



Deliverable 2.2 (V1.0)

Different transport modes and their sustainability

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Disclaimer

¹ **DATA** = data sets, **DEC** = Websites, patent filings, videos, etc; **DEM** = Demonstrator, pilot, prototype, **ETHICS**; **OTHER**; **R** = Document, report.

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Abbreviations

AI	Artificial Intelligence
ASIF	Activity x modal Share x energy Intensity x carbon intensity of Fuel
BEV	Battery Electric Vehicle
CAVs	Connected and Automated Vehicles
CCUS	Carbon Capture, Utilisation and Storage
CII	Carbon Intensity Indicator
CNG	Compressed Natural Gas
CO ₂	Carbon Dioxide
DWPT	Dynamic Wireless Power Transfer
EC	European Commission
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operation Indicator
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gases
ICE	Internal Combustion Engine
ICR	Inductive Charging Roads
IMO	International Maritime Organization
IoT	Internet of Things
LNG	Liquefied Natural Gas
METS	Maritime Emissions Trading System
N ₂ O	Nitrous Oxide
NO _x	Nitrogen Oxides
PM ₁₀	Particulate Matter with diameter of 10 micrometers and smaller
PM _{2.5}	Particulate Matter with diameter of 2.5 micrometers and smaller
SDGs	Sustainable Development Goals
SO _x	Sulphur Oxides
TEG	Thermoelectric Generators
TRL	Technology Readiness Level
WP	Work Package
WPL	Work Package Leader
WTH	Well-to-Hull

Publishable Executive Summary

The present report is the Deliverable from task 2.2 of the ADMIRAL – *Advanced Marketplace for Low Emission and Energy Transportation* project, funded by the European Union under the HORIZON-CL5-2022-D6-02 with Grant Number 101104163. ADMIRAL aims to transform supply chain management in freight transportation by developing a cutting-edge digital marketplace for multimodal logistics. It seeks to shift the focus on indirect emissions, reduce overall emissions in logistics and transportation and enhance transparency throughout the supply chain.

ADMIRAL WP2 – *Sustainable development of logistics & transport* addresses key sustainability issues in the transport and logistics sector such as zero (low) emissions logistics, reduction of energy consumption from fossil fuels in transport and enhancement of collaborative logistics to reach common sustainability goals in the pilots to be implemented in Finland, Lithuania, Portugal-Spain and Slovenia-Croatia. Task 2.2 – *Different transport modes and their sustainability now and in the future*, is centred on the identification of the main current transport modes, their sustainability impact and what are the new modes arising at the macro and micro levels.

To our knowledge this is the former research and innovation project that developed network-based methods and AI tools for analysing the transport decarbonisation/energy efficiency related literature.

Overall, the research methodology used to develop task 2.2 included the following:

- a) Knowledge Discovery in scientific databases and data mining techniques are used to identify the main technologies under development and their expected impacts and applications.
- b) A survey tool was developed on transport technology options addressing reduction of CO₂ emissions and energy efficiency measures that targeted worldwide companies (macro level). The QR code of this survey (new tool for mobile connections) was delivered to partners before the Transport Innovation Forum 2023 in Vilnius held on 23-24 November 2023.
- c) Semi-structured interviews were conducted between 12th December 2023 and 5th March 2024 at the micro level, aiming to engage a representative sample of companies at each Pilot level. The engagement of these stakeholders enables us to assess in each specific context their needs and actions to reach Net Zero (synergies of WP2 and WP5), focusing on the role of transport and technology along with other non-technology factors and perceived sustainability impacts.

Results are important to advancing analytical tools in research and innovation studies and are useful for policy makers and foster the dialogue across the whole community of stakeholders across pilots to converge to sustainable transition pathways towards Net Zero.

1 Introduction

1.1 Objectives

The present report « Different transport modes and their sustainability » is one result of task 2.2 - Different transport modes and their sustainability now and in the future, which integrates ADMIRAL WP2 - Sustainable development of logistics & transport. Following ADMIRAL's project Grant Agreement 101104163, the main goal of task 2.2 is:

to identify the main current transport modes, their sustainability impact and what are the new modes arising at the macro and micro levels. LNEC [National Laboratory for Civil Engineering], UPM [Technical University of Madrid], UL [University of Ljubljana] and NORM [Normalis Tech] to develop this activity a survey will be conducted with worldwide companies and data mining techniques will be used to identify the main technologies under development and their expected impacts and their applications.

1.2 Methodology

Considering that the ADMIRAL project is a research and innovation action we aimed to respond to the challenge of the EC funding through the European Climate, Infrastructures and Environment Executive Agency (CINEA). Therefore, we moved beyond the traditional literature review approach to develop an innovative approach that merged transport engineering, AI tools and network-science methods. To identify the new modes and, hence, the main technologies aligned with low emissions and energy transportation modes to greening freight transport we developed network-based methods and network community detection algorithms to analyse the scientific literature on green logistics and transport decarbonisation technologies comprising the following transport modes: road, rail, maritime and cross-modal. One of the novel features of the research pursued is that it addressed an already identified gap in the literature regarding the integration of bibliographic coupling and semantic analysis into a single network graph to offer a novel perspective in network science and document analysis. This represents a step further in the analysis of big sets of documentation with varied scientific contributions to the research goals, and potentially replicable by other EU-funded projects.

Considering the collaborative approach in ADMIRAL, sustainability transitions research is also considered as a founding analytical framework to set a survey and the complementary semi-structured interviews with stakeholders at the micro (Pilot) levels. Sustainability transitions represent major shifts in established industries, socio-technical industries, socio-technical systems, and societies towards more sustainable modes of production and consumption (Geels, 2018). Since transition processes involve social and technical aspects, the aim is to explore the role of technology versus non-technology factors now and in the future (2030).

The research methodology used in task 2.2 comprises the following:

- a) Knowledge Discovery in scientific databases and data mining techniques are used to identify the main transport modes/technologies under development and their expected impacts and applications.
- b) A survey tool was developed on transport technology options addressing reduction of CO₂ emissions and energy efficiency measures that targeted worldwide companies (macro level).

The QR code of this survey (new tool for mobile connections) was delivered to partners on 09.11.2023, before the Transport Innovation Forum 2023 in Vilnius on 23-24 November 2023.

- c) Semi-structured interviews were conducted between 12th December 2023 and 5th March 2024 at the micro level, engaging a representative sample of companies at the micro (Pilot) level. The engagement of these stakeholders also enabled us to assess their needs and actions to reach Net Zero (synergies of WP2 and WP5), focusing on the role of transport and technology along with other non-technology factors and perceived sustainability impacts.

1.3 Report Structure

Considering the Deliverable 2.2 goals and research methodology (sections 1.1 and 1.2), the ADMIRAL sustainability challenges related to greening supply chains across transport modes are revisited in section 2. Section 3 presents the analysis of the scientific literature on transport technologies to reduce carbon related emissions and improve energy efficiency using the developed network-based methods and community detection algorithms for road, rail, maritime and cross-modal. Section 4 presents the findings from the survey and the semi-structured interviews conducted at the micro level. The range of technologies are comprehensively reviewed in section 5 and their potential impacts to reduce GHG emissions are identified. This enables to develop in section 6 an integrated taxonomy for “low emission and low energy transportation,” a roadmap of screened technologies and sustainability impacts cards. Finally, section 7 concludes by summarizing the main contributions and findings for the sustainable development of transport & logistics.

2 Greening freight transport across modes

2.1 European Strategies

The EU's Green Deal strategy envisages to transform the EU into the first climate-neutral economy by 2050, and transport is one of the key sectors to be addressed.

The European Green Deal, presented in December 2019, is a comprehensive and ambitious strategy to make the EU's economy more sustainable and resilient, while achieving the climate neutrality target by 2050. It covers all sectors and policies, including energy and transport, and sets out concrete actions and targets to reduce greenhouse gas emissions, enhance circular economy, promote innovation and green finance, and protect natural resources, with a view to a socially just transition to a clean and circular economy, contributing to the restoration of biodiversity and the reduction of pollution. The Green Deal is an integral part of the EU's strategy to realise the SDGs of the United Nations 2030 Agenda. The European Green Deal identifies eight policy areas: 1. Raising the EU's climate ambition for 2030 and 2050; 2. Providing clean, secure and affordable energy; 3. Mobilising industry for the clean and circular economy; 4. Building and renovating in an energy and resource efficient way; 5. Accelerating the transition to sustainable and smart mobility; 6. "From farm to fork": designing a fair, healthy and environmentally friendly food system; 7. Preserving and restoring ecosystems and biodiversity; and 8. Adopt a zero-pollution ambition for an environment free of toxic substances.

Key Targets (by 2050):

- Achieve Net Zero greenhouse gases emissions.
- 90% reduction in greenhouse gas emissions from transport.
- Economic growth is decoupled from resource use.

The EU's commitment to climate neutrality through the EU Green Deal and the mid-term goal of reducing net greenhouse gas emissions by at least 55% by 2030 (relative to 1990 levels), are made legally binding by the European Climate Law (Regulation (EU) 2021/119).

The European Sustainable and Smart Mobility Strategy, presented by the European Commission in December 2020, aims to transform the EU transport sector, and align it with the European Green Deal. The strategy sets out the ambition for a green, digital, and resilient transport system, with its GHG emissions reduced by 90% until 2050. To achieve this vision, the strategy identifies 10 key areas for action and 82 initiatives that will guide the Commission's work for the next four years. The strategy is expected to create an irreversible shift to zero-emission mobility while making the EU transport system more efficient and resilient to future crises.

Key Targets (by 2030):

- At least 30 million zero-emission vehicles will be in operation on European roads.
- 100 European cities will be climate neutral.
- High-speed rail traffic will double.
- Scheduled collective travel of under 500 km should be carbon neutral within the EU.

- Automated mobility will be deployed at large scale.
- Zero-emission vessels will become ready for market.

Key targets (by 2050):

- Zero-emission large aircraft will become ready for market.
- Nearly all cars, vans, buses as well as new heavy-duty vehicles will be zero emission.
- Rail freight traffic will double.
- High-speed rail traffic will triple.
- The multimodal Trans-European Transport Network (TEN-T) equipped for sustainable and smart transport with high-speed connectivity will be operational for the comprehensive network.

