuel considered are shown in Table 6.8.

Table 6.14: Fuel consumption and cost for the selected journey.

	Values
Fuel consumption [kg]	35,000
Fuel cost [€]	14,000

Then, the quantity (expressed in tonnes of carbon dioxide equivalent) of the different considered gases are evaluated and presented in Table 6.15. The cost of the EU ETS is calculated separately for each greenhouse gas. Considering a voyage between two EU ports, the 100% of the emissions will be counted. EUA cost is fixed at 60 €/tCO_2eq. Table 6.16 shows the related EU-ETS costs for the period from 2026 onwards.

Table 6.15: Total GHG emissions and detailed for the different GHGs

Type of GHG Emissions	Values
CO_2 emissions [kg]	108,990
CH_4 emissions [kg]	1.75
N_2O emissions [kg]	6.3
GHG emissions [kg]	108,998

Table 6.16: EU-ETS cost for the period 2026-onwards (100% share on 100% of total emissions)

EU-ETS extra-costs	Values
CO_2 cost [€]	6,539.4
CH_4cost [€]	0.1
N_2O cost [€]	0.4
EU-ETS cost [€]	6,540

6.4.3. Numerical results

Finally, the total cost is calculated based on the sum of the fuel cost, the EU-ETS cost, and the other costs. Table 6.17 summarise the results. The impact of the additional EU-ETS costs on the total costs is approximately 14%, i.e. with an increase of 16% on the cost without the EU-ETS.

Table 6.17: Fuel cost, EU-ETS cost, other costs and total costs

Costs	Value	Share [%]
Fuel cost [€]	14,000	29%
EU-ETS cost [€]	6,540	14%
Other costs [€]	27,250	57%
Total costs [€]	47,790	-

6.5. Conclusion

Based on the EU-ETS Regulation and the new adoption of the Mediterranean ECA, this chapter presented a cost model considering GHG emissions. Two case studies were performed, analysing the voyage of a container ship between the port of Shanghai and the port of Rotterdam and a Ro-Ro voyage between the Italian ports of Cagliari and Genoa. The aim was to assess the impact of the extra-costs produced by the EU-ETS on the total cost of a maritime voyage. The first case study also included the environmental and economic impacts of different alternatives.

The results of case study n.1, related to the containerized voyage, show that the EU-ETS extra-costs can represent, on average, 9% of the total voyage costs. Although further research is needed to determine the conditions under which these costs can be minimised, this first result is important to highlight the research gap. Indeed, the recent inclusion of the maritime sector in the EU-ETS, and the future developments by the IMO to standardise a global market-based system, are issues that still need to be addressed and understood. This application has some limitations that could be addressed in further research. For example, the methodology does not reflect the full complexity of the problem, but only a specific instance of it. This issue could be resolved by testing the mathematical model using alternative origin-destination scenarios and different types of container vessel. Another limitation relates to the choice of variables: further studies are needed to investigate the effect of speed variation on costs and the use of alternative fuels (e.g. methanol and hydrogen).

The results of case study n.2, which is related to the Ro-Ro voyage, reveal that the additional EU-ETS costs account for around 14% of the total costs, representing a 16% increase on the cost without the EU-ETS. This result, also compared to the previous case study, highlights the significant impact of this policy on the Ro-Ro segment. Indeed, on routes to and from islands, where maritime transport is often the only option for freight transport, these costs could undermine transportation prices. Furthermore, these additional costs are often passed on by the carrier to the shippers, resulting in increased transport costs. This is particularly the case for the European Ro-Ro segment, which is strongly affected by these extra-costs due to its high fuel consumption and the nature of its services. These surcharges are applied based on the quantity of freight. In the case of containerized transport, the cost is defined per TEU, whereas for Ro-Ro transport, it is defined per lane metre or per vehicle, in line with how Ro-Ro freight is priced. Therefore, the results of the application emphasise the importance of introducing suitable emission intensity metrics for the different sectors of the shipping industry, to ensure that the correct amount of emissions is allocated to transported cargo. This finding is consistent with the analysis in the previous chapter. The author therefore suggests adopting new metrics, such as those presented in Chapter 5, in this case too.

7. Final conclusions

7.1. The contribution of the research

The transport sector is a major source of greenhouse gas emissions, and the pressure to adopt emission reduction policies is steadily increasing. The need to define clear decarbonization strategies can no longer be postponed. In this context, the aim of this research was to provide useful and original insights into a possible integration between GHG emissions quantification methodologies and emissions reduction measures, identifying also critical aspects and weaknesses. To achieve this aim, this research defined five specific objectives which were investigated in the research. The contribution of this research can be summarized as follows:

The research provided an overview of the International Regulatory context for decarbonising the maritime transport sector and a focus on the European Regulatory Framework, including related climate policies and highlighting critical issues.

It also provided an overview and a critical analysis of the potential greenhouse gas emission reduction measures and policies in the maritime transport sector.

Then, it critically classified the latest available methodologies for quantifying greenhouse gas emissions in intermodal freight transport chains, identifying the ISO 14083 standard as the most comprehensive one.

It performed an application of the quantification methodology proposed by the ISO 14083 standard, in combination with the GLEC Framework, to an intermodal Ro-Ro maritime transport chain. This application revealed some of the operational difficulties that companies may encounter when using this methodology to quantify their carbon footprint. One of the main issues is acquiring and monitoring primary data, which is highly recommended for accurate results. Furthermore, the results of the case study highlighted a critical issue in the GHG emission intensity metric recommended by the ISO 14083 standard. The emission intensity is indeed calculated based on the quantity of goods transported in tonnes. However, this is not always appropriate for pure Ro-Ro maritime transport, particularly when combined with other modes of transport. This highlights the need for alternative metrics, for example, based on lane metres or vehicles.

