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Sustainable Supply Chain Transportation

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Abstract

Freight transportation, both in Europe and globally, contributes significantly to the global CO_2 emissions. The current state of freight transportation, both in Europe and worldwide, is undeniably unsustainable. Various stakeholders, including NGOs, policymakers, governments, industries, and consumers, are taking action to establish environmentally conscious transportation networks. Despite initiatives targeting carbon neutrality by 2050, concerns about their sufficiency remain. In this thesis, the future trajectories and emission factors for different transportation modes were assessed based on available data on emissions, fuel consumption, policies, and emerging technologies. In this thesis, we could conclude that all modes of transport are committing to decarbonise by usage of less carbon-intensive fuels and more efficient power trains. Air cargo is likely to see reduced emissions due to the uptake of more Sustainable Aviation Fuel (SAF) and e-kerosene usage. Road freight and shipping are introducing new technologies such as hydrogen, e-fuel, and electric power trains to do the same. Whereas railways are focusing on electrification and grid decarbonization to reduce their carbon intensity while promoting their usage. In terms of general emission-reduction methods in this study, modal shift and intermodal transportation has emerged as crucial aspect in increasing efficiency and lowering emissions where lesser carbon-intensive modes such as railway and shipping. The report emphasizes the importance of system-based solutions, optimization, and digitization in bridging the gaps between diverse modes of transportation. The report also highlights other gaps or obstacles in the current freight transportation system in Europe to help stakeholders overcome obstacles, take advantage of opportunities, and transition smoothly to sustainable freight transportation.

Keywords Freight transport, policies, regulations, emission factor.

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Abbreviations

IEA	International Energy Agency
ITF	International Transport Forum
GHG	Greenhouse gas
IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
SEEMP	Ship Energy Efficiency Management Plan
ICAO	International Civil Aviation Organization
UN	United Nations
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
IATA	International Air Transport Association
UNFCCC	United Nations Framework Convention on Climate Change
GLEC	Global Logistics Emissions Council
CDP	Carbon Disclosure Project
EU	European Union
EPA	Environmental Protection Agency
PM	Particulate matter
NOx	Nitrogen oxides
AFIR	Alternative Fuels Infrastructure Regulation
SERA	Single European Railway Area
ERTMS	European Railway Traffic Management System
CII	Carbon intensity indicator
EEXI	Energy Efficiency Existing Ship Index
RFBNO	Renewable fuels of non-biological origin
tkm	Tonnes-kilometre
CAF	Conventional aviation fuel
SAF	Sustainable aviation fuel
HDV	Heavy duty vehicles
LNG	Liquified natural gas
CNG	Compressed natural gas
FCEV	Fuel cell electric vehicle
ICE	Internal combustion engine
ZEV	Xero emission vehicle
RED	Renewable Energy Directive
FAME	Fatty Acid Methyl Ester
SERA	Single European Railway Area
WTW	Well-to-wheel
WTT	Well-to-tank
TTW	Tank-to-wheel

1 Introduction

Since industrialisation, international trade has grown at an exponential rate, having a significant impact on the global supply chain. As more products were available for trade, the demand for more cost-effective, efficient, and dependable modes of transportation grew. With time due to globalization and regional fragmentation of product production and material sourcing, complicated extended supply chains have emerged. The supply chain today spans countries and continents and employs many forms of transportation such as roads, trains, aeroplanes, and waterways. However, the tremendous growth associated with this sector has come with a significant environmental cost. As seen in Figure 1, according to the International Energy Agency (IEA) report, the transportation sector accounts for nearly 23 per cent of the global carbon dioxide emission. Furthermore, the emissions solely from freight transport today, excluding emissions from warehouses and ports, represent about 8% of global carbon emissions [1]. According to the International Transport Forum (ITF) Transport Outlook 2021, freight transport is predicted to expand 2.6-fold by 2050 [2].

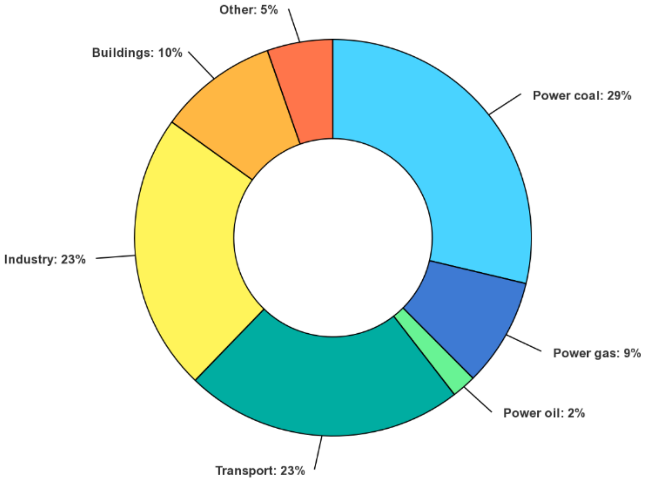


Figure 1 Sector-wise CO2 emission [3]

Unlike most other sectors, the majority of freight transportation, whether aviation, land, or maritime, continues to rely on fossil fuels and is one of the most difficult sectors to decarbonize due to limited possibilities. For example, freight ships, mainly run on fuel oil and release significant volumes of CO_2 as well as other pollutants like sulphur dioxide (SO_2) and nitrogen oxides (NO_x). Air cargo/freight, which is predominantly powered by jet fuel, also adds significantly to emissions. Lastly, road freight although has seen a relatively large amount of effort in decarbonization, still relies on diesel fuel, which emits significant amounts of CO_2 and particulate matter.

Furthermore, both the Paris Agreement and the European Green Deal emphasize global and regional pledges to decarbonize the transportation sector, particularly freight transportation. These efforts provide a forum for governments, organizations, and stakeholders to work together to reduce emissions, promote sustainable practices, and stimulate innovation in the transportation industry as a whole. Following this, several countries and international organizations implemented regulations to reduce emissions related to global freight transportation, as well as steps to create frameworks that support sustainability and the adoption of cleaner technologies.

1.1 Research Objectives

The purpose of this thesis is to provide a thorough sustainable supply chain transportation by looking at the current global supply chain, identifying problems, and exploring potential future trends and technology. In this study, we describe the key driving factors of CO_2 emissions from freight transport.

- Identify the policies and regulations that affect the emission in railways, roadways, airways, and waterways in 2025 and 2030.
- Scanning all new technologies that aid in emission reduction in all modes and analysing the market development.

1.2 Scope and Limitation

This study was conducted and completed within a span of five to six months. To ensure the successful completion of this thesis within the limited time, certain constraints were imposed to narrow down the scope of this otherwise vast topic.

To simplify the scope, total GHG emissions from transportation were measured in CO_2e to include other harmful gases such as nitrogen oxides (NO_X) or other sulfur compounds. The research conducted included new technologies, energy sources, policies, and regulations discovered during the research. It is probable that some elements were overlooked, since this industry is quite dynamic, with new legislation and technologies being introduced on a regular basis. As a result, there is a possibility that inaccurate or outdated assumptions are being used in this study.

2 Theoretical Background

2.1 Global emission

Global freight transport emissions are divided into two categories: direct and indirect emissions. Direct emissions are caused by the combustion of fossil fuels such as diesel or gasoline, which power vehicles, ships, and planes that transport goods. Indirect emissions, on the other hand, are created by the production of these fuels as well as the manufacture of automobiles and transportation infrastructure. Figure 2 shows the global direct CO_2 emissions from transport.

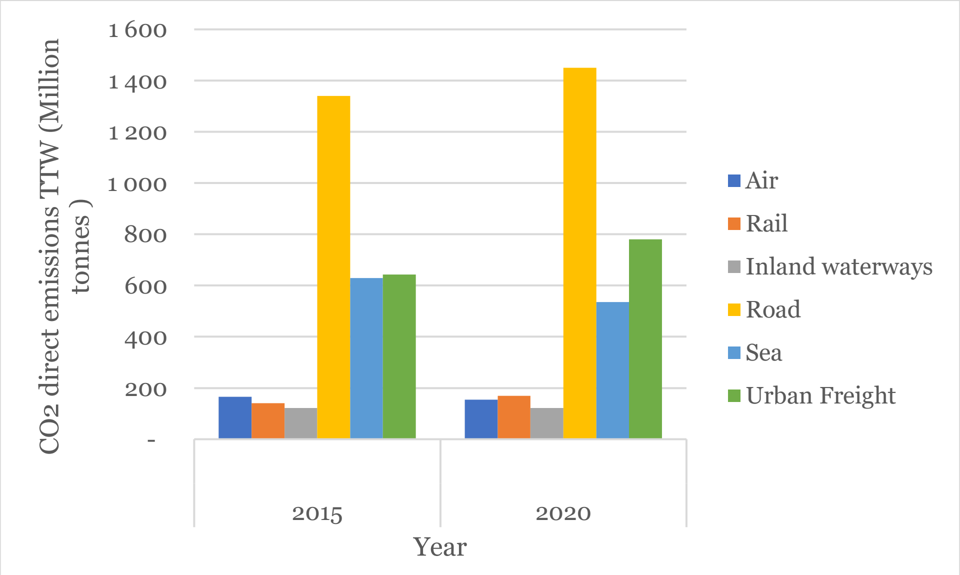


Figure 2 Global direct CO_2 emissions from transport [2]

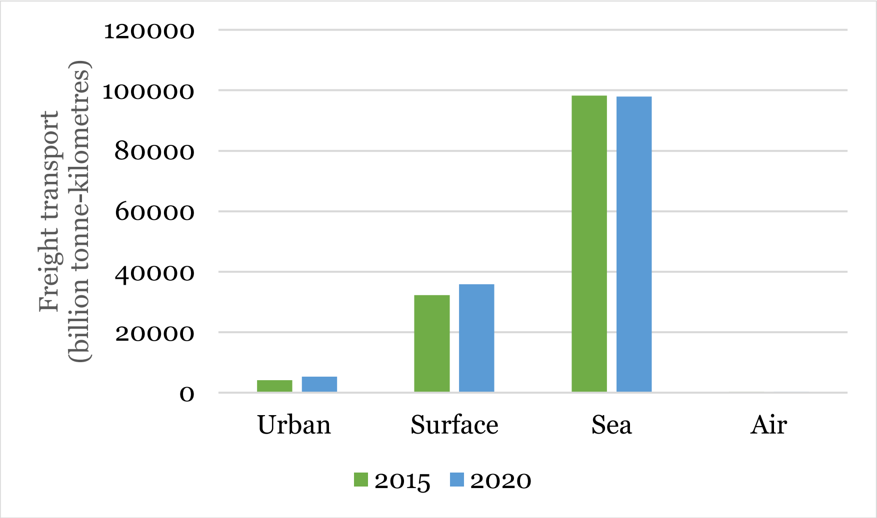
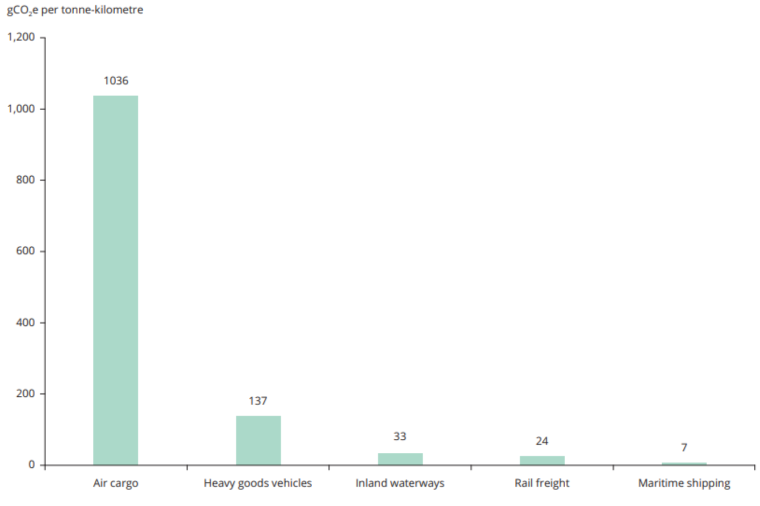


Figure 3 Global demand for freight transport by mode [2]

Road, sea, and air freight are the primary sources of emissions from worldwide freight transport. Figure 3 shows the global demand for freight transport by mode urban, surface (road, railway and inland waterways), maritime and air.