Following the Communication from the Commission on “Greening Freight Transport” presented in July 2023, transport of freight accounts for over 30% of transport CO₂ emissions and is an important source of air pollutant emissions (source: PRIMES model; EC, 2023). Also, freight transport volumes are projected to increase by around 25% by 2030, and 50% by 2050, and greening transport represent a key sustainability challenge.

Europe’s Fit for 55 Package set a target of reducing net GHG emissions by at least 55% by 2030 to combat climate change and enable achieving carbon neutrality by 2050. It comprises actions aligned with greening of freight transport, with a focus on making each transport mode more sustainable in terms of vehicle efficiency and emissions, using sustainable fuels, and making available the recharging and refuelling infrastructure needed to decarbonise transport across modes. The EU Fit for 55 also encompasses legislation to enable a transition to renewable and low-carbon fuels across modes, including maritime transport.

The European Green Digital Coalition (EGDC) is an initiative of companies, supported by the European Commission and the European Parliament, that aims to harness the enabling emission-reducing potential of digital solutions.

ADMIRAL’s task 2.2 focused contribution is on “low emission and low energy transportation” encompassing a cross-modal/multimodal perspective and CO₂ emissions (scope 1,2 and 3) along the entire logistics supply chains.

2.2 Freight Transport Decarbonisation

Freight transportation is considered one of the most difficult economic activities to decarbonize as fossil fuels are still the main energy source for most transportation modes (Meyer, 2020).

Around 52.0% of freight (tonne-km) was transported by road in 2019 while in 2000 it was 48.7% (EEA, 2022). The volume of freight (tonne-km) transported by road increased at approximately the same rate as the economy. Sea transport was the second most important freight transport mode in terms of volume (tonne-km) which accounted for 28.9% in 2019. Also, the volume transported by sea increased by 26.2% between 2000 and 2019. Considering the UNCTAD’s Review of Maritime Transport (UNCTAD,

2023) greenhouse gas emissions have risen 20% over the last decade in the shipping industry due to the operation of an ageing fleet that runs almost exclusively on fossil fuels.

Following the European Environmental Agency (EEA, 2023), Member States foresee a continued increase in transport GHG emissions in the coming years. Road transport represents the highest proportion of overall transport emissions - emitting 76% of all EU's transport GHG emissions (including domestic transport and international bunkers, 2021 data). However, this share is likely to decrease as road transport is expected to decarbonise faster than other transport modes (Figure 1). One main reason is that most existing and planned measures in the Member States focus on road transport.

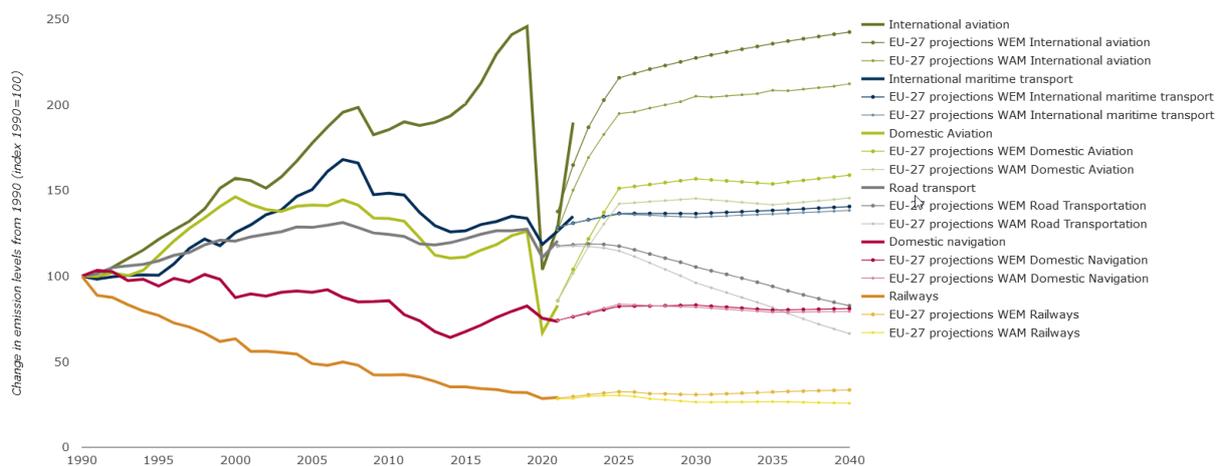


Figure 1: Projections of GHG emissions from transport modes in Europe (source: EEA, 2023)

Considering the EC DG MOVE (2023), all the scenarios that limit warming to below + 1.5 °C or below + 2 °C, as set in the Paris Agreement, rely heavily on research and technology progress and its uptake. The European Technology Platform Alliance for Logistics Innovation through Collaboration in Europe (ALICE) roadmap towards zero emission logistics 2050 (ALICE-ETP, 2019), also noted that the total emissions from freight need to be almost fully decarbonised by 2050 compared to the 2015 levels if we are to meet the climate ambitions set out in the Paris Agreement, which came into force in 2016.

Considering the International Energy Agency (IEA, 2021), 50% of the global reductions in CO₂ emissions by 2050 will have to come from technologies that are currently in the demonstration or prototype phase. Following the Net Zero Emissions (NZE) scenario developed by the International Energy Agency, decarbonisation also relies on policies to promote modal shifts and more efficient operations, along with improvements in energy efficiency. Efficient operations include, for example, seamless integration of various modes (intermodal transport) and slow steaming in shipping. Transport modes will not decarbonise at the same rate as technology maturity varies markedly between them (Figure 2). Two major technology transitions are expected to happen first:

- Shifts to electric mobility and fuel cell electric vehicles.
- Shifts towards higher fuel blending ratios & direct use of low-carbon fuels (biofuels and hydrogen-based fuels).

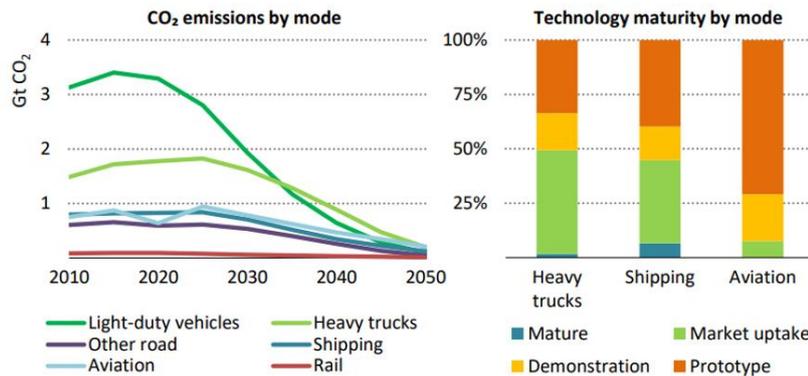


Figure 2: CO₂ emissions and technology maturity by mode (source: IEA, 2021)

Innovation is key to developing new clean energy technologies and advancing existing ones (IEA, 2021). To this end, there are several ongoing EU-funded projects related to clean energy innovation addressing waterborne and other transport modes, that are being implemented as part of co-programmed Partnerships for Zero Emissions. The “RETROFIT55 – Retrofit solutions to achieve 55% GHG reduction by 2030” project aims to develop decarbonisation solutions and green technologies that can be implemented in existing ships to reduce fuel consumption and GHG emissions including e.g., weather routing strategies based on AI and the electrification of power plants using renewable energy sources. It envisages TRL 7 (system prototype demonstration in operational environment) and plans to reach TRL 8 (system complete and qualified) until 2030. The AMMONIA 2-4 project addressing deep sea shipping aims to demonstrate at full scale two types of dual fuel marine engines running on ammonia as main fuel: a) a two-stroke (2-stroke) medium-pressure ammonia fuel injection platform, for retrofitting on existing 2-stroke marine engines, and b) a four-stroke engine, demonstrated in lab conditions closely mimicking real-life operations in ambient conditions. It expects a reduction of more than 80% GHG emissions (including nitrous oxide emissions) and achieve NO_x emissions below IMO Tier III regulations and a negligible ammonia slip below 10ppm (Euro 6 compliant). On the other hand, the FLEXSHIP project explores the potential of incorporating batteries in the waterborne fleet and aims to develop and validate safe, reliable, flexible, modular and scalable solutions for electrification of the waterborne sector. It includes a) two vessel demonstrations to validate the concept at full scale, b) real-life proof of fully electric operation on short routes, and c) virtual demonstration of operation on long routes, expecting to achieve TRL 7.

3 Identification of Freight Transport Technologies across Modes and Impacts

3.1 Background

Several researchers have studied sustainable transport from various perspectives using the bibliometric analysis method (Bao et al, 2023). However, the number of studies using data-driven review approaches is limited. Meyer (2020) used bibliometric and network analysis to examine road freight decarbonisation.

The methodology delineated in this section derives its foundation from the study submitted by LNEC authors on 26.04.2024 to an Elsevier Journal. The work submitted, in turn, draws methodological inspiration from a previously paper of the authors published in the Knowledge Based Systems journal, "Using Dynamic Knowledge Graphs to Detect Emerging Communities of Knowledge". Central to the methodologies of both studies is the employment of Bidirectional Encoder Representations from Transformers (BERT) for tasks related to semantic similarity and annotation, showcasing a cohesive application of advanced natural language processing techniques to elucidate patterns and relationships within complex data sets.

The exploration of key technologies within multimodal transport (Road, Rail, Maritime, and Crossmodal) and their research communities is undertaken through an analysis of paper networks. This research delves into community identification and analysis, drawing on foundational work by Börner et al. (2004) and extending it into the previous works on the road transport mode by Meyer (2020). Our study advances the field by incorporating semantic theme identification, evaluating cutting-edge algorithms for community detection, while addressing and emphasizing the multimodal aspect of transportation research.

3.2 Bibliographic Graph Construction

Papers are mapped as nodes within a graph, with edges representing shared references and semantic links. The edge weight between two papers, i and j , is determined by the quantity of references they share, reflecting the depth of their bibliographic connection.

3.2.1 Enhancing Semantic Connectivity

We utilize the BERT-based SentenceTransformer model to transform abstracts into high-dimensional vectors, capturing a broad spectrum of datasets. These vectors facilitate the computation of pairwise cosine similarities, creating a secondary graph (Gabstract) where edges signify semantic connections, focusing on vector orientation to encapsulate semantic nuances.

3.2.2 Unified Graph Model and Standardization

The bibliographic and semantic graphs are merged, with edge weights integrated and normalized based on both bibliographic co-occurrence and semantic parallels. Insignificant connections are pruned based on a predefined threshold, streamlining the graph to emphasize substantial links.