Finally, the economic impact of the extra-costs related to the European Emission Trading System was analysed by implementing an economic and environmental model. The numerical results related to the impact of the extra-costs showed that the EU-ETS can represent, on average, 9% of the total voyage costs when referring to a containerized voyage, and 14% if considering a Ro-Ro short sea shipping voyage in the Mediterranea area. Furthermore, this second application showed that, from the carrier's perspective, technical and operational reduction measures can, in general, help to contain the extra-costs related to the implementation of the maritime EU-ETS. However, these additional costs are often passed on by the carrier to the shippers, resulting in increased transport costs. This is particularly the case for the European Ro-Ro segment, which is strongly affected by these extra-costs due to its high fuel consumption and the nature of its services. These surcharges are applied based on the quantity of freight. In the case of containerized transport, the cost is defined per TEU, whereas for Ro-Ro transport, it is defined per lane metre or per vehicle, in line with how Ro-Ro freight is priced. Therefore, the results of the application highlighted the need to introduce appropriate emission intensity metrics for the various segments of the shipping sector, in order to allocate the correct amount of emissions to transported cargo. Further research is needed to determine the conditions under which these costs can be minimised, this first result is important to highlight this research gap. Indeed, the recent inclusion of the maritime sector in the EU-ETS, and the future developments by the IMO to standardise a global market-based system, are issues that still need to be addressed and understood.

7.2. Practical implications

In order to solve the misalignment between the emission intensity evaluated from the carrier's perspective and the one form the shipper's perspective, this research suggests the use of alternative metrics, based on length or vehicles, rather than tonnes.

The first emission intensity uses the length (measures in lane meters - LM) of the semitrailer, or of the vehicle in general, instead of the tonnes of gross/net freight, while the second metric uses a new unit called Heavy-Vehicle Equivalent Unit (H-VEU). One H-VEU represents a standard semitrailer measuring 13.6 metres. As with the TEU, this unit enables different vehicles to be converted into it. Similar units are already in use in the sector, such as for example the "Cargo Equivalent Unit" proposed by the European Association of Vehicle Logistics (ECG) for the car carrier segment, and the "Standard Passenger Equivalent Unit" adopted by the ISO 14083 methodology for the Ro-Pax segment. However, there is no specific unit defined for the pure Ro-Ro segment (particularly for the transport of semitrailers associated to short sea shipping). Therefore, this unit is intended to be applied on pure Ro-Ro ships.

The emission intensity measured with these alternative metrics does not change. This is a key factor in simplifying the allocation calculations, in particular in the case of intermodal freight transport chains, where Ro-Ro transport is combined with other transport modes. Furthermore, another advantage of these alternative metrics, is the relationship with the ship’s capacity measured in lane meters or number of semitrailers. In this way, the load factor of the ship can be evaluated, and therefore the environmental efficiency.

References

Acciaro, M., 2014. Real option analysis for environmental compliance: LNG and emission control areas. Transportation Research Part D: Transport and Environment, Emission Control Areas and their Impact on Maritime Transport 28, 41–50. https://doi.org/10.1016/j.trd.2013.12.007

Agavanakis, K., Quitard, R., Kousias, N., Mellios, G., Elkaim, E., 2023. Driving Sustainability in Logistics Value Chains: A Telematics Data Hub Implementation for Accurate Carbon Footprint Assessment and Reporting Using Global Standards-based Tools. Presented at the AIP Conference Proceedings. https://doi.org/10.1063/5.0171377

Anderson, C.B., 2012. Marine Pollutionand the “PolluterPays” Principle: Should the Polluter also Pay Punitive Damages?

Åström, S., Yaramenka, K., Winnes, H., Fridell, E., Holland, M., 2018. The costs and benefits of a nitrogen emission control area in the Baltic and North Seas. Transportation Research Part D: Transport and Environment 59, 223–236. https://doi.org/10.1016/j.trd.2017.12.014

Auvinen, H., Clausen, U., Davydenko, I., Diekmann, D., Ehrler, V., Lewis, A., 2014. Calculating emissions along supply chains — Towards the global methodological harmonisation. Research in Transportation Business & Management 12, 41–46. https://doi.org/10.1016/j.rtbm.2014.06.008

Bahman, N., Naser, N., Khan, E., Mahmood, T., 2025. Environmental science, policy, and industry nexus: Integrating Frameworks for better transport sustainability. Global Transitions 7, 29–40. https://doi.org/10.1016/j.glt.2024.12.001

Barbieri, F., Cannava, L., Colicchia, C., Perotti, S., 2024. Modelling the environmental performance of logistics distribution processes: a business case in the agri-food supply chain. BIJ 32, 51–78. https://doi.org/10.1108/bij-07-2024-0634

Barrass, B., 2004. Ship design and performance: for masters and mates. Butterworth-Heinemann, Oxford.

Barthakur, A., 2021. Polluter Pays Principle As The Key Element To Environmental Law. IJSRP 11, 274–277. https://doi.org/10.29322/IJSRP.11.03.2021.p11137

Bengue, A.A., Alavi-Borazjani, S.A., Chkoniya, V., Cacho, J.L., Fiore, M., 2024. Prioritizing Criteria for Establishing a Green Shipping Corridor Between the Ports of Sines and Luanda Using Fuzzy AHP. Sustainability 16, 9563. https://doi.org/10.3390/su16219563

Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell, G., Lindner, M., Marelli, L., Paré, D., Pingoud, K., Yeh, S., 2016. Forest biomass, carbon neutrality and climate change mitigation (From Science to Policy), From Science to Policy. European Forest Institute. https://doi.org/10.36333/fs03

Beskovnik, B., Golnar, M., 2020. EVALUATING THE ENVIRONMENTAL IMPACT OF COMPLEX INTERMODAL TRANSPORT CHAINS. Environ. Eng. Manag. J. 19, 1131–1141. https://doi.org/10.30638/eemj.2020.107

BSI, 2011. PAS 2050:2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institute, London, England.

Bucak, U., Ayaz, İ.S., Esmer, S., 2025. The principal-agent problem in the inclusion of maritime transport into the EU ETS: Which kind of incentives are best? Research in Transportation Business & Management 62, 101459. https://doi.org/10.1016/j.rtbm.2025.101459

Cariou, P., Guët, A.T., Monios, J., Halim, R.A., 2024. The economic impact of the Mediterranean Sulfur Emission Control Area. Marine Policy 168, 106300. https://doi.org/10.1016/j.marpol.2024.106300

Cariou, P., Parola, F., Notteboom, T., 2019. Towards low carbon global supply chains: A multi-trade analysis of CO2 emission reductions in container shipping. International Journal of Production Economics 208, 17–28. https://doi.org/10.1016/j.ijpe.2018.11.016

Carr, E.W., Corbett, J.J., 2015. Ship Compliance in Emission Control Areas: Technology Costs and Policy Instruments. Environ. Sci. Technol. 49, 9584–9591. https://doi.org/10.1021/acs.est.5b02151

Cavallaro, F., Costa, C., De Biasi, I., Fabio, A., Nocera, S., 2024. Sustainable pathways for mitigating externalities in long-distance terrestrial transport. Transport Policy 154, 207–221. https://doi.org/10.1016/j.tranpol.2024.05.026

CCWG, 2015. Clean Cargo Working Group Carbon Emissions Accounting Methodology 2015.