Source: EEA (2021h).

Figure 4 Average GHG emissions (gCO$_2$e per tonne-km), well-to-wheel, for freight transport in the EU [4]

Road transport contributes the most to emissions, accounting for roughly 65% of freight transport emissions as its emission per ton-km is high [1][4]. ITF also suggests that road freight is expected to continue to outnumber other surface modes of transport and may more than double in 2050 compared to 2015 and can be responsible for more than an additional 15% of the emission [2][5].

Sea transport is the second-largest contributor to emissions, accounting for approximately 20-25% of freight transport emissions [2]. Ships burn heavy fuel oil, which is a high-polluting fuel that emits sulphur oxides, nitrogen oxides, and particulate matter. The International Maritime Organization (IMO) has implemented regulations to reduce emissions from ships, including a cap on sulphur content in fuel.

Air freight transport is the smallest contributor to emissions, accounting for approximately 2% of freight transport emissions but they also happen to account for less than 1% of the goods transported [6][7]. However, air transport emissions have a higher impact on the environment due to their altitude as other gas emissions, such as NOx, react with other atmospheric gases to have a larger climate impact [8]. The aviation industry is working to reduce emissions through the use of biofuels, electric planes, and improved air traffic management.

2.2 Monitoring and Reporting of GHG Emissions in Freight Transport

The first step in lowering emissions in any industry is to accurately monitor and record them to better understand the source of the emissions and discover carbon reduction opportunities to combat climate change. Currently, several organizations and initiatives around the world at national and international levels have been playing a play crucial role in monitoring, reporting, and assessing the GHG emissions in the transportation of freight. This section investigates who and how these emissions are monitored and reported internationally. The most widely used method for monitoring GHG emissions is the Greenhouse Gas Protocol (GHG Protocol), which provides guidelines for calculating emissions from various sources [9].

2.2.1 International Organizations and Initiatives

Several organizations and initiatives track and report GHG emissions from freight transportation. The International Transport Forum (ITF) is a non-profit organization that serves as a think tank for transportation policy research and analysis [10]. The ITF has published reports on worldwide maritime, aviation, and land transport GHG emissions. The papers detail trends, sources, and initiatives for lowering emissions in various industries. They also offer a database with statistics and information on freight and passenger transportation networks, road safety, traffic, vehicle technology, fuel use, and infrastructure [11].

The International Maritime Organization (IMO) is a United Nations-specialized organization that oversees shipping. To monitor and minimize emissions from ships, the IMO's Marine Environment Protection Committee (MEPC) has adopted standards such as the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) [12][13]. The IMO has enacted restrictions to limit ship emissions, including a sulphur content cap in gasoline. The IMO also requires ships to report their fuel use and energy efficiency.

International Civil Aviation Organization (ICAO): The ICAO, a UN agency, regulates international aviation, especially air cargo transit [14]. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was established by the organization to monitor and offset CO_2 emissions from international flights [15]. All airlines are expected to publish their emissions statistics annually under this scheme.

Another international trade group that represents airlines is the International Air Transport Association (IATA). It is a trade association that has set a goal of reducing net aviation emissions to half of 2005 levels by 2050. To minimize emissions, the IATA also supports the development of alternative fuels and enhanced air traffic management.

UN Framework Convention on Climate Change (UNFCCC): It is an international convention aimed at preventing dangerous anthropogenic interference with the climate system. The Paris Agreement offers a structure for countries to monitor, report, and verify their GHG emissions under the pact. Countries must submit to the UNFCCC regular national inventories of emissions, including those from freight transportation [16].

Global Logistics Emissions Council (GLEC): It is a collaboration of prominent firms, industry associations, and specialists working to create a global framework for logistics emissions accounting and reporting. The framework was developed by GLEC to give rules for enterprises to measure and report emissions in their logistics activities, including freight transport [17].

Carbon Disclosure Project (CDP): The CDP is a global nonprofit organization that collects and disseminates environmental data from corporations all over the world. It is one of the most important reporting frameworks for GHG emissions. It encourages businesses, notably those involved in freight transportation, to publish their emissions and climate-related actions [18], [19]. CDP data helps investors, customers, and policymakers make informed decisions.

In addition to the multiple organisations, there are also individual companies that monitor and report their emission in freight transport. In some case, there are more than one international organization that does the same in the same region.

2.3 Modal Choice and importance of modal share

The modal mix is the share of different modes of transportation, such as road, sea, and air to deliver freight. Freight mode selection and intermodal mix are crucial factors in determining emissions from goods transportation. The use of certain modes of transportation and the integration of numerous modes through multimodal transportation can have an impact on emissions in both positive and negative ways.

Several variables influence freight transportation mode selection, including distance, geographic location of the destination, type of good (weight, volume, cost, perishability and so on), cost of transport, transit time, reliability, flexibility, and availability [20][21]. All these factors have varying levels of effect on the choice of mode. For transportation within countries depending on the region and the country’s geography they would have different modal shares. As seen in Figure 5 EU has a higher share of road transport (nearly 70%) whereas in the US the road and railway have nearly an equal share. Similarly different countries within Europe could have different shares of various modes.

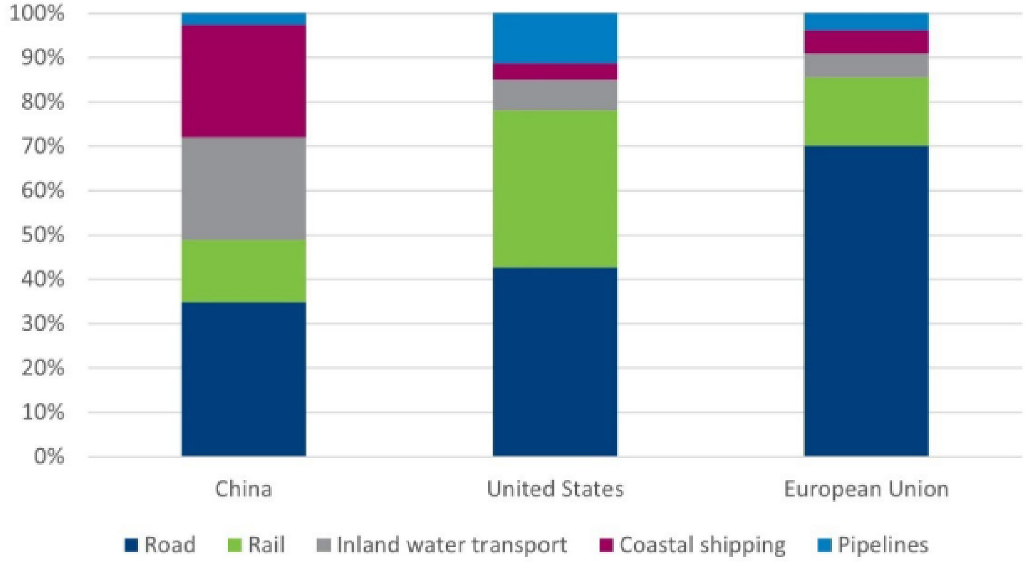


Figure 5 Modal shares in freight transport (in percentage of tonne-km) in 2018 [20]

Here's how freight mode selection and intermodal mix might affect emissions:

1. Modal shift: Modal shift, or the change from one mode of transport to another, is an important strategy in reducing the emissions from freight transport. Eom et al. [22] analysed the trends in road freight emissions and found that in the industrialized countries studied in their research, switching from trucks to rail freight presents a significant potential to cut down on freight CO_2 emissions. Similarly, LAN et al. [23] investigated the effects of modal shifting from road and air transport to rail transit and determined that modal shifting would result in a 14.5% reduction in carbon dioxide emissions.

2. Energy Efficiency: The energy efficiency of various means of transportation varies, resulting in variable emission levels. Trucks, for example, use more fuel than railroads or ships, resulting in higher emissions [20]. As a result, choosing modes with higher energy efficiency and lower emissions per unit of commodities moved can help reduce overall freight transport emissions and cost in some cases [24], [25].

3 Research material and methods

The methodology adopted for this thesis was a comprehensive literature review where required data was collected from online sources and other databases rather than solely relying on academic literature. This approach was used as the topic of this thesis is a highly dynamic and rapidly evolving field, where practical applications often outpace the pace of traditional academic research in some cases.

3.1.1 Research Design

Data related to the emissions from freight movement was collected to estimate the emissions in 2025 and 2030 for roadways, airways, waterways, and railways. For each of the modes the study aimed to gather data from various online sources, while identifying several factors that affect the emission and these factors were used to estimate the emission in the future. After understanding the current state of play the findings were tabulated, and subsequently used to determine the possible trends.

3.1.2 Data Collection

The collection of the theoretical evidence was done by identifying a set of relevant online sources, journals, databases, industry reports, non-governmental organisations, and government publications. This was done by searching for keywords and phrases related to the topic of freight emissions, energy sources and transportation technology.

Academic databases were used to access peer-reviewed journal articles, conference papers, and dissertations, including PubMed, IEEE Xplore, Google Scholar, and Elsevier. These sites provided extensive research on emissions, energy sources, and technical advances in freight transportation.

Industry Reports: To acquire complete data on emissions, energy use, and technology trends, reports published by industry organizations, research institutions, and consulting firms were analysed. Some of these include Airbus, Maersk, DHL, the European Automobile Manufacturers' Association and so on.

Governmental Publications: Government agencies and departments, such as Environmental Protection Agencies (EPA) and the Department of Transport in the UK, published reports, guidelines, and policy documents related to emissions and energy use in freight transport. These sources offer official data, regulations, and initiatives pertaining to the sector.

Relevant Websites: Websites of international organizations like the ITF, IEA, IMO, ICAO, and UNFCCC were some of the other sources used for official documents, databases, and guidelines on emissions monitoring, reporting, and mitigation strategies.

3.1.3 Data Selection and Tabulation

The necessary data was collected from only relevant reliable sources from 2010 onwards. To ensure accuracy and consistency, the collected data was examined, cleaned, and standardized. Irrelevant or duplicate data was deleted, and the remaining data were put in a table in a structured manner, taking into account critical variables such as emission kinds, modes of transportation, geographic locations, and time frames.

3.1.4 Data Analysis

Thematic and content analysis was applied to identify common themes, emerging trends, and qualitative insights related to emissions, energy sources, and technological advancements. Furthermore, using this information, along with certain assumptions, emissions and technology projections were made for the years 2025 and 2030.

Emission calculation: Emissions calculations for the years 2025 and 2030 were made using the collected data. Based on projected changes in the sector, technical breakthroughs, policy developments, and the use of cleaner energy sources, assumptions and projections were created.

Technology Assessment: The analysis also involved an assessment of the technological landscape in freight transport. Data on existing technologies, ongoing research, and emerging innovations were considered to gauge the potential technological advancements that could contribute to emissions reduction in the future. By analysing the data and understanding the current state of technology, projections were made regarding the potential adoption of these technologies by 2025 and 2030.

4 Research findings and discussion

4.1 Transport emission reduction initiatives

European Green Deal is a roadmap designed by the EU parliament which has set targets to reduce emissions by 55% in 2030 and become carbon neutral by 2050. Through this deal, by 2050 it plans to reduce emissions related to transport by 90%. To do so the EU Commission in 2021 proposed legislation known as 'Fit for 55' that reduces emissions in many sectors including the transportation sector [26][27].

The Sustainable and Smart Mobility Strategy was announced in 2020. It outlines the vision and goals for the future to develop a well-connected Europe and compliments the European Green Deal of reaching carbon neutrality by 2050. It has a total of 82 initiatives focusing on the future of transport being more sustainable, smart, and resilient [28].