3.3 Dissecting Communities and Evaluation Techniques

A suite of algorithms is employed to delineate distinct community structures within the graph, guided by a comprehensive set of metrics tailored to evaluate the algorithms' efficacy. These metrics interrogate the graph's structural intricacies, ensuring a thorough and multifaceted analysis. Modularity metrics, each offering unique insights into community density and separation, are pivotal in this analysis. They range from Erdős-Rényi and Newman-Girvan modularity to Modularity Density and Z-Modularity, facilitating a broad understanding of community coherence and comparative network structure. The Silhouette Score is adapted to graph data, evaluating node placement within communities by calculating intra- and inter-community distances, offering a nuanced perspective on community fit and separation. Normalized Cut and the Normalized F1 score further dissect the community landscape, focusing on boundary clarity and the precision of community detection, respectively. These metrics underscore the algorithms' ability to accurately reflect the network's intricate community structures. Internal Density and other such metrics shine a light on the intricacy of community interrelations, highlighting the cohesiveness within and the permeability between different research clusters.

This methodological approach not only updates the scope and timespan of the analysis but also deepens our understanding of community dynamics within multimodal transportation research, setting the stage for future advancements in the field. Using the corpus from green logistics for different types of transport modes we instantiate the methodological section. To extract the scientific documentation, we used the SCOPUS database and research queries based on Meyer's Road Freight Decarbonisation Technology related research query (Mayer, 2020), however focused now the directions to several transport modes and in a different time interval, between 2020 and 2024.

The queries chosen for each one of the modes were:

- **Road:** 349 papers: (road AND freight AND transport* OR road AND goods AND transport* OR road AND logistics OR last AND mile AND logistics OR last AND mile AND deliver* OR urban AND freight AND transport* OR city AND logistics OR urban AND logistics OR ((truck* OR heavy AND goods AND vehicle OR heavy AND dutyvehicle OR large AND goods AND vehicle OR medium AND goods AND vehicle OR medium AND duty AND vehicle) AND (logistics OR transport* OR deliver* OR ship*)) AND green OR decarboni* OR environmental AND sustainab* OR ((fuel OR carbon AND emission OR carbon AND dioxide AND emission OR CO2 AND emission OR greenhouse AND gas OR ghg) AND (reduc* OR improve* OR efficiency)) AND Technology
- **Rail:** 274 papers: ("Rail* freight transport*" AND green OR decarboni* OR environmental AND sustainab* OR ((fuel OR carbon AND emission OR carbon AND dioxide AND emission OR co2 AND emission OR greenhouse AND gas OR ghg) AND (reduc* OR improve* OR efficiency)) AND "Technology")
- **Maritime:** 111 papers: (("Maritime freight" OR "Sea freight") AND green OR decarboni* OR environmental AND sustainab* OR ((fuel OR carbon AND emission OR carbon AND dioxide AND emission OR CO2 AND emission OR greenhouse AND gas OR ghg) AND (reduc* OR improve* OR efficiency)) AND "Technology")

- **Crossmodal:** 236 Papers: ("Port hinterland") AND (logistics OR transport* OR deliver* OR ship*) AND green OR decarboni* OR environmental AND sustainab* OR ((fuel OR carbon AND emission OR AND carbon AND dioxide AND emission OR co2 AND emission OR greenhouse AND gas OR ghg) AND (reduc* OR improve* OR efficiency)) AND technology

3.4 Application of Different Community Finding Algorithms

Based on the review of the algorithms for community finding Table 1), we applied this methodology for a modelling the network of scientific papers and used the following algorithms of community finding.

Table 1: Community finding algorithms tested for modelling the network of scientific papers.

Variant Implementation	Algorithm	Key Process	Detail	Applicability and Resulting Community Structure
Dongen, 2000	Markov Clustering	Random walks	Utilizes Markov chain simulations for flow analysis	Effective in identifying communities through random walk patterns in networks
Girvan and Newman, 2002	Girvan-Newman	Edge betweenness centrality	Identifies communities by removing high-centrality edges	Ideal for expansive networks, albeit with high computational demands. Finds communities connected through weaker links
Aaron, 2004	Greedy Modularity	Fast modularity optimization	Employs a greedy approach to enhance modularity	Fits large-scale networks seeking quick modularity improvements
Pons and Latapy, 2005	Walktrap	Random walks	Measures node proximity through the length of random walks	Best for detecting tightly-knit communities within networks having distinct community divisions
Newman, 2006	Eigenvector	Eigenvector centrality	Relies on the leading eigenvector of the network's adjacency matrix	Suitable for networks where nodes' centrality indicates their community affiliation
Ulrike, 2007	Spectral Clustering	Spectral graph theory	Leverages the Laplacian matrix's eigenvalues	Fits networks where spectral attributes hint at community presence
Rosvall and Bergstrom, 2008	Infomap	Information flow and random walks	Optimizes partitioning by minimizing the map equation	Excels in delineating communities in networks defined by information flow dynamics
Blondel et al., 2008	Louvain Method	Modularity optimization	Iterative modularity optimization across the network	Optimized for uncovering densely interconnected communities in vast networks
Reichardt et al., 2006	RB Potts	Potts model simulation	Adapts statistical physics' spin model	Suitable for complex networks exhibiting overlapping communities
Nandini et al., 2007	Label Propagation	Local community formation	Operates through the dynamics of label spreading	Efficient in rapidly pinpointing communities within large, locally-structured networks
Aldecoa and Martin, 2011	Surprise Communities	Surprise maximization	Seeks to maximize surprise across all partitions	Ideal for revealing unanticipated community structures within networks
Lancichinetti et al., 2011	Significance Communities	Statistical significance	Utilizes null model comparisons	Effective for networks with statistically notable community traits

Coscia et al., 2012	Demon	Ego-network analysis	Focuses on overlapping ego networks	Perfect for networks with fluid, overlapping community constructs
Coscia et al., 2014	Angel	Density-based clustering	Takes a local-first approach to identifying density	Useful in large networks with communities of varying sizes
Traag et al., 2019	Leiden Algorithm	High-resolution modularity	Enhances the Louvain method with an additional refinement step	Adept at precise community detection in networks with clear community outlines
Chen et al., 2023	Paris	Hierarchical agglomeration	Agglomerates based on similarity metrics	Suitable for hierarchical networks with communities at multiple scales

We tested 13 state of the art community finding algorithms with and without the proposed semantic weighting, in total 26 variants. The best performing one across the sum of the metrics was the Louvain with the proposed semantic similarity.

Figure 3 represents the mean scores of the community detection algorithms, providing a comparative view of their performance. The scores highlight the effectiveness of each algorithm in grouping semantically and bibliographically related documents, with higher scores indicating a stronger alignment with the underlying community structure.

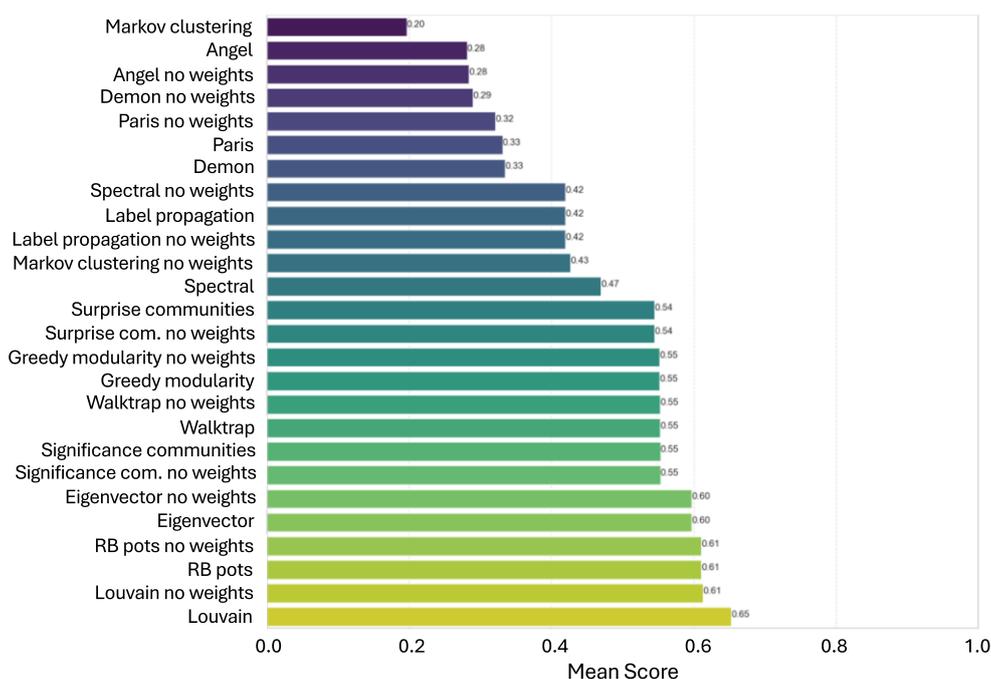


Figure 3: Mean scores obtained for the tested algorithms across the network of scientific papers.

3.5 Results

This section shows the results obtained with the developed approach for community finding within the transport modes of green logistics. Each community (cluster) is analysed based on its key technologies and approaches, its specific contributions to reduce CO₂ emissions and achieve carbon neutrality and mains KPI used for impact assessment (input to task 6.1). The review of scientific papers is discussed in more detail in chapter 5.

3.5.1 Road Transport

This section delves into the resulting communities in road transport, that focus on urban delivery, green transportation methods, and the integration of smart technologies for sustainable logistics. Figure 4 shows the network representation of the communities of papers and how they interact. The larger community is on “Sustainable urban delivery and autonomous logistics”, which seems to reflect the importance of efficiency and sustainability related criteria in urban areas where most of the population is concentrated. A distinct large community found relates to "Sustainable Logistics in Rural and Long-Distance Transport" which seems to point out the existence of a differentiated approach for addressing logistics decarbonization challenges at the urban and interurban (long-distance) scales. The smaller community, "Urban Freight Planning and E-commerce Impact," with 8 nodes, might be indicative of an emerging research area or a response to a recent trend as the impact of e-commerce on urban freight planning is becoming increasingly important. As this field grows, it might become more integrated with larger communities focused on last-mile distribution and systematic urban planning, reflecting the evolving nature of consumer habits, the emergence of new modes for cargo and the direct effect on urban transport infrastructures.