CE Delft, 2020. STREAM Freight Transport 2020, Emissions of freight transport modes.

CE Delft, Directorate-General for Mobility and Transport (European Commission), Essen, H. van, Fiorello, D., El Beyrouty, K., Bieler, C., Wijngaarden, L. van, Schroten, A., Parolin, R., Brambilla, M., Sutter, D., Maffii, S., Fermi, F., 2020. Handbook on the external costs of transport: version 2019 – 1.1. Publications Office of the European Union.

Chen, J., 2021. Carbon Neutrality Towards Sustainable Future. The Innovation 2, 100127. https://doi.org/10.1016/j.xinn.2021.100127

Chen, J., Zhang, Y., Shi, J., Pang, C., She, S., Chen, X., Xu, J., 2025. Cost-benefit analysis of ships NOx Emission Control Areas (NECA) along China's coastal area. Marine Pollution Bulletin 215, 117830. https://doi.org/10.1016/j.marpolbul.2025.117830

Christodoulou, A., Cullinane, K., 2024. The prospects for, and implications of, emissions trading in shipping. Marit. Econ. Logist. 26, 168–184. https://doi.org/10.1057/s41278-023-00261-1

Christodoulou, A., Dalaklis, D., Ölçer, A.I., Ghaforian Masodzadeh, P., 2021. Inclusion of Shipping in the EU-ETS: Assessing the Direct Costs for the Maritime Sector Using the MRV Data. Energies 14, 3915. https://doi.org/10.3390/en14133915

Cullinane, K., Yang, J., 2022. Evaluating the Costs of Decarbonizing the Shipping Industry: A Review of the Literature. Journal of Marine Science and Engineering 10. https://doi.org/10.3390/jmse10070946

Davydenko, Hopman, Van Gijlswijk Bsc, Rondaij, Spreen, 2019. Towards harmonization of Carbon Footprinting methodologies: a recipe for reporting in compliance with the GLEC Framework, Objectif CO2 and SmartWay for the accounting tool BigMile™. https://doi.org/10.13140/RG.2.2.10883.45601

Davydenko, I., Ehrler, V., de Ree, D., Lewis, A., Tavasszy, L., 2014. Towards a global CO2 calculation standard for supply chains: Suggestions for methodological improvements. Transportation Research Part D: Transport and Environment 32, 362–372. https://doi.org/10.1016/j.trd.2014.08.023

Dehdari, P., Wlcek, H., Furmans, K., 2023. An updated literature review of CO2e calculation in road freight transportation. Multimodal Transportation 2, 100068. https://doi.org/10.1016/j.multra.2022.100068

den Boer, E., Hoen, M. 't, 2015. Scrubbers: An economic ecological assessment. CE Delft.

Dobers, K., Ehrler, V.C., Davydenko, I.Y., Rüdiger, D., Clausen, U., 2019. Challenges to

Standardizing Emissions Calculation of Logistics Hubs as Basis for Decarbonizing Transport Chains on a Global Scale. Transportation Research Record: Journal of the Transportation Research Board 2673, 502–513. https://doi.org/10.1177/0361198119844252

Dobers, K., Jarmer, J.-P., :Unav, 2023. Guide for Greenhouse Gas Emissions Accounting at Logistics Hubs.

Doudnikoff, M., Lacoste, R., 2014. Effect of a speed reduction of containerships in response to higher energy costs in Sulphur Emission Control Areas. Transportation Research Part D: Transport and Environment 28, 51–61. https://doi.org/10.1016/j.trd.2014.03.002

du Plessis, M., van Eeden, J., Goedhals-Gerber, L., 2022. Carbon mapping frameworks for the distribution of fresh fruit: A systematic review. Global Food Security 32, 100607. https://doi.org/10.1016/j.gfs.2021.100607

Durmuş, A.N., 2025. EU ETS and Maritime Transport: Allocation of Costs and Implications for Trade. https://doi.org/10.54648/GTCJ2025083

EC, 2025. Report from the Commission 2024. CO2 emissions from maritime transport. {COM(2025) 39 final} https://data.europa.eu/doi/10.2834/8958061. Publications Office, LU.

EC, 2024a. Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC (Text with EEA relevance).

EC, 2024b. Guidance Document. The EU ETS and MRV Maritime General guidance for shipping companies. Guidance document No.1 Updated Version, 5 November 2024 (online).

EC, 2023a. 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 (Text with EEA relevance).

EC, 2023b. Regulation of the european parliament and of the council on the accounting of greenhouse gas emissions of transport services, COM(2023) 441 final.

EC, 2023c. Commission Decision (EU) 2023/1575 of 27 July 2023 on the Union-wide quantity of allowances to be issued under the EU Emissions Trading System for 2024. Official Journal of the European Union.

EC, 2023d. COMMISSION DELEGATED REGULATION (EU) 2023/2776 of 12 October 2023 amending Regulation (EU) 2015/757 of the European Parliament and of the Council as regards the rules for monitoring greenhouse gas emissions and other relevant information from maritime transport (Text with EEA relevance).

EC, 2020a. Sustainable and Smart Mobility Strategy – putting European transport on track for the future. {SWD(2020) 331 final}.

EC, 2020b. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. Sustainable and Smart Mobility Strategy – putting European transport on track for the future {SWD(2020) 331 final}.

EC, 2020c. Report from the Commission 2019. Annual Report on CO2 Emissions from Maritime Transport {C(2020) 3184 final}.

EC, 2019. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal.