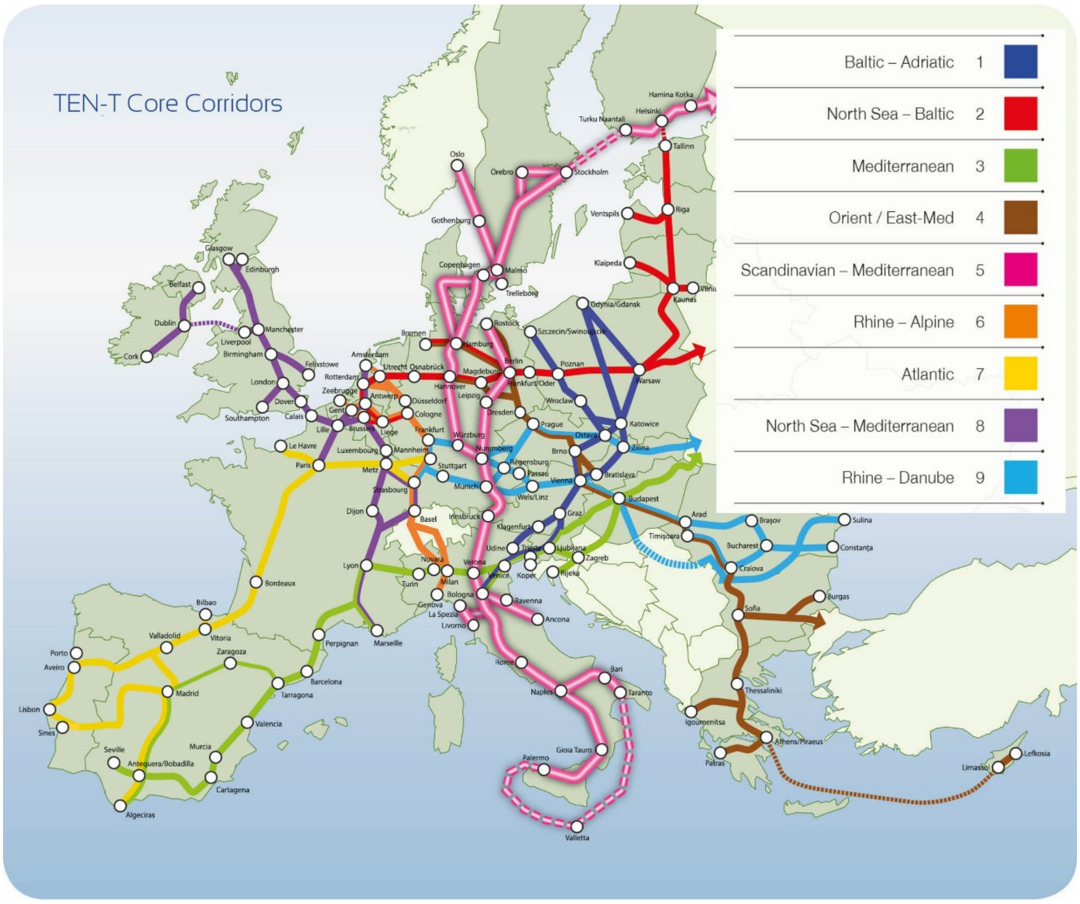


Figure 6 The 9-corridor network of the core TEN-T network [29]

The Trans-European Transport Network (TEN-T) policy aims to develop a comprehensive multimodal transport network across the EU. It includes provisions for enhancing transport (rail, water, waterway and maritime) infrastructure, improving connections, and facilitating efficient and sustainable freight transport. It has 9 main corridor networks that provide good connectivity to the majority of Europe (Figure 6) [30][31].

The Alternative Fuels Infrastructure Regulation (AFIR) goal is to ensure the development of an adequate and effective network of alternative fuel infrastructure for road vehicles, aircraft, and maritime vessels by setting technical specifications [32].

The Connecting Europe Facility (CEF) program provides funding for transport-related infrastructure to improve connectivity, sustainability, and interoperability in the European transport network. It supports initiatives aimed at reducing emissions and promoting sustainable freight transport [33].

The Renewable Energy Directive (RED) establishes targets for the inclusion of renewable energy sources, including transportation fuels, in the EU's energy mix. In 2023 it set the European renewable energy target of a minimum of 42.5% by 2030 but targeting 45% [34].

The RED II directive states that all states must account for 14% of their energy consumed in road and rail transport from a renewable source [35]. It also specifies GHG emission saving threshold for transport biofuel. Since 2021 only biofuels with emission reduction greater than 65% can be labelled as biofuel and used in transportation. It also specifies that biofuels produced from ANNEX IX part B of the directive should be limited to a maximum of 1.7% and the rest should be produced from the feedstock mentioned in ANNEX IX part A [36]. It has also established a set of GHG emissions and sustainability guidelines to be followed for biofuels used in transportation. Annex V (for liquid biofuels) and Annex VI (for solid and gaseous biomass for power and heat production) of the RED II contain default GHG emission levels and calculation methodology [35].

The Energy Taxation Directive (ETD) is a directive of the EU that has provided a framework for the taxation of energy products within member states for many sectors including transport. The tax rates are based on the energy content and the environmental impact of the fuel. The directive's main purpose is to promote energy efficiency and sustainability by standardizing energy pricing policies in the EU [37]. It has the potential to encourage the update of sustainable technology and practices.

4.2 Aviation

Global airfreight plays a minor role in the global freight industry, accounting for less than 1% of total freight activity measured in tonne-kilometres [2]. This can be explained by the fact that air transportation is largely used for the transfer of high-value and lightweight goods [38], [39]. Given its efficiency in delivering such commodities, it has become the favoured choice for sectors that require the safe and fast delivery of their pricey and short-lived products across international borders. Other industries that favour this approach include those with high competition, sales, and monthly demand fluctuation [40].

However, air cargo is by far the most carbon-intensive mode of freight transport. In 2019 alone all commercial flights globally emitted approximately one billion tons of CO_2 ($GtCO_2$), equalling Japan's total domestic emissions [41]. According to estimates by the ITF based on data from the IEA, airfreight emissions are approximately 20 times higher than the average emissions of the entire freight sector per tonne-kilometre [2]. It is considered one of the most challenging sectors to decarbonize and is predicted to increase at a 4% annual rate through 2050. The decarbonization of this sector is hampered by the long life of aeroplanes and the slow advancement of technology that can withstand its harsh working conditions [42].

As the global freight industry continues to evolve, finding a balance between the benefits of airfreight and its environmental impact becomes increasingly important. Efforts are being made to explore innovative technologies and sustainable practices to reduce carbon emissions associated with air cargo. Additionally, some businesses are reevaluating their transportation strategies, optimizing supply chains, and adopting greener alternatives wherever feasible, aiming to strike a balance between the need for efficient logistics and the imperative to mitigate climate change.

4.2.1 The current state of play

Aviation fuels are more specialized and controlled when compared to fuel used in other applications. To assure the engine's safety at high altitudes, they are inspected further with extra specifications about additives, density, boiling range, flash point, thermal stability, and many more [43]. Currently, there are two types of fuels conventional and sustainable aviation fuel. Conventional aviation fuel (CAF) consists of AVGAS and Jet fuel.

AVGAS also known as aviation gasoline is used in piston aircraft and light helicopters [44]. The fuel is very hazardous as lead is used to produce the high-octane levels required to prevent engine knock, particularly in high-power plane engines. For environmental and economic reasons, many countries have abandoned this fuel [45].

Jet Fuels are used to power gas-turbine engines or CI engines. The majority used in aviation is jet fuel namely, Jet A (mainly used in the US) and Jet A-1 [46].

Sustainable aviation fuels (SAF) are fuels produced from non-fossil-based sustainable feedstocks. They are considered cleaner as they can burn cleaner and have the potential to be carbon neutral. The estimated current production as of 2019 for sustainable aviation fuels was around 200,000 metric tons (~0.06% of current aviation fuel consumption) [47]. Although nine pathways for SAF production have been approved by ASTM International, the current production uses organic feedstocks and the hydro-processed Esters and Fatty Acids (HEFA) process. More details on the conversion process, technology readiness and commercial projects can be seen in Annex A - Aviation.

4.2.2 Emission

Air freight emissions from different sources for three main different types of flight journeys were collected (more data can be seen in Annex A - Aviation) to form the bar graph shown in Figure 7. All emissions are measured in kg CO_2 per tonne-km. Domestic, short-distance flights tend to have greater emissions as they carry the same weight for a shorter distance and fuel consumed for a km travelled is maximum during take-off and landing [48].

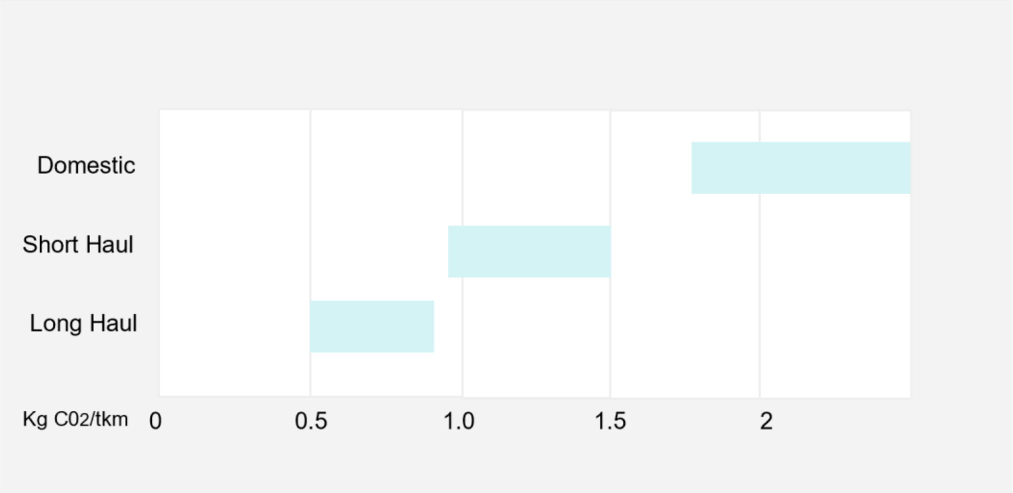


Figure 7 Current Emission Intensity for Air Transport

4.2.3 Aviation's Emission Reduction Landscape

The 'Fit for 55' legislative recommendations were issued in 2021, outlining how the Commission will meet the European Green Deal's target. Some of its policies such as the revised EU Emission Trading Directive, the ReFuelEU Aviation Initiative, the Renewable Energy Directive, and the Renewable Energy Taxation Directive will have an impact on the aviation industry. As part of this package, all EU airports are mandated to use a minimum of 2% of SAF by 2025 and 5% by 2030 [49].

ReFuelEU Aviation: ReFuelEU Aviation, part of the European Green Deal, aims to decrease aviation emissions and transition the industry to a low-carbon future. The primary goal of ReFuelEU Aviation is to promote and encourage the use of Sustainable Aviation Fuels (SAFs) [50]. These are drop-in fuels derived from renewable sources such as waste and agricultural residues, algae, and synthetic processes utilizing renewable energy. SAFs are produced from renewable resources like biomass, trash, or carbon dioxide collected. When compared to traditional jet fuel, they have the potential to lower emissions by up to 80% [51].

Table 1 below shows the fuel share mandate proposed by the European Commission and the Council. In comparison to the Commission proposal, Parliament recommends raising the SAF targets to 85% and 50% synthetic by 2050 [52]. Other proposed requirements include requiring aeroplanes departing from EU airports to fill just the fuel needed for the voyage and for all EU airports to ensure the availability of SAF fuelling infrastructure [53].

Table 1 Sustainable and synthetic aviation fuel mandates [54]

Year	% of Sustainable aviation fuel share	% of Synthetic aviation fuel
2025	2%	-
2030	5%	0.7%
2035	20%	5%
2040	32%	8%
2045	38%	11%
2050	63%	28%

The RED II directive as previously mentioned in section 4.1 provides minimum renewable energy consumption for 2030 and has a feedstock list from which fuels are to be produced. It has also established a set of GHG emissions and sustainability guidelines to be followed for biofuels used in transportation. Annex V (for liquid biofuels) and Annex VI (for solid and gaseous biomass for power and heat production) of the RED II contain default GHG emission levels and calculation methodology [35].