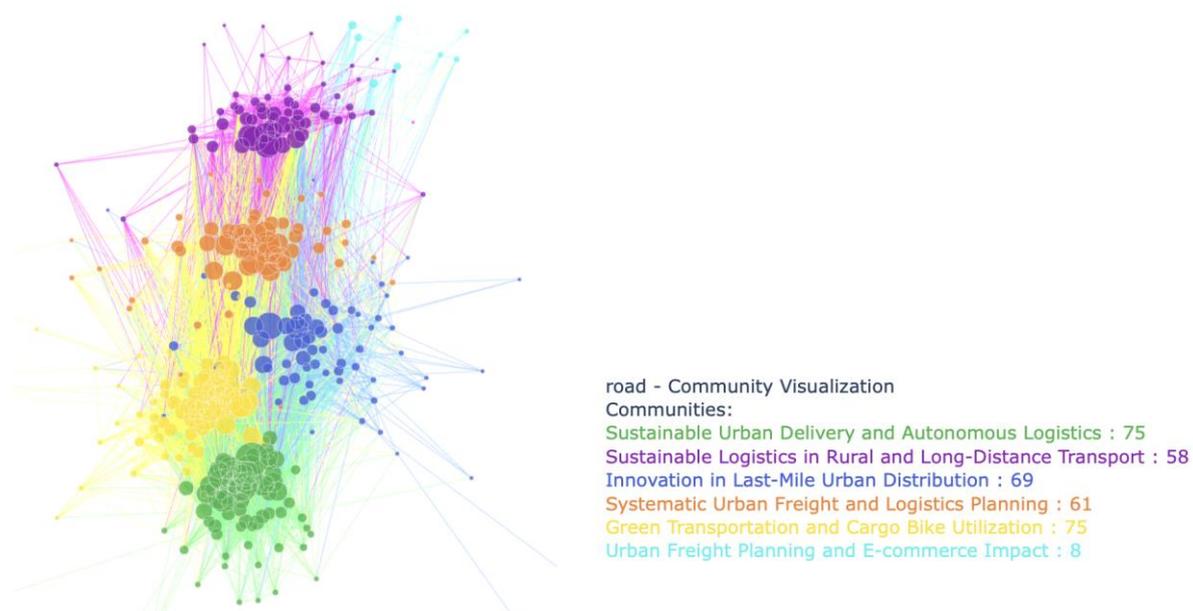


Figure 4: Road Transport Communities Graph Output.

Table 2: Road transport communities (clusters), key technologies, contribution to carbon neutrality and KPI themes

Community Name	Key Technologies	Contribution to Carbon Neutrality	KPI Themes
Sustainable Urban Delivery and Autonomous Logistics	Autonomous delivery vehicles, AI-driven route optimization, Electric and hybrid delivery vehicles, and robotic delivery systems	Reduction of emissions through optimized delivery routes and efficient urban logistics	GHG emissions (kg CO2e), Energy consumption (kWh), Increase in vehicle telematics utilization (%)

Green Road Transportation and Cargo Bike Usage	Advanced bike-sharing systems, Electric cargo bikes, Infrastructure for bike lanes and charging stations	Reducing reliance on fossil fuels and promoting low emission road transport	Energy consumption (kWh), Renewable energy usage (%), Fuel renewable sources
Systematic Urban Freight and Logistics Planning	Big data analytics IoT devices for real-time tracking, Smart city integration for goods distribution, Digital communities	Enhanced logistics efficiency and reduced traffic congestion	Supply chain efficiency (%), Urban transport emissions (MtCO2e)
Sustainable Logistics in Rural and Long-Distance Transport	Electric long-haul trucks, Advanced fleet management systems, Renewable energy integration in logistics hubs with Biofuels and Electric vehicles, Long-distance route optimization	Reducing emissions in long-distance road transport and enhancing supply chain sustainability	Adoption of renewable energy sources, Energy usage (Liters of fuel or kWh), Renewable energy sources adoption (%)
Urban Freight Planning and E-commerce Impact	AI and machine learning for demand forecasting, Urban warehousing solutions, E-commerce logistics optimization, Urban freight planning technologies	Optimizing delivery networks and reducing the carbon footprint of e-commerce logistics	Emissions per delivery (MtCO2e), Time spent in traffic (hours), On-time delivery rate (%)
Innovation in Last-Mile Urban Distribution	Smart Material Handling Solutions, Home-refill delivery services, Smart technology for tracking and tracing containers, Electric vehicle for urban logistics	Using advanced logistical solutions and environmentally conscious delivery methods to reduce carbon footprint in urban areas	Delivery time (minutes), First-time delivery success rate (%), CO2 emissions per delivery (kg CO2e)

3.5.2 Rail transport

This section presents the resulting communities in rail transport, which emphasizes the key role of multimodal freight transportation optimization and environmental impacts of freight corridors in supply chains.

Figure 5 shows the network representation of the communities of papers and how they interact. The cluster "Multimodal Freight Transportation Optimization" is a highly central and interconnected community suggesting a major hub of innovation and focus within the rail mode. The topology shows that larger communities are interconnected, suggesting that disciplines such as "Environmental Impacts of Freight Corridors" and "Emission Analysis in Transportation Modes" are not operating in silos but rather are sharing knowledge and possibly influencing each other.

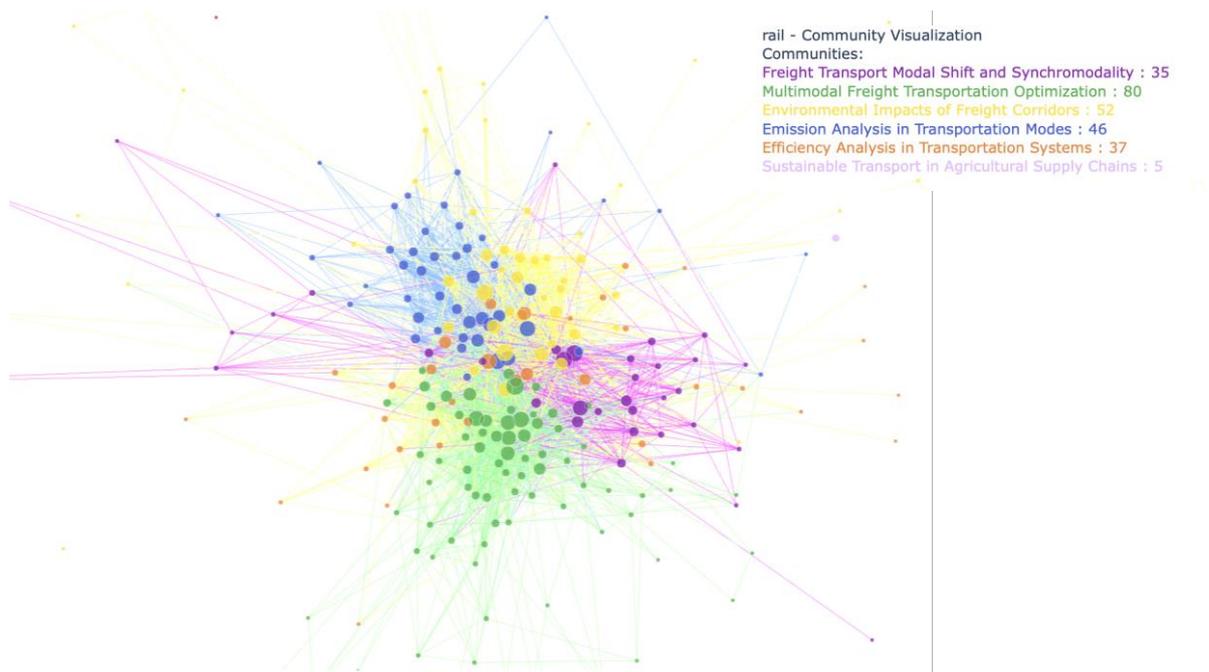


Figure 5: Rail Transport Communities Graph Output

Table 3: Rail transport communities (clusters), key technologies, contribution to carbon neutrality and KPI themes

Community Name	Key Technologies	Contribution to Carbon Neutrality	KPI Themes
Multimodal Rail Freight Optimization	Route optimization, Optimization of Cargo Load, Supply chain management	Advances in route optimization lead to fewer empty runs and decreased fuel usage. Enhanced cargo load efficiency reduces the number of trips and related emissions.	Energy efficiency improvement (%), GHG emissions reduction (kg CO ₂ e per tonne-km), Modal shift (%)
Environment Impacts of Freight Corridors	Air Pollutants monitoring, Emission analysis tools, Sustainable freight models, Environmental impact assessment	Monitoring of air pollutants informs strategies to reduce emissions in freight operations. Implementation of freight models that lowers carbon footprint	Particulate matter reduction (PM ₁₀ , PM _{2.5} , µg/m ³), Noise level (dB)
Emission Analysis in Rail	ASIF method, accounting methods, Alternative fuels	Promoting cleaner fuels, Accurate environmental assessments	VOC emissions reduction (kg per mile), Biofuel utilization rate increase (%)

<p>Efficiency Analysis in Rail Systems</p>	<p>Belief rule-based systems, Braking technology, Cross efficiency evaluation, Autonomous driving, Centralized data envelopment analysis for efficiency, Real-time fleet management software</p>	<p>Adoption of energy efficient driving technologies minimizes power consumption. Datacentric approaches to fleet management optimize operational efficiency, curtailing emissions.</p>	<p>Efficiency gain in transport systems (%)</p>
<p>Freight Transport Modal Shift and Synchromodality</p>	<p>Synchromodality with Integrated transport platforms, Intermodal transport scheduling systems, Blockchain-based systems, Dual sourcing</p>	<p>Promoting efficient transport modes, Reducing emissions through Modal shift strategies, Improved transparency</p>	<p>Efficiency in modal shift (% improvement), Supply chain optimization level (%)</p>
<p>Supply Chains for Alternative fuels</p>	<p>Biofuel production techniques, Biomass energy systems, Conversion technologies</p>	<p>Reducing fossil fuel dependency promoting renewable energy, Higher efficiency in conversion</p>	<p>Water Usage Efficiency in Biofuel Production (L/GJ), Energy Yield per Hectare for Biofuel Crops (GJ/ha), Reduction in Metric Tons of CO2 Equivalent Reduced (MtCO2e), Biofuel Production Efficiency (L/ton)</p>

3.5.3 Maritime transport

This section discusses the generated communities in maritime transport. These point out emerging advancements in maritime logistics innovation and on sustainability and safety in harsh environments, and the role of technology in reducing environmental impacts.