EC, 2005. Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading Within the Community and Amending Council Directive 96/61/EC. https://doi.org/10.1017/CBO9780511664885.043

ECG, SFC, 2023. Association of European Vehicle Logistics and Smart Freight Centre. Guidance document for a GHG accounting and reporting methodology for the Ro-Ro sector.

EcoTransIT, 2024. Environmental Methodology and Data Update 2024.

EEEG, 2023. Guidance for Greenhouse Gas Emission Footprinting for Dry Bulk Terminals.

EEEG, 2017. Guidance for Greenhouse Gas Emission Footprinting for container terminals.

EEEX, 2025. European Energy Exchange, EUA Primary Auction Spot [WWW Document]. URL https://www.eex.com/en/market-data/market-data-hub/environmentals/eex-eua-primary-auction-spot-download (accessed 4.2.25).

Ehrler, V., Davydenko, I., Ree, D., Ton, J., Auvinen, H., Lewis, A., Seidel, S., Lischke, A., Maurer, H., 2013. Standardized Emission Calculations along Supply Chains as a Basis for Smart Global Transport Solutions in a “Reality of Less” – Is an Approach within Reach?

Ehrler, V.C., Seidel, S., Lischke, A., Davydenko, I., Dobers, K., Lewis, A., Val, S., Luzzini, D., 2018. Standardization of Transport Chain Emission Calculation – Status Quo and What Is Needed Next.

EMSA, 2025. THETIS-MRV Database: CO2 emission report [WWW Document]. URL https://mrv.emsa.europa.eu/#public/emission-report (accessed 3.31.25).

Erbach, G., Jensen, L., Chahri, S., Claros, E., 2024. Towards climate neutrality.

EU, 2023a. REGULATION (EU) 2023/851 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 April 2023 amending Regulation (EU) 2019/631 as regards strengthening the CO2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union’s increased climate ambition.

EU, 2023b. Regulation (EU) 2023/957 of the European Parliament and of the Council of 10 May 2023 Amending Regulation (EU) 2015/757 in order to provide for the inclusion of maritime transport activities in the EU emissions trading system and for the MRV; European Council: Brussels, Belgium, 2023; Volume 2023, pp. 105–114.

EU, 2023c. Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU.

EU, 2023d. 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).

EU, 2015. Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC (Text with EEA relevance). Official Journal of the European Union 2015; L123:55–76.

Fagerholt, K., Gausel, N.T., Rakke, J.G., Psaraftis, H.N., 2015. Maritime routing and speed optimization with emission control areas. Transportation Research Part C: Emerging Technologies 52, 57–73. https://doi.org/10.1016/j.trc.2014.12.010

Fancello, G., Vitiello, D.M., Serra, P., 2023. Evaluating the Environmental Sustainability of an Intermodal Freight Logistic Chain Using the GLEC Framework. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in

Bioinformatics) 14110 LNCS, 563–576. https://doi.org/10.1007/978-3-031-37123-3_39

Froese, E.J., Töter, S., Erdogan, I., 2014. GREEN EFFORTS DELIVERABLE 12.1 Recommendations Manual for Terminals.

Gallo, A., 2022. The Logistic Carbon Footprint: A Dynamic Calculation Tool for an Indicator of the Sustainability of Logistic Processes with a Case Study on the Port of Trieste, in: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (Eds.), Computational Science and Its Applications – ICCSA 2022 Workshops, Lecture Notes in Computer Science. Springer International Publishing, Cham, pp. 109–123. https://doi.org/10.1007/978-3-031-10548-7_9

Ghaforian Masodzadeh, P., Ölçer, A.I., Ballini, F., Christodoulou, A., 2022. How to bridge the short-term measures to the Market Based Measure? Proposal of a new hybrid MBM based on a new standard in ship operation. Transport Policy 118, 123–142. https://doi.org/10.1016/j.tranpol.2022.01.019

Gilbert, P., Bows-Larkin ,Alice, Mander ,Sarah, and Walsh, C., 2014. Technologies for the high seas: meeting the climate challenge. Carbon Management 5, 447–461. https://doi.org/10.1080/17583004.2015.1013676

Goicoechea, N., Abadie, L.M., 2021. Optimal slow steaming speed for container ships under the eu emission trading system. Energies 14. https://doi.org/10.3390/en14227487

Gregor, E., 2020. Monitoring, reporting and verification of CO2 emissions from maritime transport. Second edition. EPRS, October 2020.

Haasz, T., Gómez Vilchez, J.J., Kunze, R., Deane, P., Fraboulet, D., Fahl, U., Mulholland, E., 2018. Perspectives on decarbonizing the transport sector in the EU-28. Energy Strategy Reviews 20, 124–132. https://doi.org/10.1016/j.esr.2017.12.007

Halim, R.A., Kirstein, L., Merk, O., Martinez, L.M., 2018. Decarbonization pathways for international maritime transport: A model-based policy impact assessment. Sustainability (Switzerland) 10. https://doi.org/10.3390/su10072243

Hazar, C., Yuksel, O., Bayraktar, M., 2025. Economic modelling and comparative analysis of scrubber technologies for various ship types utilising different marine fuels. Clean Techn Environ Policy. https://doi.org/10.1007/s10098-025-03268-9

Hazar, C., Yüksel, O., Bayraktar, M., 2023. The cost analysis and evaluation of scrubber investments for ship installation.

HBEFA, 2022. Handbook emission factors for road transport 4.2.