ICAO has set an industry-level goal to obtain a 50% GHG emission reduction by 2050 when compared to 2005 [55]. IATA has also committed to achieving carbon-neutral growth beginning in 2020 and a 50% reduction in global CO_2 emissions by 2050 [56]. To achieve this, they developed a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA intends to mandate that all airlines offset emissions above a certain threshold from 2024 onwards. ICAO also developed a series of Tracker Tools to provide a centralized source of information that is constantly updated with all of the newest CO_2 reduction advances for aviation [57].

The EU Emissions Trading System (EU ETS) is a market-based mechanism that limits the overall quantity of greenhouse gases that this sector can produce. It has proposed imposing a higher reduction cap of 4.2% per year and extending CORISA to non-EEA flights [58]. This system is expected to promote the use of SAF and more efficient flights to reduce emissions.

Table 2 Overview of Aviation's Emission Reduction Landscape

Regulation/Initiatives	**Goals**
AFIR Alternative Fuel Infrastructure Regulation [32]	• All EU airports should provide electricity supply for aircraft at the terminal by 2025
Refuel EU aviation [54]	• Minimum share of supply of sustainable aviation fuel (SAF) - 2% in 2025, 6% in 2030, 20% in 2035 and 63% in 2050. • Airlines departing from the EU are to carry only fuel necessary fuel. • EU airports to guarantee infrastructure for SAF refuelling.
ICAO [59]	Industry goal • to achieve carbon neutrality from 2020 and a 50% GHG emission reduction by 2050 when compared to 2005. • Developed a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA to mandate all airlines to offset emissions above the baseline of 85% of 2019 emissions from 2024 onwards.

4.2.4 Future Outlook

SAF including synthetic aviation fuel or e-kerosene has the highest potential in reducing emissions from air freight transport. Currently, only 0.05% of the total jet consumption is SAF but the EU has mandated that all airports consume SAF share as 2 % from 2025 and 5 % from 2030 (0.7% of the 5% as PtL) [47] [49]. Although electric flights and hydrogen-powered flights may enter the market in the next decade, they will mostly be used to transport passengers and not heavy goods. The only way for hydrogen to be used in aviation is in the form of e-fuels.

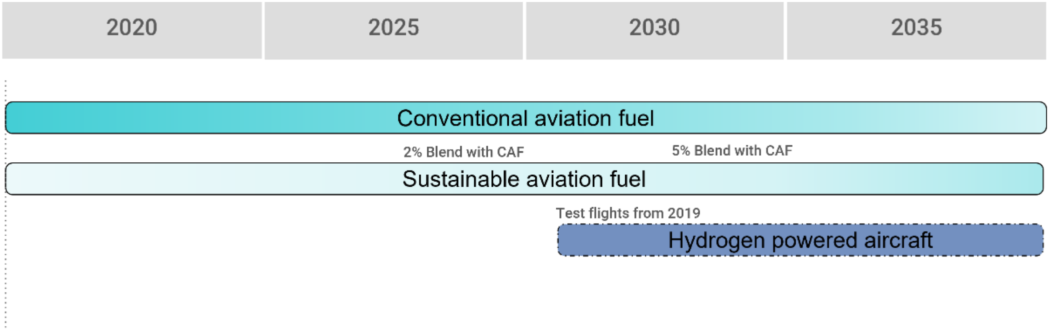


Figure 8 Aviation Future Outlook

Annex A - Aviation provides the methodology using which the emission reduction and emission factor for different types of freight (air freight and belly freight) can be calculated. In the case study calculation, it is observed that with an increase in the distance, the emission factor of the mode of transport decreases significantly. As per this calculation if we assume the same fuel economy as today for 2025 and 2030 in 2025 there would be a 1% reduction in emission per tonne-km assuming all EU airports use 2% SAF with 0.04% synthetic fuel. By 2030 compared to 2019 there would be a 5% emission reduction per tonne-km if all EU airports have a 5% SAF share with 2% accounting for the synthetic fuel. Currently, the use of SAF has a minimum of 65% reduction and synthetic fuels have a 90% reduction in emissions. Naturally, if the fuel economy, emission factor of the fuels and blending are increased, higher emission education can be observed.

4.2.5 Key Takeaways

- Emissions stemming from the group's control, cargo loading, and unloading procedures have not been factored into these calculations. Additionally, increasing payload capacity and optimal flight planning (step climb as opposed to continuous rise) has the potential to reduce emissions per tonne-kilometre.

- Untraceable and unsustainable biomass feedstock for biofuel production has the potential risk of shifting or displacing the emissions to other GHG scopes which could increase the well-to-wheel emission.

- CORSIA represents a step towards addressing aviation's climate impact, as mentioned in Table 2. Since this scheme encourages the industry to offset its emissions, it could potentially undermine the Paris Agreement. Offsetting may not drive the industry to adopt fundamental changes in technology and operations that could otherwise reduce emissions significantly.

4.3 Road

Heavy duty vehicles (HDVs) account for only 2% of vehicles on the road in the EU, yet they account for nearly 30% of road transport carbon emissions and transport 77% of the goods moved on land [60][61]. It is also responsible for roughly one-third of overall CO_2 emissions from transportation. Road transportation in general is one of the most significant causes of particulate matter (PM) and nitrogen oxides (NOx) pollution (around 39% of emissions) [62][63]. Compared to other modes of transport road transport has a higher emission intensity per tonne-kilometre. According to the ITF, road freight emissions will increase from 53% in 2010 to 56% by 2050 but its share will likely fall [64][2].

4.3.1 The current state of play

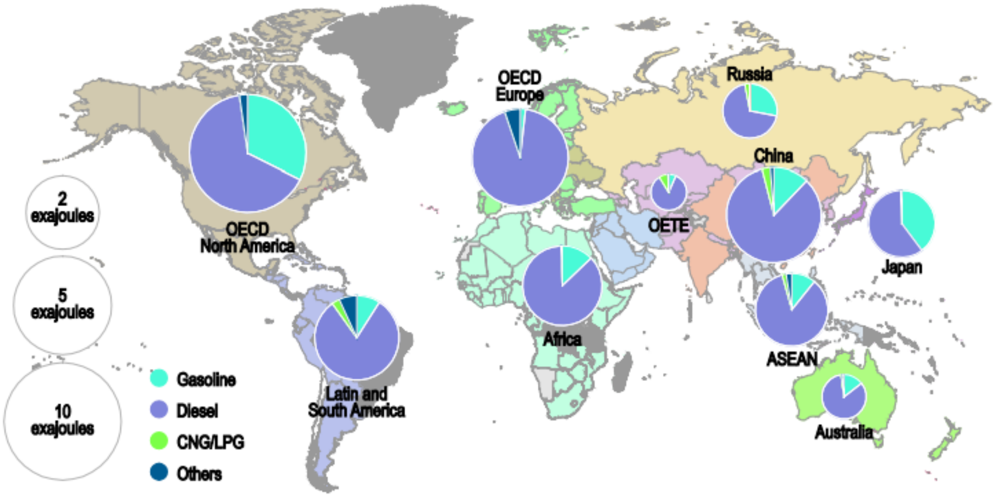


Figure 9 Fuel consumption of road freight [65]

According to an IEA assessment, the majority of the world market including the EU prefer diesel as the source of energy for freight transport Figure 9. Road freight is also one of the modes that have witnessed the most technological advancement in the sector's decarbonization. As a result, the fuels used can have a considerable impact on environmental sustainability.

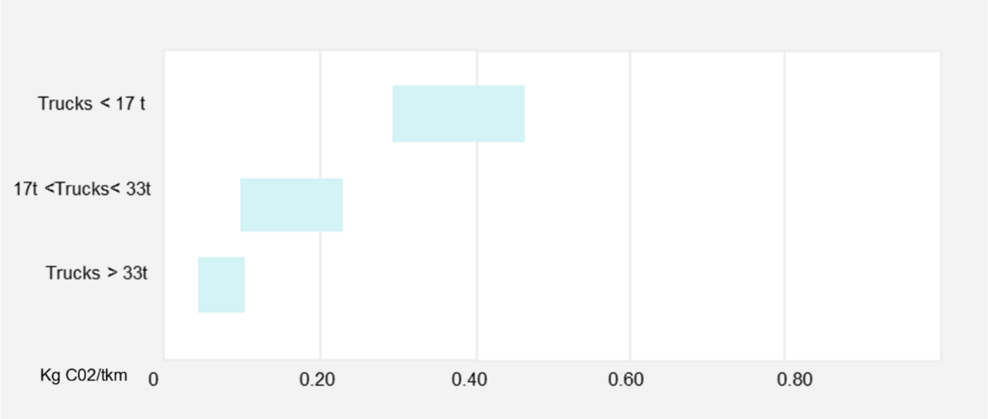


Figure 10 Current Emission Intensity for Road Transport

Road freight transport can be divided into urban freight, regional delivery trucks and long-haul heavy-duty trucks. Although for this study the urban freight was excluded, it produces the highest CO_2 equivalent per tonne-km of all as it transports relatively smaller weight of goods for a shorter distance in a more fuelling consuming driving condition. The current emission intensity for road transport is shown in Figure 10.

Currently, due to diesel's higher energy efficiency than gasoline, the majority of HDVs employ this type of ICE. However, diesel combustion releases several types of pollutants including CO_2, NO_x, and PM. Studies have suggested that diesel engines despite their high emissions will remain a preferred technology in the near future and will continue to be favourable due to their well-established infrastructure and affordability [66]. Gasoline/Petrol on the other hand are more uncommon in road freight in the EU and if used they are mainly used to transport lightweight goods and in some urban freight movement. Although their emissions are much lesser due to their lower fuel efficiency they are very rarely used.

LNG and CNG are alternative fuels utilized in road freight in the EU. LNG is natural gas that has been liquefied by being cooled to -162 degrees Celsius and CNG is natural gas that has been compressed to a pressure of 200 to 250 bar [67]. Both LNG and compressed natural gas (CNG) have several advantages over typical diesel fuel. They burn cleaner, which means they emit fewer pollutants such as nitrogen oxides (NOx), particulate matter (PM), and carbon monoxide (CO). They are also more efficient than diesel fuel, therefore they can aid with fuel economy. [68], [69].

Biodiesel, a diesel alternative that is made from renewable resources that include vegetable oils and animal fats, is a more environmentally friendly option. It can be combined with conventional diesel or utilized in its pure form in some engines, lowering carbon emissions and increasing resource efficiency [70]. RED II directive has also specified feedstocks from which biofuels are produced in its ANNEX IX [36].

Bioethanol is an environmentally friendly substitute for gasoline-powered vehicles and is usually blended with conventional fuels. It reduces overall CO_2 emissions when compared to traditional gasoline, but it may require large agricultural resources, raising questions about food versus fuel depending on the feedstock used for its production [71].

Electric trucks powered by lithium-ion batteries are gaining traction as the EU endeavours to decarbonize road freight. BEVs have zero tailpipe emissions, which reduces local air pollution and reliance on fossil fuels [72][73]. A typical battery freight vehicle has a range of 200-500 kilometres on a single charge [74]. However, their adoption faces challenges related to range limitations, charging infrastructure, and the carbon intensity of electricity generation.

Hydrogen-powered trucks of two kinds of hydrogen internal combustion vehicles (H2-ICE) and fuel cell vehicles (FCEV). H2-ICE trucks combust hydrogen and are more efficient than diesel trucks, but they still produce small amounts of NOx and CO_2 emissions. Similar to an electric truck FCV has zero tailpipe emission and only produces water vapour [75]. At end-2021, there were about 4500 fuel cell trucks worldwide [76].

4.3.2 Emission Reduction Measures in Road Transportation

The EU truck market is highly segmented, with 17 separate vehicle categories differentiated depending on various parameters including the trucks' axle configuration, gross vehicle weight, engine power, and emission profile. Currently, only four of these vehicle groups responsible for 73% of the HDV CO_2 emissions are regulated under EU Regulation 2019/1242 [61][77]. This regulation sets CO_2 standards for HDV manufacturers to reduce their average fleet emission from new HDVs by 15% in 2025 and 30% in 2030. Another regulation ((EU) 2017/2400) required manufacturers to publish their emissions and fuel consumption using a VECTO tool which was then used to set the baseline for the (EU) 2019/1242 regulation [77]. Vehicle manufacturers plan to do this by increasing the sales of zero-emission vehicles (ZEVs). The same rule imposes a credit system to encourage the development and use of ZEVs, as well as punishes manufacturers €4,250/vehicle for 1gCO_2/t-km of excess emissions from 2024 onwards [78].