Figure 6 shows the maritime graph representation of the communities of papers and how they interact. The "Maritime Logistics Innovation" community has higher spread due to more semantic heterogeneity, meaning less cohesion which may indicate a starting stage of new research directions. The "Arctic Shipping Routes" and "Arctic Maritime Safety and Sustainability" communities, while distinct, both have a significant number of nodes, and their proximity in the network suggests that they are likely interrelated fields with co-evolution.

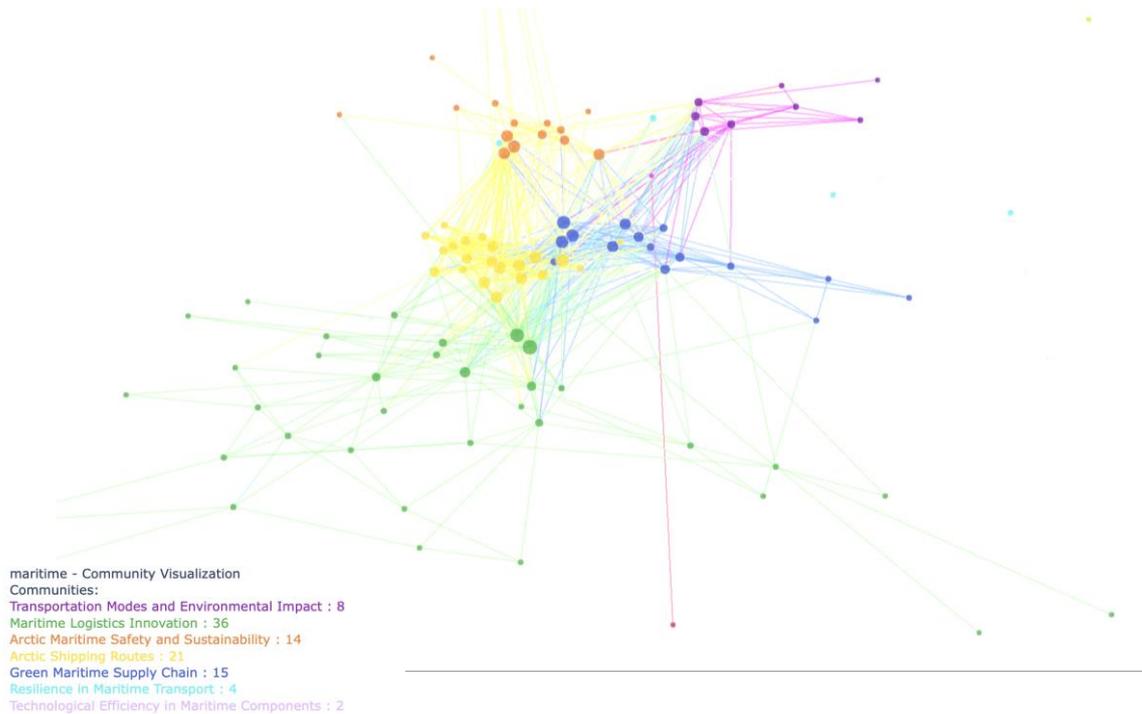


Figure 6: Maritime Transport Communities Graph Output

Table 4: Maritime transport communities (clusters), key technologies, contribution to carbon neutrality and KPI themes

Community Name	Key Technologies	Contribution to Carbon Neutrality	KPI Themes
Maritime Logistics Innovation	Blockchain, IoT services, Digital platforms, Smart technology for tracking and tracing containers	Streamlining maritime logistics through digitalization leading to reduced fuel consumption and operational efficiencies.	GHG emissions reduction (Metric Tons CO _x , NO _x and SO _x), Energy consumption reduction (GJ), Increase in document digitalization rate (%)
Arctic Maritime Safety and Sustainability	Autonomous ships, Ice prediction technologies, Advanced navigation systems, Ice-resistant hull designs, SO _x Scrubbing Systems, Selective Catalytic Converters, Cold ironing in shipping, Route optimization, Slow steaming, Wind Power for energy production	Enhancing navigational safety and reducing the need for heavy fuel use in Arctic conditions. Reducing the distance and time of voyages, hence lowering fuel use and emissions.	SO ₂ emissions reduction (kg per nautical mile), CO ₂ emissions reduction through EEDI (%), Ice prediction accuracy improvement (%), Emissions reduction (GHG, NO _x , SO ₂ , CO ₂) per ton-mile (kg CO ₂ e), Voyage time reduction (hours)
Green Maritime Supply Chain	LNG, Biofuels, Electricity (from renewable sources) and e-fuels, Environmental management systems	Implementing eco-friendly practices in maritime supply chains, thereby reducing emissions and promoting sustainability.	Particulate matter reduction (PM ₁₀ & PM _{2.5} and µg/m ³), Improvement in energy efficiency ratio (%)

Maritime Transportation and Environmental Impact	Energy efficiency technologies like hull designs and air lubrication, Hydrogen, Solar Power, Wind Power for energy production	Focusing on reducing the carbon footprint of various fuel and design types including the adoption of cleaner fuels.	CO2 emissions reduction per EEOI (gCO2/tonne-km), Biofuels utilization rate (%)
Resilience in Maritime Transport	AI-driven simulation models, Crisis management protocols, Real-time monitoring of shipping, Fleet/emissions monitoring along the supply chain	AI models and real-time monitoring boost shipping efficiency, cutting down on idle time and fuel use. Crisis protocols and emissions oversight aid in maintaining low-carbon operations for fleets.	Operational carbon intensity reduction (CI) annually (% of gCO2/tonne-km), Energy consumption reduction (TJ)
Technological Efficiency In Maritime Transport	High-performance materials, Energy-efficient manufacturing processes, Waste Heat recovery systems, Coating to reduce drag	Advancing the efficiency of maritime transport, leading to lower energy usage and reduced emissions in the maritime sector.	Improvement in energy efficiency (%), GHG emissions reduction per tonne-km (kg CO2e)

3.5.4 Cross-modal transport

This section details the generated communities within cross-modal transport. These focusing on the central role of innovative logistics and transportation optimization, port operations, and the role of technology in enhancing efficiency and sustainability. Figure 7 shows the network representation of the communities of papers and how they interact. "Advanced Logistics and Transportation Optimization" cluster indicates not just a large community, but one with potentially high levels of interaction among its members suggesting a dynamic and active field where research, policies, or technologies are rapidly evolving and where collaboration is frequent. The cluster "Environmental Impact of Urban-Port Interfaces" is less connected to other communities, it might operate within a more specialized or regulatory framework. Conversely, "Blockchain and Sustainability in Shipping," interconnectedness suggests a synergy between different areas of practice, where developments in one area could have cascading effects on others.

Communities that are positioned on the periphery of the network, such as "Resilience and Government Role in Port Systems," often represent emerging or specialized disciplines that may not yet be fully integrated into the main thematic areas. Their position in the network might also reflect a nascent stage of development, indicating potential areas for future investment and research as their relevance grows in response.

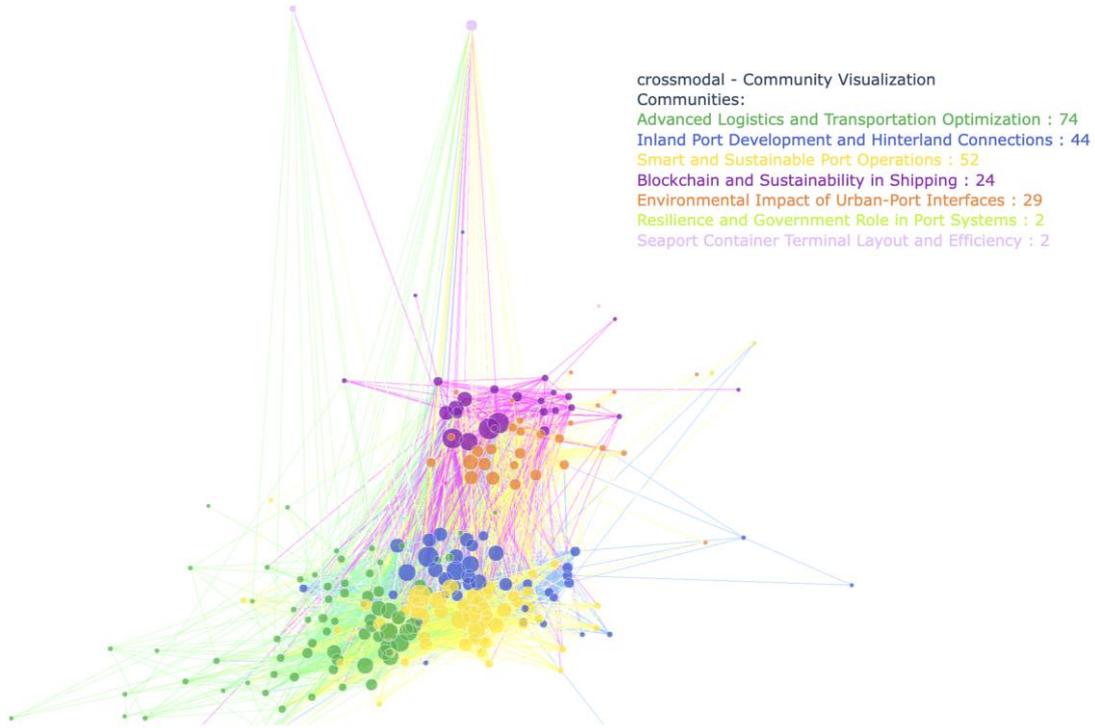


Figure 7: Cross-modal Transport Communities Graph Output

Table 5: Cross-modal transport communities (clusters), key technologies, contribution to carbon neutrality and KPI themes