Helm, D., 2003. The Assessment: Climate-Change Policy. Oxford Review of Economic Policy 19, 349–361. https://doi.org/10.1093/oxrep/19.3.349

Herdzik, J., 2021. Decarbonization of Marine Fuels—The Future of Shipping. Energies 14, 4311. https://doi.org/10.3390/en14144311

Hermansson, A.L., Hassellöv, I.-M., Grönholm, T., Jalkanen, J.-P., Fridell, E., Parsmo, R., Hassellöv, J., Ytreberg, E., 2024. Strong economic incentives of ship scrubbers promoting pollution. Nat Sustain 7, 812–822. https://doi.org/10.1038/s41893-024-01347-1

Hörandner, L., Egger, L.-M.P., Beil, D., 2023a. Calculating Emissions Along Multimodal Transport Chains - Standards, Difficulties and Problems, in: Li, Y., Hu, Y., Rigo, P., Lefler, F.E., Zhao, G. (Eds.), Proceedings of PIANC Smart Rivers 2022, Lecture Notes in Civil Engineering. Springer Nature Singapore, Singapore, pp. 1338–1341. https://doi.org/10.1007/978-981-19-6138-0_117

Hörandner, L., Putz-Egger, L.-M., Specht, P., Denise, B., 2023b. Standardized logistics emission calculation in inland navigation: Status quo and challenges ahead. Transportation Research Procedia 72, 1483–1490. https://doi.org/10.1016/j.trpro.2023.11.614

Hülemeyer, D., Schoeder, D., 2019. Carbon Footprint Accounting for General Goods—A Comparison, in: Teuteberg, F., Hempel, M., Schebek, L. (Eds.), Progress in Life Cycle Assessment 2018, Sustainable Production, Life Cycle Engineering and Management. Springer International Publishing, Cham, pp. 139–153. https://doi.org/10.1007/978-3-030-12266-9_11

IATA, 2022a. Recommended Practice 1678 for Cargo CO2 Emissions Measurement Methodology.

IATA, 2022b. Recommended Practice 1726 Passenger CO2 Calculation Methodology.

ICAP, 2025. International Carbon Action Partnership, Allowance Price Explorer [WWW Document]. URL https://icapcarbonaction.com/en/ets-prices (accessed 4.2.25).

IEA, 2024. World Energy Outlook 2024.

IEA, 2018. CO2 Emissions from Fuel Combustion 2018, CO2 Emissions from Fuel Combustion. OECD. https://doi.org/10.1787/co2_fuel-2018-en

IMO, 2024. Guidelines on life cycle GHG intensity of marine fuels, Annex 10, Resolution MEPC.391(81).

IMO, 2023. IMO Strategy on Reduction of GHG emissions from ships, Annex 1, Resolution MEPC.377(80).

IMO, 2021. RESOLUTION MEPC.328(76): AMENDMENTS TO THE ANNEX OF THE PROTOCOL OF 1997 TO AMEND THE INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS, 1973, AS MODIFIED BY THE PROTOCOL OF 1978 RELATING THERETO, Revised MARPOL Annex VI 2021.

IMO, 2020. Fourth IMO Greenhouse Gas Study 2020: Safe, secure and efficient shipping on clean ocean, London: International Maritime Organization (IMO).

IMO, 2018. Initial IMO strategy on reduction of GHG emissions from ships, Annex 1, Resolution MEPC.304(72).

IMO, 2016. Resolution MEPC.278 (70)—Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto (Data Collection System for Fuel Oil Consumption of Ships); International Maritime Organization (IMO): London, UK, 2016; pp. 1–7.

IMO, 2009. Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI).

IMO, 2008. Annex 13 Resolution MEPC.176(58) Amendments to the Annex of the protocol of 1997 to amend the International convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto (Revised MARPOL Annex VI).

IPCC, 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647.

ISO, 2023. ISO 14083:2023. Greenhouse Gases-Quantification and Reporting of Greenhouse Gas Emissions Arising from Transport Chain Operations. ISO: Geneva, Switzerland, 2023. Available online: https://www.iso.org/obp/ui/#iso:std:iso:14083:ed-1:v1:en:sec:13.4.1.

Jia, Z., Lin, B., 2021. How to achieve the first step of the carbon-neutrality 2060 target in China: The coal substitution perspective. Energy 233, 121179.

https://doi.org/10.1016/j.energy.2021.121179

Jiang, L., Kronbak, J., Christensen, L.P., 2014. The costs and benefits of sulphur reduction measures: Sulphur scrubbers versus marine gas oil. Transportation Research Part D: Transport and Environment 28, 19–27. https://doi.org/10.1016/j.trd.2013.12.005

Kachi, A., Mooldijk, S., Warnecke, C., 2019. Carbon pricing options for international maritime emissions.

Kellner, F., 2022. Generating greenhouse gas cutting incentives when allocating carbon dioxide emissions to shipments in road freight transportation. OR Spectrum 44, 833–874. https://doi.org/10.1007/s00291-022-00675-y

Kellner, F., 2016. Allocating greenhouse gas emissions to shipments in road freight transportation: Suggestions for a global carbon accounting standard. Energy Policy 98, 565–575. https://doi.org/10.1016/j.enpol.2016.09.030

Kellner, F., Schneiderbauer, M., 2019. Further insights into the allocation of greenhouse gas emissions to shipments in road freight transportation: The pollution routing game. European Journal of Operational Research 278, 296–313. https://doi.org/10.1016/j.ejor.2019.04.007

Kim, H., Yeo, S., Lee, J., Lee, W.-J., 2023. Proposal and analysis for effective implementation of new measures to reduce the operational carbon intensity of ships. Ocean Engineering 280, 114827. https://doi.org/10.1016/j.oceaneng.2023.114827

Kirschstein, T., Bierwirth, C., 2018. The selective Traveling Salesman Problem with emission allocation rules. OR Spectrum 40, 97–124. https://doi.org/10.1007/s00291-017-0493-z

Kotzampasakis, M., 2025. Maritime emissions trading in the EU: Systematic literature review and policy assessment. Transport Policy 165, 28–41. https://doi.org/10.1016/j.tranpol.2025.02.014

Kukjans, I., Jurgelane-Kaldava, I., Juruss, M., 2025. A blockchain-enabled taxation framework for implementing the polluter-pays principle in transportation. Journal of Open Innovation: Technology, Market, and Complexity 11, 100612. https://doi.org/10.1016/j.joitmc.2025.100612

Lagouvardou, S., Psaraftis, H.N., 2022. Implications of the EU Emissions Trading System (ETS) on European container routes: A carbon leakage case study. Marit. Transp. Res. 3. https://doi.org/10.1016/j.martra.2022.100059

Lagouvardou, S., Psaraftis, H.N., Zis, T., 2020. A Literature Survey on Market-Based Measures for the Decarbonization of Shipping. Sustainability 12, 3953. https://doi.org/10.3390/su12103953

Lam, J.S.L., 2011. Patterns of maritime supply chains: slot capacity analysis. Journal of Transport Geography 19, 366–374. https://doi.org/10.1016/j.jtrangeo.2010.03.016

Lewis, A., 2016. Towards a Harmonized Framework for Calculating Logistics Carbon Footprint, in: Lu, M., De Bock, J. (Eds.), Sustainable Logistics and Supply Chains, Contributions to Management Science. Springer International Publishing, Cham, pp. 163–181. https://doi.org/10.1007/978-3-319-17419-8_9

Lindstad, H.E., Rehn, C.F., Eskeland, G.S., 2017. Sulphur Abatement Globally in Maritime Shipping.