Other specific fuel use standards are covered by numerous directives and regulations as follows:

Renewable Energy Directive (RED): The RED establishes targets for the inclusion of renewable energy sources, including transportation fuels, in the EU's energy mix [79]. It encourages the use of biofuels in road freight, such as biodiesel and bioethanol, as well as other sustainable fuels. As previously discussed in section 4.1, the RED II directive establishes emission guidelines for biofuels.

The Alternative Fuels Regulation (AFIR) goal is to ensure the development of an adequate and effective network of alternative fuel infrastructure, such as electric car charging stations, natural gas and hydrogen refuelling stations, to aid in the transition to cleaner fuels in road transportation. One of their deployment targets is to have dedicated charging stations for HDVs with a minimum output of 350 kW every 60 km along the trans-European transport (TEN-T) core network. From 2025 onwards, one charging point will be installed every 100 kilometres on the bigger TEN-T comprehensive network, with total network coverage expected by 2030. Similarly, it also has targets set out to deploy hydrogen refuelling stations every 200km along the core TEN-T network by 2030 [80].

Euro Emission Standards are a set of European Union (EU) rules and emission standards designed to reduce the pollutants generated by vehicles. Euro VI is the latest edition of these standards that imposes tight limitations on NOx, PM, HC, and CO for HDVs [81]. However, a new Euro VII standard is expected to come into effect from 2025 which has more stringent targets for the pollutants. However, there is a possibility of being pushed further as it is experiencing some pushback from the automotive industry as they worry it might be vehicles less affordable [82].

Table 3 Overview of emission reduction measures in road transportation

Regulation/Initiatives	**Goals**
AFIR Alternative Fuel Infrastructure Regulation [32]	Electric trucks • Fast-charging stations every 60 km by 2025 along the core TEN-T and by 2030 along the comprehensive TEN-T. • For trucks minimum of 2 charging points in safe and secure parking areas (by 2027) and 4 charging points by 2030. Hydrogen trucks • H_2 refuelling stations every 200km by 2030. • Capacity of providing 1t of 700 bar H2 per day. LNG/Bio-LNG trucks • Install LNG or Bio-LNG re-fuelling points.

Table 3 Continued

Regulation/Initiatives	Goals
EU Regulation 2019/1242 [78]	• Sets CO_2 standards for HDV manufacturers to reduce their average fleet emission from new HDVs by 15% in 2025 and 30% in 2030. • Manufacturers publish their emissions and fuel consumption using a VECTO tool. • Manufacturers will be penalized €4,250/vehicle for 1gCO_2/t-km of excess emissions from 2024 onwards.

4.3.3 Future Outlook

Many alternative energy sources and technology for emission reduction in road freight are emerging in the market today. The most promising of them all is the use of ZEVs, BEVs and e-diesel. Some of the technologies are explained below.

E-Diesel also known as synthetic diesel or power-to-liquid (PtL) diesel is produced from green hydrogen and captured CO_2 through processes such as Fischer-Tropsch or methanol-to-diesel synthesis [83]. This diesel alternative reduces emissions as it uses captured CO_2, it is also compatible with existing diesel engines and refuelling infrastructure. In most scenarios and studies its use is expected to start in 2030 [84][85].

Biodiesel is one of the most mature technologies available as an alternative compared to the rest. In 2019 in Europe, less than 5% of the energy consumption in road transport was biodiesel [4]. Currently, the majority of the biodiesel is FAME with a small amount of HVO. Both of which is expected to increase with HVO production doubling by 2025 [86].

Bio-CNG/Bio-LNG is a technology that is already in wide use. Although it can reduce emissions by 60% to 80% compared to diesel and gasoline it has seen low penetration in the European market [87]. In 2020, Europe had around 15,000 trucks fuelled with liquefied gas (LNG/LBG) on the roads and the number is expected to grow [88]. Regulations such as AFIR are also promoting the use of biogas by installing more refuelling stations along the TEN-T network.

Electric vehicles (EVs), including battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel-cell electric vehicles, are gaining traction in the road freight industry. The future of ZEVs in road freight in Europe seems optimistic. To encourage the adoption of more sustainable trucks, governments and policymakers are designing policies (AFIR) aimed at doing the same. The majority of all the big OEMs in Europe are supporting and have set targets to achieve a certain percentage of the sales in the future to be ZEVs [89], [90].

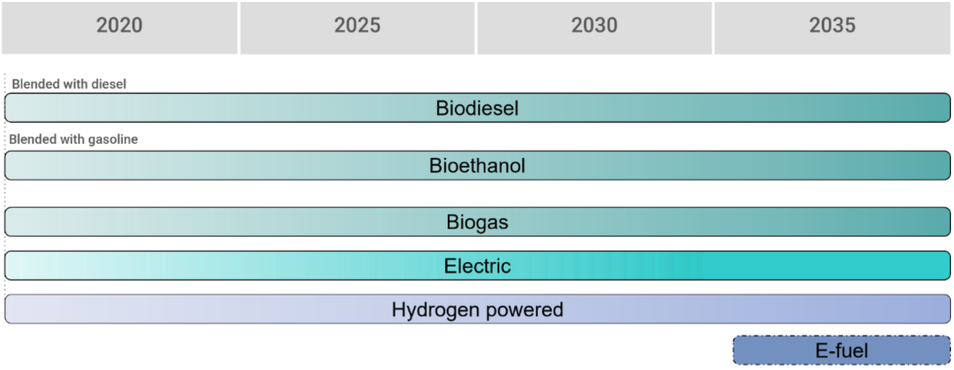


Figure 11 Road freight future outlook

Annex B has a case study that compares the emissions from freight movement using diesel, electric and hydrogen-powered trucks for now and 2030. The 2025 calculation was ignored as no adequate data was found for the calculation. Similarly, the calculation for diesel was also ignored due to the lack of sufficient data for 2025 and 2030. According to the calculation in Annex B - Road

- Assuming the predicted electricity decarbonization, as projected by the European Environment Agency (EEA), with the same energy efficiency as today's battery-powered vehicles, the emission can be reduced by nearly 9% in 2025 and 59% in 2030 on average in the EU.
- Using the IEA prediction for emission from hydrogen mix in EU 2030 the emission reduction was calculated to be 60%.
- But the emission factor in 2030 for 40t BEV is 8.8 gCO_2/tkm and for 40t FCEV is 13.85 gCO_2/tkm. Electric trucks are more energy-efficient and produce fewer emissions than the FCEVs.

4.3.4 Key takeaways

- Emission reduction produced by FCEVs heavily depends on the method of hydrogen production. With the current method of production, it provides only a 15 to 20% emission reduction compared to diesel (Annex B - Road).
- Bio-CNG and Bio-LNG naturally provide a greater emission reduction (well-to-wheel reduction of up to 90%) and are a better option than currently available hydrogen and battery-powered trucks [88]. However, the regular CNG/LNG's short-term GWP for methane is higher than diesel [91].

- A report by Transport and Environment suggests that with the current targets, it is not possible to reach climate neutrality by 2050 target [92]. Reports from ACEA suggest that the current AFIR targets for zero-emission heavy vehicle trucks do not meet the actual infrastructure requirement for 2025 and 2030. It recommends an increase in total power output and the number of charging stations for battery-powered trucks and deploying more hydrogen refuelling faster with lesser distance between them [93].
- EU Regulation 2019/1242 and the European Commission classifies dual fuel engines (trucks that partially run on diesel) as zero emission. This would only further increase emissions and not aid in emission reduction from the industry.
- The same above-mentioned regulation plans to use an emission credit and debit system to encourage manufacturers to improve sales of new ZEVs. This only encourages the sale of ZEVs belonging to certain groups of trucks and does not encourage research on existing vehicle efficiency. Additionally, this reduction mandate does not motivate a reduction in the upstream fuel production, it only accounts for the tail-pipe reduction.
- Fuel Quality Directive was a directive that produced a framework to reduce GHG intensity in fuels that was last updated to provide targets for 2020. An update on the directive can complement Regulation 2019/1242 to effectively reduce emissions.
- Biodiesel feedstocks have low traceability and the majority of the fuel produced today is from crop oil or unsustainable feedstock that compete for land and water with food crops. Europe also imports copious amounts of used cooking oil for fuel production from 3rd world countries. Transport and Environment reports also show concern that the imported cooking oil might be not used and could increase deforestation in said countries [86].

4.4 Railways

The railway is one of the least carbon-intensive modes of land transport and it is only becoming greener as more of Europe's rail system is electrified. Rail freight has various advantages over other means of transportation, such as road or air, including cost-efficiency, large capacity, and decreased environmental impact. This mode of transport is more energy efficient in terms of energy consumed and emission for one tonne-km. Its emissions are fewer than transport by most inland waterways, roads, and air [94]. In 2018 around 15% of the total freight transported in Europe was transported by railways but the modal share of rail freight is slowly increasing [20][2].

4.4.1 The current state of play

Rail transport in Europe is primarily powered by diesel and electricity. In Germany, a hydrogen-powered train with zero carbon emissions has recently been developed, with the potential to replace diesel trains [95].

Electric rail systems provide a cost-effective and environmentally sustainable means of freight transportation. These systems use electricity to power the trains using overhead wires or a third rail, removing the need for onboard combustion engines [96]. They have several advantages over diesel rail, including lower GHG emissions, lower air pollution, quieter operations, and higher energy efficiency. As of 2021 around 57% of the total railway is electrified [97].

Diesel rail systems play a key role in rail transportation, especially in locations where electrification is difficult or economically challenging. These systems use diesel engines to generate power and propel trains, allowing them to run on both electrified and non-electrified tracks. In Europe, 43% of the total freight transported by railway uses diesel but other countries such as the US rely heavily on diesel where nearly 100% of their freight is transported by diesel-powered trains [98][97].

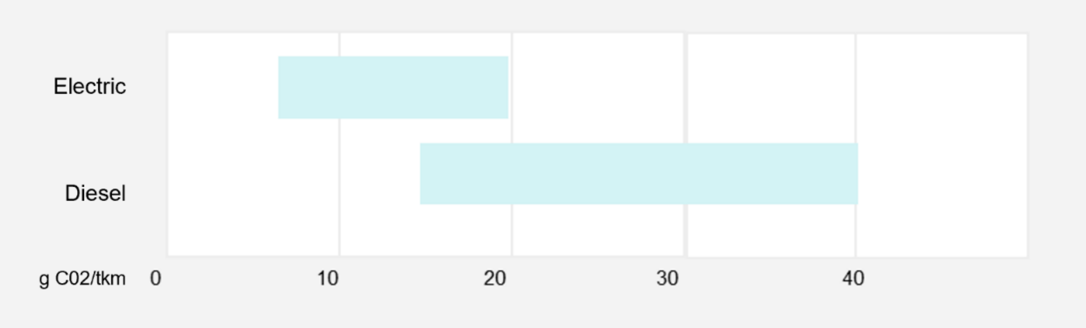


Figure 12 Current Emission Intensity for Rail Transport

Figure 12 represents the emission intensity for the rail collected from various literature (Annex C - Railway). Electric train emissions depend on the source of the electricity. Notably, electric trains have the potential to be greener than other modes of transportation, such as shipping, with some emission factors lesser than those of shipping. The key to all of this is the source of the electricity. When electric trains use networks that are predominantly powered by renewable sources such as wind, solar, or hydropower, their emissions can be significantly lesser.

4.4.2 Emission Reduction Measures in Railway Transportation

The EU has set specific regulations and targets for freight transported by rail to promote sustainability and encourage modal shifts. Here are some key regulations and targets for 2025 and 2030:

The Fourth Railway Package consists of four legislative packages introduced between 2001 and 2016. It measures and aims to create a more competitive and integrated European rail market. It includes provisions for enhancing market access, interoperability and improving regulatory frameworks to develop a Single European Railway Area (SERA) [99][100][101].