Community Name	Key Technologies	Contribution to Carbon Neutrality	KPI Themes
Advanced Logistics and Transportation Optimization	Advanced optimization algorithms, Predictive analytics, AI-driven logistics planning	Optimizing routing and scheduling to reduce fuel consumption and minimize logistics operations leading to carbon emissions reduction	Supply chain efficiency (%), Energy consumption (GJ), Carbon emissions (Mt CO2e)
Smart and Sustainable Port Operations	IoT sensors and smart grid systems, Blockchain, Smart contracts, Digital ledger technology, Renewable energy integration, Energy Storage Systems (ESS)	Facilitating efficient supply chain management, Reducing redundant operations and emissions in shipping	GHG emissions (Mt CO2e), Energy efficiency (%), Document digitalization rate (%)
Inland Port Development and Hinterland Connections	Intermodal transport systems, Efficient cargo handling, Logistics management software	Streamlining cargo transfer and improving connectivity decreasing transport-related emissions	Modal shift (%), Intermodal connectivity efficiency (%)

Resilience And Government Role in Port Systems	Sustainability Reporting Standards, Risk Management Software, Stakeholder collaboration platforms	Ensuring sustainable port operations and long-term carbon emissions reduction through government policies and resilience planning	Climate Policy Integration, Technology Readiness Level (TRL)
Seaport Container Terminal Layout and Efficiency	Layout optimization software, Automated container handling systems	Reducing fuel use and operational inefficiencies in container terminals, cutting down carbon emissions	Unit cost of delivery, Load factor (%)
Environment Impact of Urban-Port interfaces	Integrated Data Management Systems, Geographic Information Systems (GIS), Environmental Management Systems	Enhanced knowledge and strategic planning, Strategic location selection of dry ports, Assessment and improvement of ecological impacts	GHG emissions, Efficiency in Cargo handling and transfer, Energy Consumption (kWh/ton)

4 Survey and Semi-Structured Interviews with Worldwide Companies across Country Pilots

4.1 The Survey and Semi-Structured Interview Development

A survey tool was developed by LNEC covering the wide range of transport technology options identified in the literature review. The aim is to further investigate the role of technology versus non-technology related factors in sustainability transitions for the Net Zero across modes, targeting worldwide companies and stakeholders related to the ADMIRAL pilots.

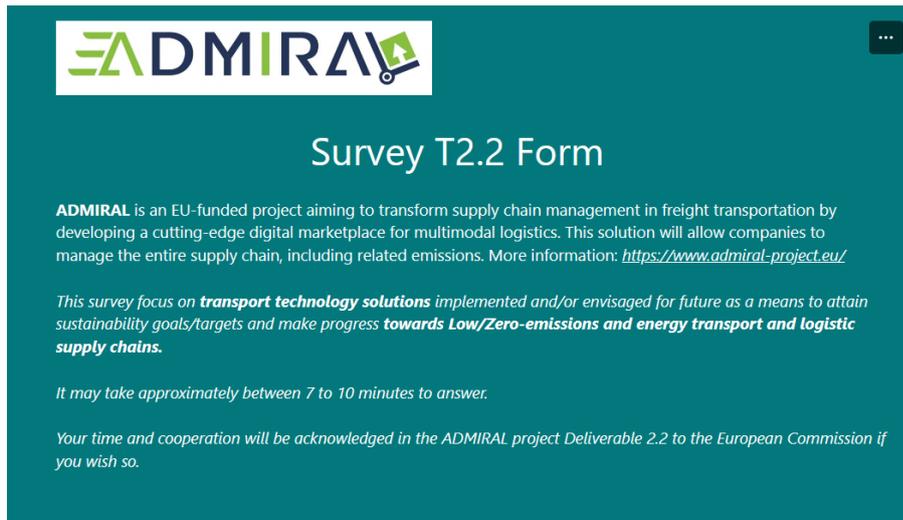
The final version of the online survey (and its QR code) was delivered to partners by 09.11.2023, before the Transport Innovation Forum 2023 in Vilnius held on 23-24 November 2023, to be included in the dissemination package to worldwide companies present in the event. Figure 8 shows the initial survey screen, the QR code for mobile phones and the introductory part. The survey model was developed in google forms and it can be easily accessed: <https://forms.office.com/e/ri5SBXa9hY>.

The survey model was transformed into an alternative semi-structured interview (Annex) to be implemented at the micro-level (Pilot level). Semi-structured interviews are a qualitative research method that allows to explore the topic addressed in the survey in depth with the interviewee company, while following a flexible and adaptable guide of open-ended questions that relate to the research. As such, other follow-up questions can be posed to each company to link with their sequential outcomes and order of questions can be slightly adapted in each part (Transitioning from “now” to the “future”).

The following methodology was agreed with all Pilot Leaders and partners in the November WP2 Working Meetings of 9.11.2023 and 30.11.2023: each Pilot leader (APS, PS, STEVECO, TIA) was asked to select 6 stakeholders (minimum of 3 stakeholders/companies with transport operations across supply chains) and to be interviewed (list of stakeholders identified in task 2.1) and promote the first contact with each of them, then make a copy of the e-mail to the WP2 Leader for LNEC to proceed with the follow-up scheduling of the interview with the indicated person(s). The interview via Teams with each company was conducted by the LNEC WPL supported by two team members. This procedure could be followed in Lithuania, Portugal-Spain, and Slovenia-Croatia.

The semi-structured interviews applied at the micro-level for the case of the Pilot Portugal-Spain also explored other issues related to expectations and needs of the stakeholders on the corridor Sines to Madrid, to explore synergies between WP2 and WP5.

At the beginning of each semi-structured interview online, LNEC asked if written notes could be taken. All interviewed companies agreed so and that the names (of companies) can be mentioned, and acknowledgments included in the Deliverable. It was agreed that LNEC will report only aggregate findings (common to more than one company) and not individual quotes that contain sensitive information.



ADMIRAL is an EU-funded project aiming to transform supply chain management in freight transportation by developing a cutting-edge digital marketplace for multimodal logistics. This solution will allow companies to manage the entire supply chain, including related emissions. More information: <https://www.admiral-project.eu/>

This survey focus on **transport technology solutions** implemented and/or envisaged for future as a means to attain sustainability goals/targets and make progress **towards Low/Zero-emissions and energy transport and logistic supply chains**.

It may take approximately between 7 to 10 minutes to answer.

Your time and cooperation will be acknowledged in the ADMIRAL project Deliverable 2.2 to the European Commission if you wish so.



Part I - Information about the "Stakeholder"

1. **Name of Company/Organization/Government ***

Introduza a sua resposta

2. Did you previously joined the **ADMIRAL "Stakeholder Forum"** by **filling the Form?** *

Yes

No

3. Please select your **Role in the Company ***

Decision-Maker (Governance, Environment, Social issues of the company)

Management role that is likely to influence Institutional decision-making

Technical/Analyst role that is likely to influence Institutional decision-making

Outro

4. Does your company publish annual **sustainability reports?** *

Yes

No

I don't know

5. Are you aware of the **European Corporate Sustainability Reporting Directive (CSRD)** that entered into force on 5 January 2023? *

Yes

No

Figure 8: Survey introduction (left) and the respective QR code (right).

Part II of the survey focused on the technology solutions implemented to address sustainability goals at present on specific categories: Alternative Fuels (Figure 9), Selective Emissions Reductors (Figure 10), Energy Efficiency (Figure 11), Digitalization and Real Time Monitoring (Figure 12) and Connectivity solutions and automated driving Systems (Figure 13).

Part II - Technology Solutions implemented to address sustainability goals

6. Has your company implemented or has under implementation any technology solution/measures to reduce **carbon related emissions and/or improve energy efficiency**? *

Yes

No

7. Please select all the measures implemented (or under implementation) for **Alternative fuels** *

Liquefied natural gas (LNG)

Biofuels

Synthetic fuels

Hydrogen

Ammonia

Electricity (production of energy from renewable sources) or e-fuels

On shore power supply from renewable energy

I have not implemented any measure of this category

Outro

Figure 9: Survey Part II – Alternative Fuels

8. Please select all the measures implemented (or under implementation) for **Selective Emissions Reductors** *

- SOx Scrubbing System
- Selective Catalytic Converter
- Carbon capture, utilization and storage
- Cold ironing in shipping
- I have not implemented any measure of this category
- Outro

Figure 10: Survey Part II – Selective Emissions Reductors

9. Please select all the measures implemented (or under implementation) for **Energy Efficiency** *

- Eco-driving
- De-speeding trucks
- Route optimization
- Reverse logistics
- Mode choice optimization
- Cargo sharing for last-mile logistics
- Optimization of Cargo Load
- Slow steaming
- Wind Power for energy production
- Solar Power for energy production

- Waste Heat recovery systems
- Coating to reduce drag
- Platooning
- Supply chain management
- I have not implemented any measure of this category
- Outro

Figure 11: Survey Part II – Energy Efficiency measures

10. Please select all the measures implemented (or under implementation) for **Digitalization and Real-time monitoring** *

- Single logistic window (management of all kinds of data, from vessel data such as contracts and reservations to human resources management, and operations)
- Smart technology for tracking and tracing containers
- Cargo planning
- Carbon emissions calculator tool
- On-line customer service
- Digital community for collaboration of various stakeholders
- Real-time monitoring of shipping
- Real-time monitoring of road cargo
- Fleet/emissions monitoring along the supply chain

- I have not implemented any measure of this category
- Outro

Figure 12: Survey Part II – Digitalization and Real-time monitoring

11. Please select all the measures implemented (or under implementation) for **Connectivity solutions and automated driving systems** *

- Truck Platooning
- Autonomous road trucks
- Autonomous rail services
- I have not implemented any measure of this category
- Outro

Figure 13: Survey Part II – Connectivity solutions and automated driving systems

Part III of the survey focused on future solutions to address sustainability goals (Figure 14), including any type of measure ranging from social, environmental to governance issues. Other questions aimed to gather information on the most important measures that are perceived by companies to be

associated to higher reductions on carbon emissions if applied until 2030 (Figure 15), and measures that are likely to be associated to higher improvements in energy efficiency (Figure 16). Other questions related to the ADMIRAL main themes that companies consider that more information or training will be useful or needed.