Lu, B., Fan, L., Wang, J.-J., Li, Y., 2025. Does the EU ETS promote shipping decarbonization? Green investment and sustainability strategies of shipping alliances. Transportation Research Part A: Policy and Practice 199, 104569. https://doi.org/10.1016/j.tra.2025.104569

Lynce de Faria, D., 2024. The EU Emission Trading System Tax Regime and the Issue of Unfair Maritime Competition. Sustainability 16. https://doi.org/10.3390/su16219474

Mao, Z., Ma, A., Zhang, Z., 2024. Towards carbon neutrality in shipping: Impact of European Union's emissions trading system for shipping and China's response. Ocean & Coastal Management 249, 107006. https://doi.org/10.1016/j.ocecoaman.2023.107006

McDonald, L.J., Hernandez Galvan, J.L., Emelue, C., Pinto, A.S.S., Mehta, N., Ibn-Mohammed, T., Fender, T., Radcliffe, J., Choudhary, A., McManus, M.C., 2024. Towards a unified carbon accounting landscape. Phil. Trans. R. Soc. A. 382, 20230260. https://doi.org/10.1098/rsta.2023.0260

McKinnon, A.C., Piecyk, M.I., 2012. Setting targets for reducing carbon emissions from logistics: current practice and guiding principles. Carbon Management 3, 629–639. https://doi.org/10.4155/cmt.12.62

McKinnon, A.C., Piecyk, M.I., 2009. Measurement of CO2 emissions from road freight transport: A review of UK experience. Energy Policy, Carbon in Motion: Fuel Economy, Vehicle Use, and Other Factors affecting CO2 Emissions From Transport 37, 3733–3742. https://doi.org/10.1016/j.enpol.2009.07.007

Mellin, A., Elkerbout, M., Hansson, J., Zetterberg, L., Fridell, E., Christodoulou, A., Woxenius, J., 2020. Including maritime transport in the EU Emission Trading System - addressing design and impacts. https://doi.org/10.13140/RG.2.2.13774.82248

Metzger, D., 2022. Market-based measures and their impact on green shipping technologies. WMU Journal of Maritime Affairs 21, 3–23. https://doi.org/10.1007/s13437-021-00258-8

Mohseni, S.A., Van Hassel, E., Sys, C., Vanelslander, T., 2019. Economic evaluation of alternative technologies to mitigate Sulphur emissions in maritime container transport from both the vessel owner and shipper perspective. J. shipp. trd. 4, 15. https://doi.org/10.1186/s41072-019-0051-8

Nassar, R., Ghisolfi, V., Annema, J., Binsbergen, A., Tavasszy, L.A., 2023. A system dynamics model for analyzing modal shift policies towards decarbonization in freight transportation. Research in Transportation Business & Management 48, 100966. https://doi.org/10.1016/j.rtbm.2023.100966

Notteboom, T., 2020. Roro shipping vs. trucking: revisiting the impact of low-sulphur marine fuel use on cost competitiveness of routing options in north Europe. WMU J Marit Affairs 19, 399–426. https://doi.org/10.1007/s13437-020-00221-z

Oberhofer, P., Dieplinger, M., 2014. Sustainability in the Transport and Logistics Sector: Lacking Environmental Measures. Business Strategy and the Environment 23, 236–253. https://doi.org/10.1002/bse.1769

Olivari, E., Caballini, C., Lluch, X., 2025. How to calculate GHG emissions in freight transport? A review of the main existing online tools. Case Studies on Transport Policy 19, 101343. https://doi.org/10.1016/j.cstp.2024.101343

Park, N.K., Suh, S.C., 2019. Tendency toward Mega Containerships and the Constraints of Container Terminals. Journal of Marine Science and Engineering 7, 131. https://doi.org/10.3390/jmse7050131

Park, S., Lee, H., Kim, D., 2024. Regulatory compliance and operational efficiency in maritime transport: Strategies and insights. Transp. Policy 155, 161–177. https://doi.org/10.1016/j.tranpol.2024.06.024

Pavlenko, N., Comer, B., Zhou, Y., Clark, N., 2020. The climate implications of using LNG as a marine fuel. The climate implications of using LNG as a marine fuel, INTERNATIONAL

COUNCIL ON CLEAN TRANSPORTATION Working paper.

Pelić, V., Bukovac, O., Radonja, R., Degiuli, N., 2023. The Impact of Slow Steaming on Fuel Consumption and CO2 Emissions of a Container Ship. Journal of Marine Science and Engineering 11, 675. https://doi.org/10.3390/jmse11030675

Peng, H., Wang, M., An, C., 2024. Implied threats of the Red Sea crisis to global maritime transport: amplified carbon emissions and possible carbon pricing dysfunction. Environ.Res.Lett. 19. https://doi.org/10.1088/1748-9326/ad59b7

Petro, F., Konečný, V., 2017. Calculation of Emissions from Transport Services and their use for the Internalisation of External Costs in Road Transport. Procedia Engineering, 12th international scientific conference of young scientists on sustainable, modern and safe transport 192, 677–682. https://doi.org/10.1016/j.proeng.2017.06.117

Pruyn, J.F.J., van Hassel, E., 2022. The impact of adding the Northern sea route to the Belt and Road Initiative for Europe: A chain cost approach. Transportation Research Interdisciplinary Perspectives 15, 100659. https://doi.org/10.1016/j.trip.2022.100659

Psaraftis, H.N., 2019. Sustainable Shipping. Paper presented at Maritime and Port Logistics of the MHCL 2019, Bar, Montenegro.