Shift2Rail is a public-private partnership between the EU and the rail sector, their main focus is on research and innovation to improve the competitiveness and sustainability of European rail. It sets objectives for developing innovative solutions and technologies for rail freight to reduce energy consumption and improve overall rail performance, cost, capacity, and emissions while also strengthening the role of rail in European mobility.

The EU's Sustainable and Smart Mobility Strategy also emphasizes the importance of shifting to more sustainable modes of transport, such as rail freight, and sets targets for reducing emissions and improving efficiency.

Rail Freight Forward is a coalition formed in 2018 by European rail freight companies to reduce the negative environmental impacts of freight transport. They want to shift 30% of all freight movement in Europe to be by rail [102]. They plan to achieve this through innovation and digitalization of rail management and operation.

Table 4 Overview of the emission reduction measures on the railway.

Regulation/Initiatives	**Goals**
TEN-T Trans-European Transport Network [103]	• Development of European Railway Traffic Management System (ERTMS) by 2030 for the TEN-T to replace the existing railway control system and increase interoperability of trains.
4th Railway Package [100]	• Enable the development of a single market for railway services (Single European Railway Area). • Standardization of rules and improved interoperable in the EU.
Rail Freight Forward [102]	• Increase the modal share of rail freight in Europe from currently 18% to 30% by 2030

4.4.3 Future

As Europe seeks to increase rail traffic, overall energy demand for railways is expected to increase. Additionally, it has plans to increase rail electrification and increase the inclusion of more renewables into the grid to decarbonize

Both these actions will decrease the emission per tonne-km. As per the simple case study analysed in Annex C - Railway with the predicted electricity grid decarbonization, as projected by the European Environment Agency (EEA), a potential emission reduction of 9% by 2025 and a substantial 60% by 2050 for every 1 tonne-km can be expected. However, the use of diesel and biodiesel in railways is uncertain, and hence its future emission reduction potential cannot be estimated. Judging by the current RED II directive biodiesel specification diesel trains can have a maximum of 65% emission reduction, depending on the blending, if biodiesel replaces biodiesel.

Regarding the use of hydrogen, there are no initiatives or targets set within the EU, as its application in rail transport is still in its infancy stage. Nestlé Waters in France as part of its supply chain decarbonization plan in 2025 has planned to use hydrogen fuel cells to power a freight train [104].

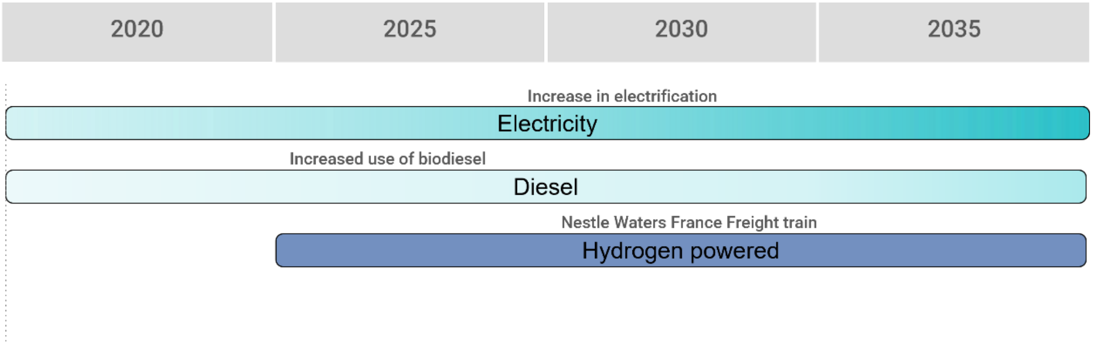


Figure 13 Rail freight future outlook

4.4.4 Key Findings

- A simple shift from the use of road freight to rail freight can reduce 60% to 90% of the emissions (for 1 tonne-km). Hence the focus on an increase in rail use has been important. Additionally, it will also reduce noise pollution, road congestion and energy demand in road transport.
- In rail transport interoperability between different regions in Europe is key to ensuring smooth cross-border transport. Reports suggest that interoperability in Europe is increasing at a very slow pace and is at a different pace in different countries (due to their different targets) which might hamper the modal shift [105].
- Technical and operational barriers such as inconsistent regulations, and no standardization stall the movement of freight at every

border. Here are some of the challenges currently experienced in cross-border rail transport:

- A need for locomotive registration for every country the train travels in [106].
- To change the train driver at every border or for the driver to know a B1 level of the language of the country the train is travelling in [107].
- Inconsistent gauge sizes (width between the rails) in European and Eurasian corridors force trains to have a bogie exchange (wheeled undercarriage that carries the cargo in the train) or physical transfer of goods from one train to the other at each border again increasing the cost and time of transport [108].
- The report on Cross-border Rail Transport Potential by the EU Agency For Railway explains the operational and technical challenges in detail [105].

4.5 Shipping

Globally most freight transport, around 70% in tonne-km, takes place via shipping and it accounts for nearly one-fifth of freight-related GHG. Although it is the least carbon-intensive mode of transport, due to the volume of transport its total emission is the 2nd largest following the emission from road freight. Over the last couple of decades, the demand and energy consumption has doubled and is only expected to increase [2].

The emission of NOx, SO_2, particulate matter (PM) and volatile compounds (VCs) in shipping is greater than in road transport. These emissions can have several harmful effects on human health and the environment, including respiratory problems, smog formation, acid rain and accelerated climate change [109][110]. Several measures are taken by the IMO to reduce shipping-related emissions, such as using cleaner fuels (LNG), improving engine efficiency, and switching to an electric propulsion system.

4.5.1 The current state of play

In international shipping, nearly all vessels are powered by fossil fuel, with a small number of ships powered by LNG and a considerably smaller number of vessels powered by alternatives such as nuclear, biofuels, and methanol. Traditionally, heavy fuel oil (HFO) has been the most commonly used fuel, but as many governments and organizations work to reduce emissions, different types of HFO marine gas oil, marine diesel oil, or intermediate fuel oils are being used. Nonetheless, they are all fossil-fuelled and emit a lot of pollution.

Heavy fuel oil is a general term used to describe a wide variety of marine residual fuels (residual oil from crude oil that is used to produce distilled products) or mixes of residual and distillate fuels [111]. It is a dark, dirty fuel with various contaminants, including sulphur which burns to produce sulphur dioxide.

Distillate fuel is produced by distilling crude oil and includes marine gas oil (MGO) and marine diesel oil (MDO). It has a lower viscosity, reduced sulphur content, and higher energy density than HFO. It also emits less SO2, NOx, and PM due to its cleaner composition [111].

Intermediate fuel oil (IFO) is a mix of residual and distillate fuel and has properties and emissions that fall between the HFO and the distillate. As seen in Figure 14 and Figure 15 it was one of the most used fuels.

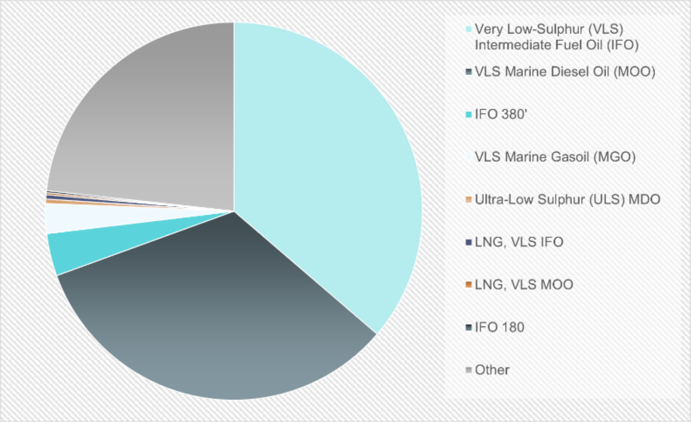


Figure 14 Share of fuel in shipping by number of ships [112]

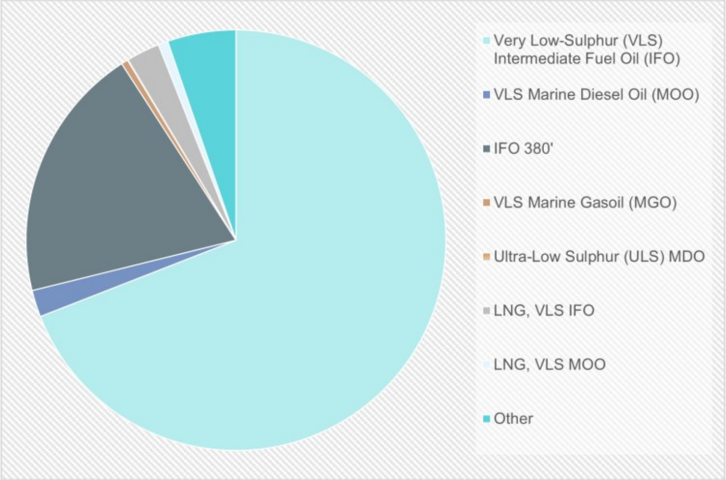


Figure 15 Share of fuel used in shipping in gross tonnage [112].

Unlike other modes, different kinds of ships are used for different goods. For example, an oil tanker is used to transport liquids such as chemicals, crude oil, and refined petroleum products. Bulk carriers are used to transport materials such as coal, grain, raw materials and so on. General cargo is a vessel that transports any cargo including raw materials and its finished products.

Finally, the container ships transport manufactured or finished products in 20- or 40-foot containers.

Figure 16 has the emission factors for some of the common types of vessels used in shipping. More data on the emission can be seen in Annex D - Shipping. From the data in Annex D - Shipping it is clear that the larger the vessel the lesser its emission factor is, and container and bulk carriers are excellent modes of transport of goods as they can potentially have emission factors as small as 3-5 gCO_2 / tonne-km.

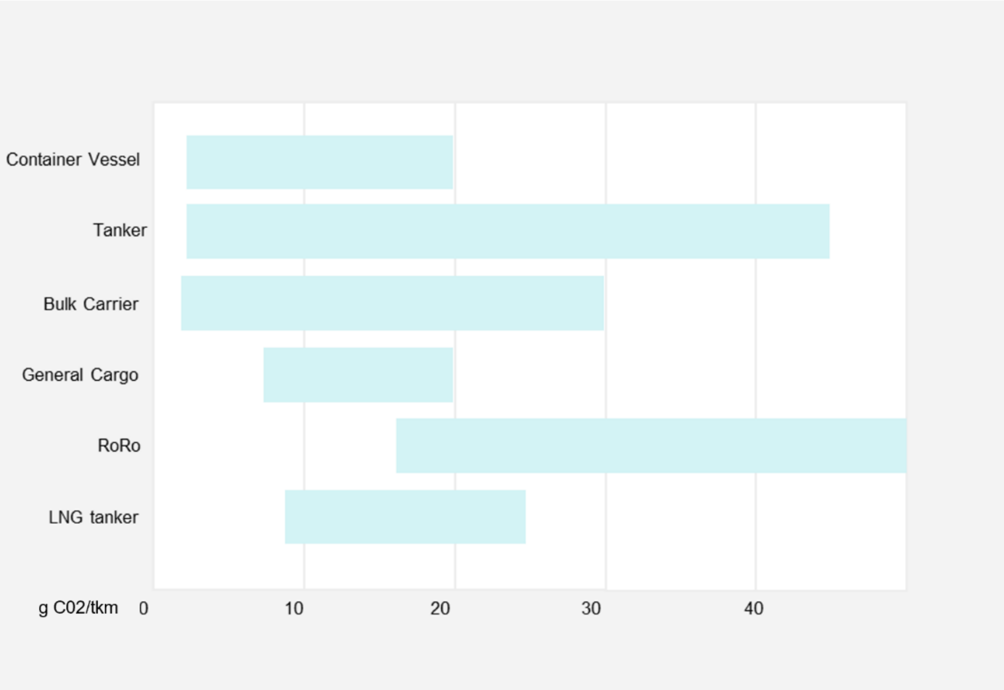


Figure 16 Emission factor of shipping vessels

4.5.2 Emission Reduction Measures on Waterways

IMO has adopted measures to reduce the emission of all vessels by 40% by 2030 to that of 2008. Additionally, it also has an energy efficiency rating system A, B, C, D and E which is determined based on the Energy Efficiency Existing Ship Index (EEXI) and operational carbon intensity Indicator (CII) ratings [113]. In 2020, as previously mentioned in section 2.2.1 it reduced SO_2 emission from ships by nearly 75% by limiting sulphur emission to 0.5% and 0.01% in emission control areas.