Part III - Future Solutions to address sustainability goals

13. **Which solutions would you like to implement until 2030 to attain sustainability goals? You can include any type of measure ranging from social, environment to governance issues**
(max 200 words)

Introduza a sua resposta

Figure 14: Survey Part III – Future solutions to address sustainability goals

14. If some measures of the list below are implemented in your company until 2030, which ones do you consider that will generate a **higher reduction on carbon related emissions in transport and supply chains?** *

- Alternative fuels in shipping
- Electrification of the road fleet
- Intermodal transport
- Truck platooning
- Automated cargo rail services
- Automated road fleets
- Alternative fuels in the production of energy for all transport surface modes
- Selective Emission Reductors (e.g. Sox in shipping)
- Digitalisation and real-time monitoring of operations
- Connectivity solutions and automated driving systems
- European Directive /Corporate Sustainability Reporting Directive – account for direct and indirect CO2 emissions along the whole supply chains
- Digital platform for collaboration of various stakeholders
- Shift of cargo from road to rail transport
- Policy incentives to greener supply chains
- Internalisation of external costs of transport through environmental charges
- I do not have information on the impacts of measures
- Outro

Figure 15: Survey Part III – Measures to conduct to a higher impact on emissions reduction

16. If some measures of the list below are implemented in your company until 2030, which ones do you consider that will generate a **higher improvement** on energy efficiency **in transport and supply chains?** *

- Electrification of the road fleet
- Fuel Cell Electric Vehicles
- Alternative fuels in shipping
- Intermodal transport
- Truck platooning
- Autonomous cargo rail services
- Autonomous road fleets
- Alternative fuels in the production of energy for all transport surface modes
- Digitalisation and real-time monitoring of operations
- Connectivity solutions and automated driving systems
- Digital platform for collaboration of various stakeholders
- Outro

Figure 16: Survey Part III – Measures to conduct to a higher improvement in energy efficiency

4.2 Main Findings from the Survey and Semi-Structured Interviews

4.2.1 Sample of respondents

Table 6 presents the sample of companies/stakeholders that participated in the survey and the semi-structured interviews. The duration of each semi-structured interviews was around 60 minutes.

The sample (Table 6) has a total of 21 participants from Finland (10%), Lithuania (29%), Portugal-Spain (38%), Slovenia-Croatia (24%). As agreed by the interviewed companies, findings from the set of semi-structured interviews (12) will be shown as aggregated (common answers/views of companies).

Table 6: Sample of respondents

Company/stakeholder	Pilot Country	Survey	Semi-structured interview date
Steveco Oy	Finland	X	-
TIA	Lithuania	X	-
Posta Slovenije	Slovenia	X	-
UAB Orion Global pet	Lithuania	X	-
Retal Baltic Films UAB	Lithuania	X	-
REAU Production LT UAB	Lithuania	X	-
Espersen Lietuva	Lithuania	X	-
UPM Logistics	Finland	X	-
Fontana d.o.o	Croatia	X	-
TML Global TEUS	Portugal-Spain	-	12.12.2023
LogiFrio	Portugal-Spain	-	19.12.2023
Medway	Portugal-Spain	-	20.12.2023
Tranfesa Logistics	Portugal-Spain	-	18.01.2024
RENFE Mercancias	Portugal-Spain	-	22.01.2024
COSCO shipping	Portugal-Spain	-	23.01.2024
PSA-BDP international	Portugal-Spain	-	20.02.2024
MSC Mediterranean Shipping	Portugal-Spain	-	27.02.2024
IKI logistics	Lithuania	-	19.01.2024
University of Maribor expert	Slovenia	-	10.01.2024
VITAPUR	Slovenia	-	05.03.2024
Tehit d.o.o.	Croatia	-	05.03.2024

4.2.2 Main findings

The findings are analysed for each case in an aggregated way, considering the agreements with the companies/stakeholders that provided answers to the survey and the semi-structured interview,

Figure 17 provides an overview of the reference state of companies (baseline) regarding the implementation of measures for reducing CO₂ emissions and to improve energy efficiency, noting that there are 8 valid answers to the survey covering inland and sea transport related companies. 25% of the companies mentioned that they are not aware of the European Corporate Sustainability Reporting Directive (CSRD) that entered into force on 5th January 2023, and 50% of these companies mentioned that they already publish annual sustainability reports. Nevertheless, all the companies mentioned to have implemented measures to reduce CO₂ emissions and/or to improve energy efficiency. In sea transport, alternative fuels (e.g., ammonia, LNG) along with digitalization and real-time monitoring measures (e.g., cargo planning and real-time monitoring of ships) and SOx Scrubbing Systems are dominant. In the case of inland transport modes energy efficiency measures are dominant (e.g., optimization of cargo load, route optimization, eco-driving, supply chain management). Overall, the reference state seems to reflect the high importance of digital/soft tools across the whole supply chain.

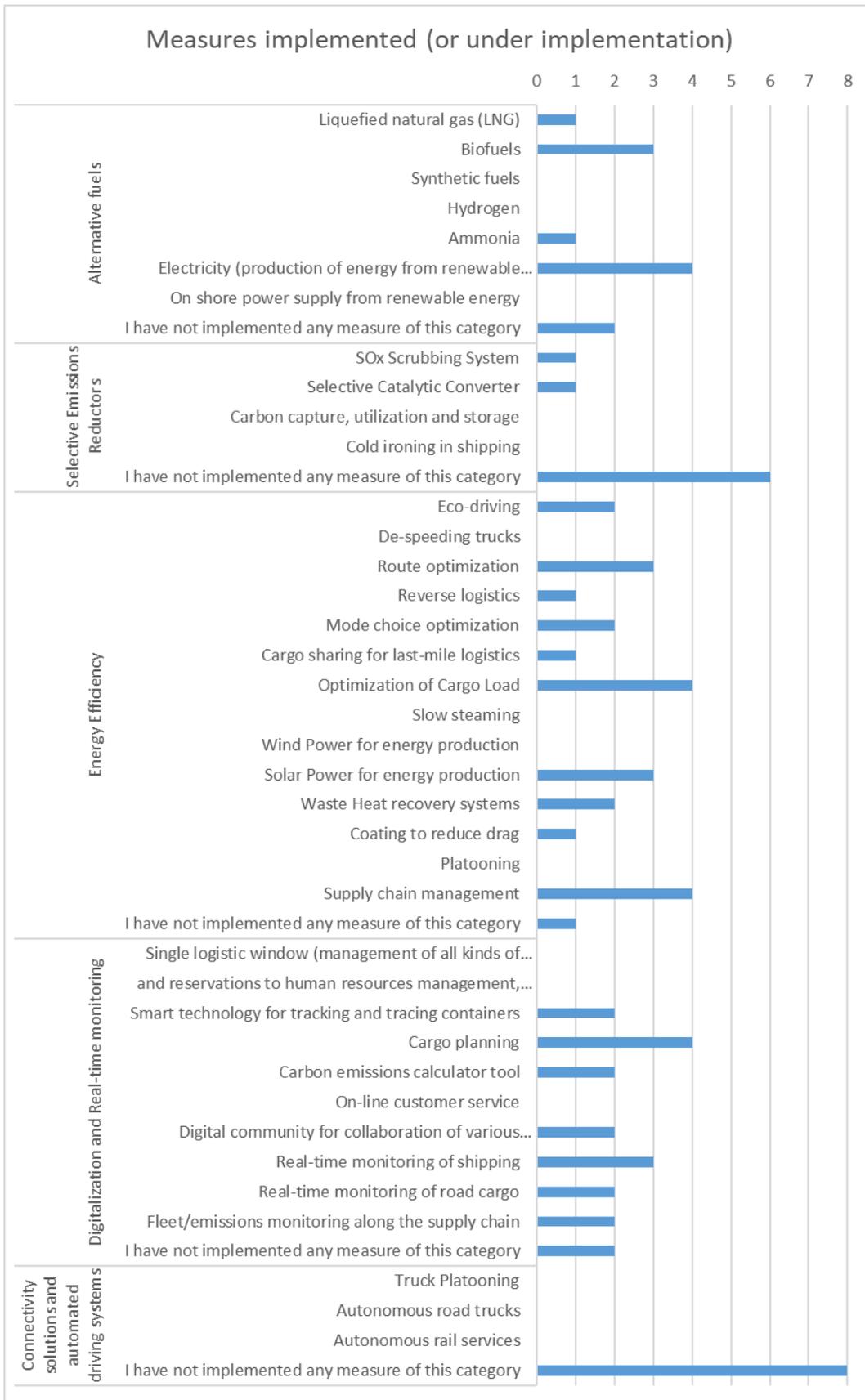


Figure 17: Reference state – Measures implemented (or under implementation) to reduce CO2 emissions and improve energy efficiency

Figure 18 shows the future state (2030) - the measures that are considered by the sampled companies to be associated with higher reductions in CO2 emissions in transport and supply chains. The most important set to be implemented comprise alternative fuels in shipping, digitalization, and real-time monitoring of operations, electrification of the road fleet, digital platform for collaboration of various stakeholders and intermodal transport.