Psaraftis, H.N., 2012. Market-based measures for greenhouse gas emissions from ships: a review. WMU J Marit Affairs 11, 211–232. https://doi.org/10.1007/s13437-012-0030-5

Psaraftis, H.N., Kontovas, C.A., 2013. Speed models for energy-efficient maritime transportation: A taxonomy and survey. Transportation Research Part C: Emerging Technologies 26, 331–351. https://doi.org/10.1016/j.trc.2012.09.012

Reynolds, K.J., 2011. Exhaust Gas Cleaning Systems Selection Guide.

Rogelj, J., Forster, P.M., Kriegler, E., Smith, C.J., Séférian, R., 2019. Estimating and tracking the remaining carbon budget for stringent climate targets. Nature 571, 335–342. https://doi.org/10.1038/s41586-019-1368-z

Santos, F.D., Ferreira, P.L., Pedersen, J.S.T., 2022. The Climate Change Challenge: A Review of the Barriers and Solutions to Deliver a Paris Solution. Climate 10, 75. https://doi.org/10.3390/cli10050075

Schmidtchen, D., Helstroffer, J., Koboldt, C., 2021. Regulatory failure and the polluter pays principle: why regulatory impact assessment dominates the polluter pays principle. Environ Econ Policy Stud 23, 109–144. https://doi.org/10.1007/s10018-020-00285-4

Schramm, H.-J., Lehner, M., 2024. Innovators and transformers: a benchmarking study of online carbon emission calculators for freight transport. International Journal of Physical Distribution & Logistics Management 54, 30–43. https://doi.org/10.1108/IJPDLM-12-2023-0460

Serra, P., Fancello, G., 2020. Towards the IMO's GHG goals: A critical overview of the perspectives and challenges of the main options for decarbonizing international shipping. Sustainability (Switzerland) 12. https://doi.org/10.3390/su12083220

SFC, 2025. Smart Freight Centre - Global Logistics Emissions Council Framework for Logistics Emissions Accounting and Reporting; v3.1 edition, revised and updated (February 2025).

SFC, STC-NESTRA, 2018. GHG Emissions Factors for Inland Waterways Transport.

Shangguan, Y., Tian, X., Jin, Y., Wang, S., 2025. Optimizing carbon emission allocation for liner shipping companies. Computers & Industrial Engineering 208, 111348. https://doi.org/10.1016/j.cie.2025.111348

Sikora, A., 2021. European Green Deal – legal and financial challenges of the climate change. ERA Forum 21, 681–697. https://doi.org/10.1007/s12027-020-00637-3

Sun, L., Wang, X., Hu, Z., Liu, W., Ning, Z., 2024. Carbon reduction and cost control of container shipping in response to the European Union Emission Trading System. Environ. Sci. Pollut. Res. 31, 21172–21188. https://doi.org/10.1007/s11356-024-32434-7

Sun, M., Vortia, M.P., Xiao, G., Yang, J., 2025. Carbon Policies and Liner Speed Optimization: Comparisons of Carbon Trading and Carbon Tax Combined with the European Union Emissions Trading Scheme. Journal of Marine Science and Engineering 13, 204. https://doi.org/10.3390/jmse13020204

Sun, Y., Zheng, J., Han, J., Liu, H., Zhao, Z., 2022. Allocation and reallocation of ship emission permits for liner shipping. Ocean Eng. 266. https://doi.org/10.1016/j.oceaneng.2022.112976

Sun, Y., Zheng, J., Yang, L., Li, X., 2024. Allocation and trading schemes of the maritime emissions trading system: Liner shipping route choice and carbon emissions. Transport Policy 148, 60–78. https://doi.org/10.1016/j.tranpol.2023.12.021

Talley, W.K., 2014. Maritime transport chains: carrier, port and shipper choice effects. International Journal of Production Economics 151, 174–179. https://doi.org/10.1016/j.ijpe.2013.10.009

Tanaka, H., Okada, A., 2019. Effects of market-based measures on a shipping company: Using an optimal control approach for long-term modeling. Research in Transportation Economics 73, 63–71. https://doi.org/10.1016/j.retrec.2019.01.006

Tongzon, J., Chang, Y.-T., Lee, S.-Y., 2009. How supply chain oriented is the port sector? International Journal of Production Economics 122, 21–34. https://doi.org/10.1016/j.ijpe.2009.03.017

Tran, N.K., Lam, J.S.L., 2022. Effects of container ship speed on CO2 emission, cargo lead time and supply chain costs. Research in Transportation Business & Management 43, 100723. https://doi.org/10.1016/j.rtbm.2021.100723

Traub, J., Morillas, C., Gil, R., Álvarez, S., Martínez, S., 2025. Evaluating Corporate Carbon Emissions Reporting: Assessing Transparency and Completeness with the Carbon Integrity Index. Sustainability 17, 7628. https://doi.org/10.3390/su17177628

Trio, W., Lanfranco, J., 2025. COUNT EMISSIONS EU.

Trosvik, L., Brynolf, S., 2024. Decarbonising Swedish maritime transport: Scenario analyses of climate policy instruments. Transp. Res. Part D Transp. Environ. 136. https://doi.org/10.1016/j.trd.2024.104457

Tu, H., Liu, Z., Zhang, Y., 2024. Study on Cost-Effective Performance of Alternative Fuels and Energy Efficiency Measures for Shipping Decarbonization. JMSE 12, 743. https://doi.org/10.3390/jmse12050743

Tuladhar, S.D., Mankowski, S., Bernstein, P., 2014. Interaction Effects of Market-Based and Command-and-Control Policies. The Energy Journal 35, 61–88. https://doi.org/10.5547/01956574.35.SI1.4

UNCTAD, 2024. Review of Maritime Transport 2024: Navigating maritime chokepoints.

UNFCC, 2015. Adoption of the Paris Agreement, In United Nations Climate Change Secretariat (UNFCCC). FCCC/CP/2015/L. 9/Rev. 1. New York, NY, USA.

US EPA, 2024a. SmartWay Air Carriers: Tools and Resources.

US EPA, 2024b. SmartWay Rail Carrier Tools and Resources.

US EPA, 2024c. SmartWay Truck Carrier Partner Resources.

US EPA, 2023. SmartWay Barge Carrier: Tools and Resources.