FuelEU Maritime regulation was started as part of the EU's "Fit for 55package" and has set the target to achieve 80% carbon intensity compared to 2020. As part of the same, it has also set other targets for every 5 years starting with a 2% emission reduction in 2025 and 6% in 2030. In addition, it requires all major EU ports to build infrastructure to provide electricity to all vessels when they are on shore by 2030 [80][114]. The regulation has also created incentives to use more renewable fuels of non-biological origin (RFNBO) and hopefully by 2034 use 2% of such fuels [115].

Getting to Zero Coalition is a consortium formed by over 200 organisations from the maritime, finance, government, and energy sectors, among others. Their main purpose is to have zero-emission vessels sailing the deep-sea routes by 2030, backed up by the infrastructure required for the vessel's energy production, storage, and refuelling stations [116].

EU Emission Trading System (EU ETS) is a cap-and-trade program used by the EU to reduce emissions from participating industries and from 2024 onwards CO$_2$ emissions from all ships larger than 5000 gross tonnage entering EU ports will be affected by this system. After 2026 methane and nitrous oxide will also be included in the ETS scope [117].

Alternative Fuels Infrastructure Regulation mandates and sets targets for electricity supply to vessels at shore for certain sized ships and for inland waterway vessels [32].

Table 5 Overview of the emission reduction measures on waterways

Regulation/Initiatives	Goals
AFIR Alternative Fuel Infrastructure Regulation [32]	By 2030 • At least 90% of containership and passenger ships to have shore-side electricity • All inland water ports to have access to shore-side electricity
FuelEU Maritime [80][114]	• Vessels above 5000 gross tons • to reduce annual average carbon emission (current baseline 91.7gCo$_2$/MJ fuel) by 2% in 2025, 6% in 2030 and 80% in 2050. • to connect to onshore electricity.
IMO International Maritime Organization [113]	• Limit sulphur emissions from 3.5% to 0.5% for all ships from 2020. • Requires ships to report their fuel use and energy efficiency. • Reduce emission of all vessels by 40% by 2030 to that of 2008.

4.5.3 Future

FuelEU Maritime has set specific targets and hence we can determine that there will be a minimum of 2% reduction by 2025 and a 6% reduction by 2030. More specific emission factors for various vessel classes depending on their loading capacity can be found in Annex D - Shipping. From the calculation, EF for bulk carriers and the oil tanker seems to be the least followed by the containership and lastly the general cargo vessels.

But with newer fuel and vessel technology these emissions could further go down. Some of these technologies include:

LNG-powered ships are increasing in popularity for non-passenger transport and are mostly used in LNG carriers. As of 2022 around 900 ships were LNG powered and more than 500 were ships on order [118]. The WTW emission reduction if LNG is produced from fossil fuel is 10% cent but if produced cellulose-based feedstock then it can be up to 80%, compared to MDO [119]. Studies from NTU Singapore say that Bio-LNG has the potential to satisfy 3% of the total shipping energy demand in 2030 and 13% in 2050 [120].

Ammonia is expected to be a good alternative to decarbonize the shipping industry as its final products are nitrous oxide and water with zero SO_x emissions. As of today, only grey ammonia (produced from fossil fuel) is available in large quantities, but many small demonstration plants do produce green ammonia. Blue ammonia (NG and carbon capture NH_4 production pathway) has an emission reduction potential of 85% and green NH_4 (Electrolysis NH_4 production) is 75% [119]. However, an LNG leak can be more harmful and toxic to the environment and animal life.

Methanol is an alternative solution that is close to commercialization. Many companies including Maersk have ordered multiple dual engines powered by methanol to join their fleet [121]. It is expected to hit the water by 2025 and green methanol can reduce emissions by 92%, compared to conventional fuel oils [119].

Battery-powered vessels can be used to replace short-sea shipping or inland waterway shipping. For long-haul shipping, it can only be used as an auxiliary power as the batteries have lower energy density and are heavy [119].

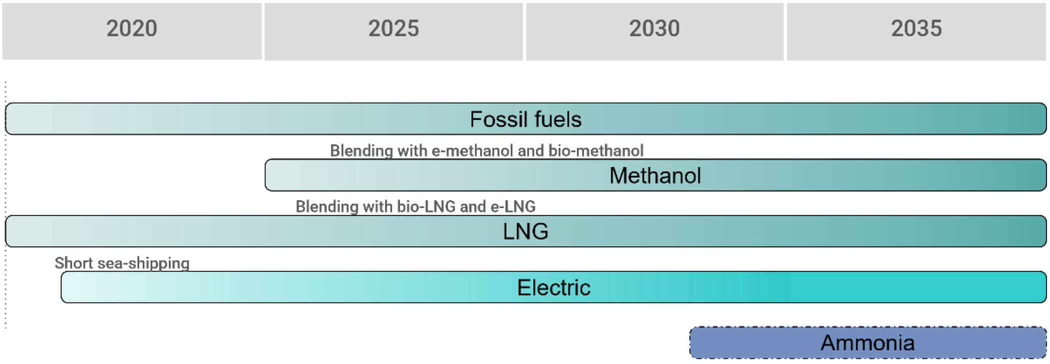


Figure 17 Water freight future outlook

4.5.4 Key takeaways

- In the next decade, LNG and methanol seem to be the only alternative fuels that would enter the market. But fossil methanol WTW emissions are greater than fuel oil [122]. Similarly, fossil LNG is equal to that of the fuel oil [119]. Thus, it is very important to increase the production of green LNG and methanol.
- The current IMO regulation requires the vessel to measure and report only the emission from TTW. Hence most of the emission factor calculated in Annex D - Shipping is greater than the one reported by other organizations in the same annex.
- FuelEU Maritime initiative starting in 2025 requires WTW emissions and will penalize emissions above a certain limit.
- MARPOL framework is designed for conventional fuel; hence it needs to be amended to include other alternative fuels that are introduced [123].
- Other operational and logistical measures such as slow speed, optimized route planning and higher capacity utilization aided with foldable containers can help reduce transport costs and emissions. Other technologies such as wind propulsion also help in the reduction of fuel consumption [124].

5 Conclusion

Freight transportation, both in Europe and globally, contributes significantly to the global CO_2 emissions. Various parties, including NGOs, legislators, governments, industry, and consumers, have begun to implement multiple policies and actions to create more environmentally conscious transportation networks. While several programs have been initiated to achieve carbon neutrality by 2050, there is still concern about their sufficiency. Throughout this research, it has become clear that decarbonizing passenger transportation has received more attention than decarbonizing freight transportation. Nonetheless, countries around the world are actively working to cut emissions in the transportation sector, which has repercussions for freight transportation as well.

With the current available data, emerging technologies and policies following conclusions could be drawn. Firstly, for aviation cargo, the landscape is expected to remain similar to the present with an increased use of SAF (Sustainable Aviation Fuel). However, the utilization of other alternative fuels such as e-kerosene holds promising potential in reducing emissions. With current regulations outlined in ReFuel Aviation, the adoption of these eco-friendly fuels could lead to a projected emission reduction of 5% per tonne-kilometre (tkm) by 2030.

The outlook for road freight, on the other hand, remains uncertain due to the lack of data for various energy sources, such as hydrogen and electric options. Moreover, the role of biofuels in this mode remains ambiguous, further hindered the estimation of emission reduction in the future.

In the railway sector, emissions are already relatively low, and efforts to further reduce them in the future are centred around two strategies: the electrification of railways and the decarbonization of the grid powering these railways. These measures underline the industry's commitment to sustainable practices.

Finally, in shipping the Fuel EU Maritime initiative projects a 6% reduction in tkm emissions by 2030. However, the development of new fuels such as e-fuels and hydrogen has the potential to reduce emissions even further but due to the nascent nature of these technologies and lack of data associated with them estimating their precise emission reduction remains a challenge.

In terms of emission-reduction methods in this study, intermodal transportation has emerged as a crucial aspect in increasing efficiency and lowering emissions. These operations use the strengths of different transportation modes to their advantage while reducing inefficiencies such as empty backhauls and suboptimal routes. The report also emphasizes the importance of system-based solutions, optimization, and digitization in bridging the gaps between diverse modes of transportation. It is critical to address the inherent inefficiencies in present freight systems, particularly in areas such as truck loading and routing. Digitalized multimodal logistic chains are essential for a sustainable future.

However, the issues of estimating emissions across multiple fuel sources and modes of transportation remain complex due to separate restrictions, lack of standardized data and the varying impact on global warming potential. The analysis was further complicated by the lack of data on cutting-edge technology, such as hydrogen and electric trucks, that is currently available. This lack of standardized data hinders a thorough understanding of their potential for emission reduction and their impact on the entire supply chain.

In the context of emerging fuels, e-fuels stand out with their potential to provide energy density advantages in sectors where electricity-based alternatives are not viable. Despite the potential, present technological obstacles make them less cost-effective. According to predictions, e-fuels could contribute to the transportation sector by 2050, mainly in aviation, maritime, and long-distance road transport. Similarly, with bio-based alternative fuels concerns also lie with the traceability of the feedstock used for the fuels and it is their overall environmental impact. However, these fuels come with varying efficiencies, and their integration requires a holistic approach that considers existing infrastructure, source of electricity to produce them, indirect land use change and so on. Furthermore, there are still concerns about the availability of adequate green fuels, as there are no specific allocations for their production, storage, and deployment.

Thus, to successfully decarbonize the freight transport sector it is evident that we require a multifaceted solution, with a collaborative effort from various stakeholders, innovative technologies, and adaptable strategies. The journey towards sustainability requires a continuous commitment to addressing challenges, harnessing opportunities, and orchestrating a harmonized transformation of the global freight transport landscape.

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6 Annex A - Aviation

This section contains the emission intensity collected from various sources that were used to create the emission intensity graph shown in Figure 7 and the calculation in the case study referenced in section 4.2.4.

Table 6 ASTM Approved Pathways and Technology Readiness [125] [126] [127] [128]

Conversion Process	Blending (by volume)	Technology Readiness	Commercial Projects
Fischer-Tropsch hydro-processed synthesized paraffinic kerosene (FT)	50%	7-8	Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell, Syntroleum
Synthesized paraffinic kerosene from hydro-processed esters and fatty acids (HEFA)	50%	8-9	World Energy, Honeywell UOP, Neste Oil, Dynamic Fuels, EERC
Synthesized iso-paraffins from hydro-processed fermented sugars (SIP)	10%	7- 8 - conventional sugar feedstock 5 - lignocellulosic sugar feedstock	Amyris, Total
Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT+SKA)	50%	6-7	Sasol
Alcohol to jet synthetic paraffinic kerosene (ATJ-SPK)	50%	7-8	Gevo, Cobalt, Honeywell UOP, LanzaTech, Swedish Biofuels, Byogy
Catalytic hydrothermolysis jet fuel (CHJ)	50%	6	Applied Research Associates (ARA)
Synthesized paraffinic kerosene from hydrocarbon-hydro processed esters and fatty acids (HC-HEFA-SPK)	10%	5	IHI Corporation
Fats, oils, and greases (FOG) co-processed (co-processed HEFA)	5%	-	-
co-hydro processing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery (co-processed FT)	5%	-	Fulcrum

Table 7 Emission factor of air freights

Aviation	Emission	Unit	Region	Reference	Year
Short	1.47	kgCO2/tkm	Other, UK	[129]	2017
	0.9	kgCO2/tkm	UK	[130]	2017
	0.95	kgCO2/tkm	UK		2017
	1.06	kgCO2/tkm	UK		2017
	1.22	kgCO2/tkm	UK	[131]	2022