Vaca-Cabrero, J., González-Cancelas, N., Camarero-Orive, A., Corral, M.M.E.-I., Ricci, S., 2024. Economic Impact of the Application of the ETS to European Ports: Analysis of Different Scenarios. Sustainability 16. https://doi.org/10.3390/su162310433

Van Hassel, E., Meersman, H., Van De Voorde, E., Vanelslander, T., 2016. Impact of scale increase of container ships on the generalised chain cost. Maritime Policy & Management 43, 192–208. https://doi.org/10.1080/03088839.2015.1132342

van Hassel, E., Vanelslander, T., Neyens, K., Vandeborre, H., Kindt, D., Kellens, S., 2022. Reconsidering nearshoring to avoid global crisis impacts: Application and calculation of the total cost of ownership for specific scenarios. Research in Transportation Economics, Disruption of global and regional supply-chains in the aftermath of Covid-19 pandemic. Analyses and forecasts 93, 101089. https://doi.org/10.1016/j.retrec.2021.101089

Vitiello, D.M., Serra, P., Fancello, G., 2026. Inclusion of the Maritime Sector in the European ETS: Analysing Future Impacts Using MRV Data, in: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Faginas Lago, M.N., Scorza, F., Braga, A.C. (Eds.), Computational Science and Its Applications – ICCSA 2025 Workshops. Springer Nature Switzerland, Cham, pp. 29–43.

Wan, Z., el Makhloufi, A., Chen, Y., Tang, J., 2018. Decarbonizing the international shipping industry: Solutions and policy recommendations. Marine Pollution Bulletin 126, 428–435. https://doi.org/10.1016/j.marpolbul.2017.11.064

Wang, J., Zhang, B., Zhu, Q., Liu, J., 2025. Emission surcharge in the European Union Emissions Trading System: A competitive analysis for shipping companies. Transportation Research Part E: Logistics and Transportation Review 202, 104338. https://doi.org/10.1016/j.tre.2025.104338

Wang, T., Cheng, P., Wang, Y., 2025. How the establishment of carbon emission trading system affects ship emission reduction strategies designed for sulfur emission control area. Transport Policy 160, 138–153. https://doi.org/10.1016/j.tranpol.2024.11.006

Wang, T., Wu, Z., Cheng, P., Wang, Y., 2024. The effect of carbon quota allocation methods on maritime supply chain emission reduction. Transport Policy 157, 155–166. https://doi.org/10.1016/j.tranpol.2024.08.011

Weitzman, M.L., 1974. Prices vs. Quantities, The Review of Economic Studies 41 (4): 477–491.

Wild, P., 2021. Recommendations for a future global CO2-calculation standard for transport and logistics. Transportation Research Part D: Transport and Environment 100, 103024. https://doi.org/10.1016/j.trd.2021.103024

World Bank, 2023. State and Trends of Carbon Pricing 2023. Washington, DC: World Bank. doi: 10.1596/978-1-4648-2006-9. License: Creative Commons Attribution CC BY 3.0 IGO.

World Meteorological Organization, 2025. State of the Global Climate 2024 (WMO-No. 1386). Geneva, 2024.

Wu, J., Liu, J., Li, N., 2024. The evasion strategy options for competitive ocean carriers under the EU ETS. Transportation Research Part E: Logistics and Transportation Review 183, 103439. https://doi.org/10.1016/j.tre.2024.103439

Wu, P.-C., Lin, C.-Y., 2021. Cost-Benefit Evaluation on Promising Strategies in Compliance with Low Sulfur Policy of IMO. Journal of Marine Science and Engineering 9, 3. https://doi.org/10.3390/jmse9010003

Xing, H., Spence, S., Chen, H., 2020. A comprehensive review on countermeasures for CO2 emissions from ships. Renewable and Sustainable Energy Reviews 134, 110222. https://doi.org/10.1016/j.rser.2020.110222

Yılmaz Uğur, C., 2022. The Polluter Pays Principle within the Framework of the European Union Emissions Trading System. Abant Sosyal Bilimler Dergisi. https://doi.org/10.11616/asbi.1102031

Zhang, J., Zhang, Z., Liu, D., 2025. Optimization of Carbon Emission Reduction Investment for Replacement Fuel Ships Based on the Shipowners' Perspective. Atmosphere 16, 141. https://doi.org/10.3390/atmos16020141

Zhang, Z., Hu, G., Mu, X., Kong, L., 2022. From low carbon to carbon neutrality: A bibliometric analysis of the status, evolution and development trend. Journal of Environmental Management 322, 116087. https://doi.org/10.1016/j.jenvman.2022.116087

Zhen, L., Hu, Z., Yan, R., Zhuge, D., Wang, S., 2020. Route and speed optimization for liner ships under emission control policies. Transportation Research Part C: Emerging Technologies 110, 330–345. https://doi.org/10.1016/j.trc.2019.11.004

Zhou, R., Luo, M., Jiang, C., Yang, D., Wang, K., 2025. How does emission allowance allocation affect shipowners' selection of emission reduction technologies? Transportation Research Part D: Transport and Environment 139, 104573. https://doi.org/10.1016/j.trd.2024.104573

Zhu, L., 2023. Some thoughts on application of the polluter pays principle for controlling marine greenhouse gas emissions. Marine Policy 158, 105877. https://doi.org/10.1016/j.marpol.2023.105877

Zhu, L., Li, X., 2025. Identifying Key Polluters: The Feasibility of Applying the Polluter Pays Principle to Marine Greenhouse Gas Emissions. Transnational Environmental Law 14, 365–391. https://doi.org/10.1017/S2047102524000372

Zis, T.P.V., Psaraftis, H.N., Tillig, F., Ringsberg, J.W., 2020. Decarbonizing maritime transport: A Ro-Pax case study. Research in Transportation Business & Management 37, 100565. https://doi.org/10.1016/j.rtbm.2020.100565

Sitography

https://bigmile.eu/
https://www.carboncare.org
https://www.ecotransit.org/en/methodology/
https://www.greenrouter.it/
https://www.tkblueagency.com/en/
https://www.icao.int/environmental-protection/environmental-tools/icec
https://www.greenfreightasia.org/
https://europeanshippers.eu/projects/past-projects/green-freight-europe/
https://www.epa.gov/smartway
https://ourworldindata.org/grapher/ghg-emissions-by-sector?overlay=download-vis
https://ourworldindata.org/grapher/ghg-emissions-by-gas