Table 7 Emission factor of air freights, continued

Aviation	Emission	Unit	Region	Reference	Year
Domestic	**1.96**	**kgCO2/tkm**	**Other, UK**	**[129]**	**2017**
	2.5	kgCO2/tkm	UK	[130]	2017
	2.5	kgCO2/tkm	UK		2017
	1.85	kgCO2/tkm	UK		2017
	2.38	kgCO2/tkm	UK	[131]	2022
Long Haul	0.61	kgCO2/tkm	Other, UK	[129]	2017
	0.8	kgCO2/tkm	UK	[130]	2017
	0.85	kgCO2/tkm	UK		2017
	0.69	kgCO2/tkm	UK		2017
	0.54	kgCO2/tkm	UK	[131]	2022

Table 8 Emission factor and emission reduction potential estimate of SAF

Emission Reduction Calculation			
Conventional Aviation Fuel (CAF)	0.95	kg	
Blend Percentage	5	%	Assumption
Sustainable Aviation Fuel (SAF)	0.05	kg	
EF. CAF	89	gCO_2e/MJ	Corisa eligibility[132]
EF. SAF (RED ii)	32.6	gCO_2e/MJ	Assuming a 65% emission reduction relative to CAF to qualify as SAF as per RED II [35]
CAF Energy density	43	MJ/kg	[133]
	48	MJ/kg	

$$CO_2\ Emission = 3.16 * (CAF + SAF * (\frac{LCA_{SAF}}{LCA_{CAF}})\ \textbf{[134]}$$

CO_2 Emission	3.06	$KgCO_2/kg$	Calculated
CO_2 Emission Reduction	3%		

Air Freight Only	Kg/tkm	Emission (gCO2/tkm)
Up to 1000km	0.691	2644.457
1000 to 4000km	0.5	1913.5
4000 to 7000km	0.211	807.497
Over 7000km	0.172	658.244

Belly Freight	Kg/tkm	Emission (gCO2/tkm)
Up to 1000km	0.61	2334.47
1000 to 4000km	0.526	2013.002
4000 to 7000km	0.35	1339.45
Over 7000km	0.306	1171.062

7 Annex B - Road

This section contains the emission intensity collected from various sources that were used to create the emission intensity graph shown in Figure 10 and the calculation in the case study referenced in section 4.3.3.

Table 9 Emission factor of road freights

Vehicle	Comment	Emission (gCO$_2$/tkm)	Reference	Region	Year
General HDVs	Average	52.7	[61]	-	-
	-	108-144	[135]	NZ	-
	-	137	[136]	EU	-
	-	90.3	[137]	Netherlands	2014
	<33 tonnes	92-155	[138]	UK	2004
	-	100		Europe	-
	HGV	433.323	[139]	Other	2017
	Road Vehicle - HGV	433.323		Other	2017
	Rigid Size 3.5 - 7.5 tonnes	659.46		UK	2017
	Rigid Size 7.5 - 17 tonnes	412.43		UK	2017
	Rigid Size >17 tonnes	200.27		UK	2017
	Rigid Size Unknown	251.15		UK	2017
	Articulated Size 3.5 - 33 tonnes	152.62		UK	2017
	Articulated Size >33 tonnes	86.78		UK	2017
	Articulated Size Unknown	88.69		UK	2017
	Euro 6	78.5	[140]	Europe	-
	-	124.27	[139]	UK	2017
Diesel truck	HHD	67	[141]	California	2015
	MHD	100	[141]	California	2015
	Articulated truck (40tonnes)	71	[142]	na	-
	Rigid >3.5 - 7.5 tonnes	486.74	[143]	UK	2022
	Rigid >7.5 tonnes-17 tonnes	340.02		UK	2022
	Rigid >17 tonnes	181.42		UK	2022
	All rigids	207.8		UK	2022
	Articulated >3.5 - 33t	126.26		UK	2022
	Articulated >33t	80.17		UK	2022
	All articulated	81.2		UK	2022
	Diesel	107.49		UK	2022
LNG truck	HHD	62	[141]	California	2015
	MHD	130		California	2015
Diesel-electric hybrid truck	HHD	63		California	2015
	MHD	97		California	2015

Table 10 Emission factor estimate for a fully loaded 40t truck

40t	**Payload capacity (t)***	**Energy Consumption**	**Energy/ fuel consumption**	**Emission Factor**			
				Now	**2030**	**Now**	**2030**
Diesel	25	0.33 l/km [144]	0.013 l/tkm	3244.8 gCO2/l [145]	-	42.8 gCO2/tkm	-
Electric	20	1.49 kWh/km [146]	0.075 kWh/tkm	292.62 gCo2/kWh [147]	118 gCo2/kWh [148]	21.8 gCO2/tkm	8.8 gCO2/tkm
FCEV	26	0.09 kg/km [146]	0.0035 kg/tkm	10000 gCo2/kgH2 [149]	4000 gCo2/kgH2 [150] **	34.6 gCO2/tkm	13.9 gCO2/tkm

* Fully loaded

** Assuming green hydrogen

8 Annex C - Railway

This section contains the emission intensity collected from various sources that were used to create the emission intensity graph shown in Figure 12 and the calculation in the case study referenced in section 4.4.3.

Table 11 Emission Factor for railway

Vehicle	Emission (gCO2/tkm)	Reference	Region	Year
Diesel	29	[135]	NZ	-
	41	[151]	UK	2017/2018
	36.9	[152]		-
	33.56	[153]	-	-
	36	[139]	Other	2017
Electric	13.2	[153]	-	-
	19.9	[152]		-
	7	[135]	NZ	-

Table 12 Emission factor of railway energy sources

Emission Factor		
EU - Electricity 2020 [147]	292.6	gCO2e/kWh
EU – Electricity 2025 [148]	265	gCO2e/kWh
EU – Electricity 2030 [148]	118	gCO2e/kWh
Diesel [154]	3900	gCO2e/kg fuel
Biodiesel*	2535	gCO2e/kg fuel

*RED II directive – 65% emission reduction in biofuels

Table 13 Emission estimate for rail freight transport

	Energy Consumption [145] (Wh/tkm)	Energy Efficiency	Emission factor (gCO2/tkm)			Emission Reduction	
			Now	2025	2030	2025	2030
Electric Trains	21.8	-	6.37	5.77	2.57	9.4%	59.7%
Diesel Trains	58.9	37%	53.52	*	*		
Biodiesel Trains			34.79**	*	*		

*Depending on the blend and emission reduction, it could change

**Assuming the energy density of diesel is 11.6 kWh/kg

9 Annex D - Shipping

This section contains the emission intensity collected from various sources that were used to create the emission intensity graph shown in Figure 16 and the calculation in the case study referenced in section 4.5.3.

Table 14 Emission factor for shipping

Vehicle	Size	Emission (gCO$_2$/tkm)	Reference	Region	Year
Ocean container vessel	2500dwt	20	[139]	UK	2017
	20000dwt	12.5		UK	2017
	-	16.14	[143]	UK	2022
	Large	15	[155]	-	2017
	0-999 teu	19.1	[156]	-	2020
	1000-1999 teu	14.5		-	2020
	2000-2999 teu	10.7		-	2020
	3000-4999 teu	9.2		-	2020
	5000-7999 teu	8.8		-	2020
	8000-11999 teu	7.2		-	2020
	12000-14499 teu	5.8		-	2020
	14500-19999 teu	4.4		-	2020
	20000-+ teu	4.3		-	2020
	844dwt	33.3	[139]	UK	2017
	18371dwt	9.1		UK	2017
	100000 dwt	5.9		UK	2017
	0-4999 dwt	37	[156]	-	2020
	5000-9999 dwt	21.2		-	2020
	10000-19999 dwt	13.6		-	2020
	20000-39999 dwt	9		-	2020
	40000-+ dwt	7		-	2020
	0-4999 dwt	45		-	2020
	5000-9999 dwt	31.2		-	2020
	10000-19999 dwt	23.8		-	2020
	20000-59999 dwt	14.2		-	2020
	60000-79999 dwt	8.4		-	2020

	80000-119999 dwt	6.5		-	2020
	120000-199999 dwt	5		-	2020
	200000-+ dwt	3.1		-	2020
	Large	3		-	2017
Bulk carrier	1720 dwt	29.2	[139]	UK	2017
	14201 dwt	7.9		UK	2017
	70000 dwt	4.1		UK	2017
	-	13	[157]	-	2022
	Regional	9	[155]	-	2017
	0-9999 dwt	20.5	[156]	-	2020
	10000-34999 dwt	6.9		-	2020
	35000-59999 dwt	5.1		-	2020
	60000-99999 dwt	4.3		-	2020
	100000-199999 dwt	2.9		-	2020
	200000-+ dwt	2.5		-	2020
General cargo	-	13.2	[143]	UK	2022
	0-4999 dwt	19.7	[156]	-	2020
	5000-9999 dwt	16.6		-	2020
	10000-19999 dwt	15.6		-	2020
	20000-+ dwt	7.6		-	2020
RoRo	Regional	51.7	[143]	UK	2022
	10000-14999 dwt	30.7	[156]	-	2020
	15000-+ dwt	15.6		-	2020
LNG	0-49999 cbm	24.8		-	2021
	50000-99999 cbm	11		-	2022
	100000-199999 cbm	8.8		-	2023
	200000-+ cbm	9.7		-	2024

Table 15 Emission factor of marine fuels

Fuel Type	Emission (gCO2e100/g fuel) [158]	Energy content (MJ/g fuel) [158]	Emission (gCO2e100/MJ fuel)	Current baseline (gCO2e/MJ fuel)	2025 target (gCO2e/MJ fuel)	2030 target (gCO2e/MJ fuel)
HFO	5.03	0.040	125.16	91.7	89.9	86.2
VLSFO	5.27	0.043	123.31			
MGO	4.72	0.042	111.79			
LNG	7.17	0.048	149.29			

Table 16 Emission estimate for fleet-average data for maritime shipping

Vessel category	Load cap. (t) [152]	Average MJ/tkm [152]	Emission (g CO2e/tkm)		
Bulk carrier			Now	2025	2030
0-4,999 dwt	4,450	0.37	33.93	33.26	31.89
5,000-9,999 dwt	8,005	0.23	21.09	20.68	19.83
10,000-34,999 dwt	28,385	0.09	8.25	8.09	7.76
35,000-59,999 dwt	42,731	0.07	6.42	6.29	6.03
60,000-99,999 dwt	80,379	0.05	4.59	4.5	4.31
100,000-199,999 dwt	1,70,075	0.04	3.67	3.6	3.45
200,000+ dwt	2,21,009	0.03	2.75	2.7	2.59
General cargo ship					
0-4,999 dwt	3,552	0.425	38.97	38.21	36.64
5,000-9,999 dwt	7,966	0.345	31.64	31.02	29.74
10,000-19,999 dwt	13,116	0.28	25.68	25.17	24.14
20 000+ dwt	30528	0.155	14.21	13.93	13.36
Oil tanker					
0-4,999 dwt	3,357	0.4	36.68	35.96	34.48
5,000-9,999 dwt	7,428	0.38	34.85	34.16	32.76
10,000-19,999 dwt	15,262	0.24	22.01	21.58	20.69
20,000-59,999 dwt	43,288	0.11	10.09	9.89	9.48
60,000-79,999 dwt	73,202	0.07	6.42	6.29	6.03

80,000-119,999 dwt	1,10,775	0.06	5.5	5.39	5.17
120,000-199,999 dwt	1,57,137	0.05	4.59	4.5	4.31
200,000+ dwt	3,10,100	0.02	1.83	1.8	1.72
Container ship					
0-999 TEU	810	0.577	52.88	51.84	49.71
1,000-1,999 TEU	1,395	0.383	35.15	34.46	33.04
2,000-2,999 TEU	2,537	0.29	26.59	26.07	25
3,000-4,999 TEU	4,119	0.223	20.48	20.08	19.25
5,000-7,999 TEU	6,200	0.177	16.2	15.88	15.23
8,000-11,999 TEU	9,244	0.14	12.84	12.59	12.07
12,000-14,499 TEU	13,625	0.093	8.56	8.39	8.05
14,500-19,999 TEU	17,546	0.08	7.34	7.19	6.9
20,000+ TEU	20,563	0.07	6.42	6.29	6.03