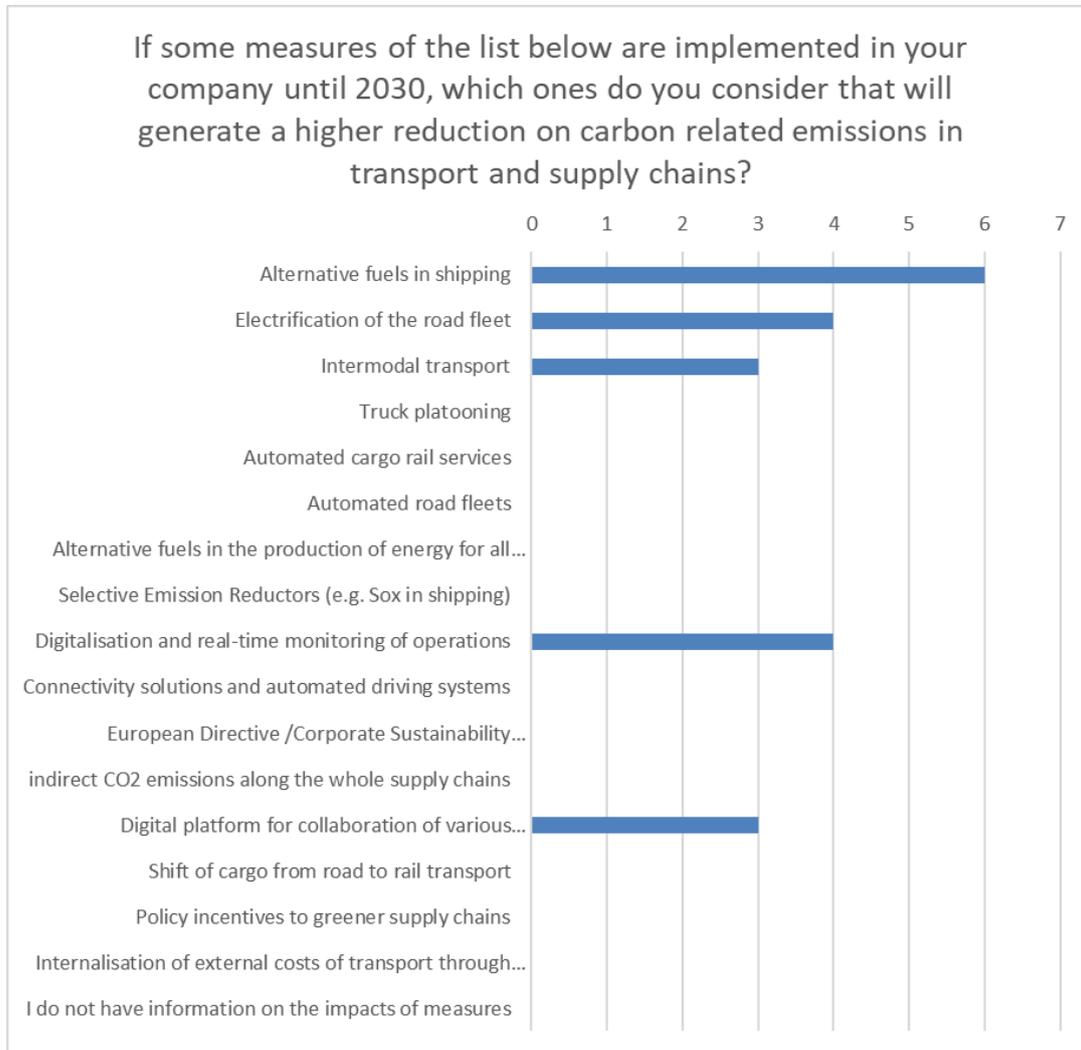


Figure 18: Future state (2030) – Measures with higher impact on reduction of CO2 emissions across modes

Figure 19 shows the future state (2030) - the measures that are considered by the sampled companies to be associated with higher improvements in energy efficiency in transport and supply chains across modes. The most important set to be implemented comprise the electrification of the road fleet, alternative fuels in shipping, intermodal transport and digitalization and real-time monitoring of operations.

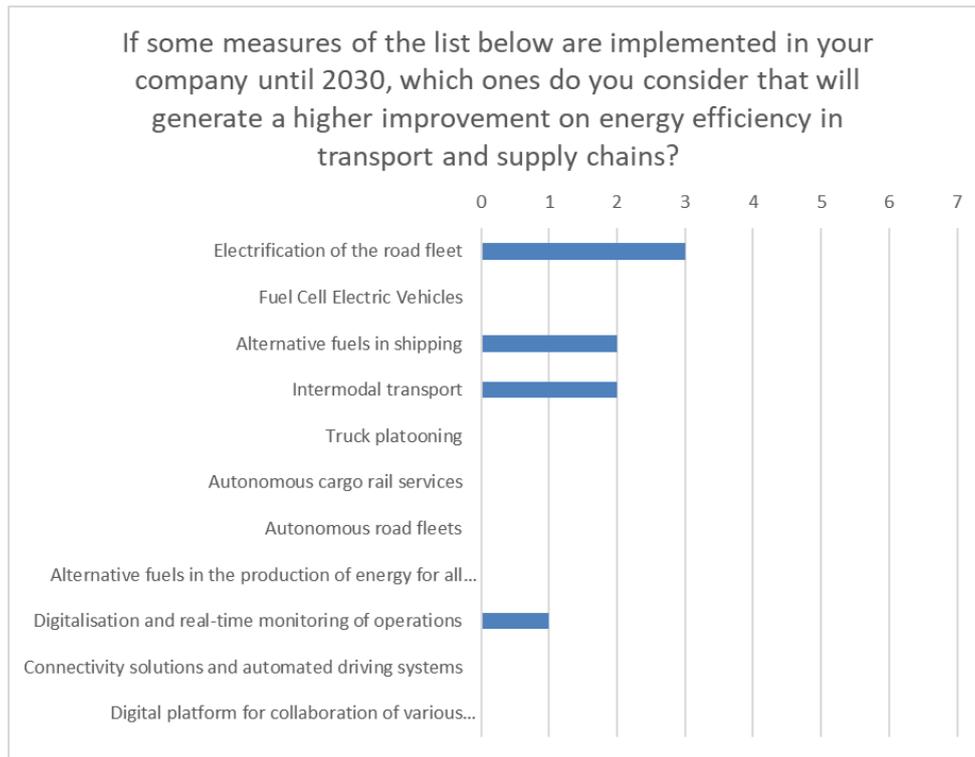


Figure 19: Future state (2030) – Measures with higher impact on improving energy efficiency

Considering the 12 semi-structured interviews conducted (Table 6), the main aggregated findings can be summarised as follows:

- Most companies said to address sustainability issues and consider important to reduce GHG emissions. Some worldwide companies interviewed already estimate direct and indirect CO2 emissions, e.g., with EcoTRANSIT (ISO 14083 and GLEC-compliant calculation).
- Common problems to most companies are on scope 3 emissions (due to the complexity), data sharing (inland transportation with shipping) and lack of primary data.
- Regarding the role of technology versus non-technological factors on the transitions to Net Zero, worldwide shipping companies attach a higher weight to IoT, blockchain and use of soft tools such as optimization tools. Also, for collaborative logistics (e.g., shipping lines with freight transporters).
- Optimization tools are important at present across all modes; however, most companies do not yet include environmental criteria in their priority. Efficiency (e.g., delivery time and cost) is the dominant criteria at present. There is a need for transparent and harmonized tool to calculate CO2 emissions (scope 1,2,3).
- Optimization to reduce “empty miles” will be determinant for business development for road and rail modes.
- Digital technologies and platforms (and improving existing ones) can play an important role in facilitating services and its productivity.
- Some companies are unsure about the future role of alternative fuels such as hydrogen and

biofuels, identifying the need to have governmental incentives, adequate regulation, and standards.

- Other companies are interested in renewable energy (alternative fuels focus) and electrification.
- Electrification of road freight transport (electric trucks) is expected to happen until 2030 but do require other measures (including higher coverage of charging stations along freight routes) and intermodal transport.
- Inland Transport Companies consider that shifting freight from road to rail is the best measure to reduce CO₂ emissions along with intermodal transport. However, this shift of mode is complex (road is dominant).
- Worldwide shipping companies consider that the implementation of measures requiring high infrastructure investments are unlikely to be implemented until 2030 and consider digital tools as the most relevant. Some inland transport companies mentioned that better use of existing resources (e.g., vehicles) can lead to emissions reduction.
- Companies seem to attach higher importance to the economic implications of technology across modes and Port tariffs and refer the need to reduce uncertainty on the costs for future adoption. This seems to indicate that complementary measures are needed to promote the desired shift to Net Zero.

One interesting finding is that worldwide shipping companies seem to attach a higher role for reduction carbon emissions and improving energy efficiency from current/future digitalization and monitoring technologies in shipping and inland transport (in comparison to all other technology categories), slow steaming and, possibly, to alternative fuels (e.g., e-Methanol, biofuels) as these are engaged in some running demonstration projects. Despite the importance sustainability has in their vision and practice, all companies confirmed the actual priority given to efficiency related criteria (time and cost related KPIs) in current optimisation tools.

5 List of Emerging Low Emission and Low Energy Transport Technologies and Methods: impact indicators to draw future scenarios

This chapter presents the detailed review of the scientific literature addressing low emission and low energy transport technologies covering the following modes: road, rail, maritime and cross-modal. The list of technologies and methods are grouped into main categories, encompassing a total of 52 solutions/measures distributed as follows: 1) Alternative fuels - 9 solutions; 2) Selective Emission Reductors - 7 solutions; 3) Energy Efficiency - 13 energy efficient solutions & 7 sustainability through collaboration related measures; 4) Digitalization and Monitoring - 9 solutions; and 5) Connectivity and Automated Systems - 7 solutions. The list of emerging technologies and their potential impacts are identified to support drawing future scenarios aligned with the Net Zero goal.

5.1 Alternative fuels

Alternative fuels (AFs) are often designated as clean fuels or non-conventional fuels and offer the potential to reduce GHG emissions through the replacement of conventional fossil fuels. Considering the European Alternative Fuels Observatory (EAFO), that started in 2015, AFs encompass fuels or power sources which serve, at least partly, as a substitute for fossil oil sources in the energy supply to transport and which have the potential to contribute to its decarbonisation and enhance the environmental performance of the transport sector. The mentioned definition of AFs is included in article 2(1) of the European Directive 2014/94/EU on the deployment of alternative fuels infrastructure.

5.1.1 Liquefied Natural Gas (LNG)

Liquefied Natural Gas (LNG) is increasingly recognized as a transitional fuel in the maritime and haulage sectors due to its lower carbon footprint compared to conventional fuels. It significantly reduces emissions of nitrogen oxides, particulate matter, and sulphur oxides. However, concerns about methane leakage during the LNG lifecycle warrant attention due to methane's potent greenhouse effect (Gray et al., 2021).

The infrastructure for LNG is also expanding, though it requires substantial investment. Additionally, LNG has the potential to reduce greenhouse gas (GHG) emissions in the maritime sector. It can reduce CO₂ emissions by 20-30% and has similar effects on other emissions such as SO_x (Livaniou et al., 2021).

However, considering Adamopoulos (2021), Maersk openly stated that LNG did not have a role to play and questioned why the shipping industry would invest so much on expensive LNG-fueled vessels and new logistics infrastructure only to secure marginal lifecycle emission gains and risk methane slip from burning LNG.

5.1.2 Biofuels (Biodiesel, Bioethanol)

Biofuels have the capability to reduce GHG emissions, but the extent of the reduction varies depending on the type of biofuel and its production process. Several studies have shown that biofuels can result in emission savings (at most 78.4%) compared to diesel and petrol (Balasubramanian et al., 2023).

Alhanif (2023) states that biodiesel can reduce GHG emissions by as much as 86%. The carbon neutrality of biofuels is attributed to the fact that the carbon dioxide emitted during combustion is offset by the carbon dioxide absorbed by plants during growth. Biofuels, including biodiesel and renewable diesel, are prominent in decarbonizing maritime and road transport. Sevim & Zincir (2022) advocate for biodiesel and renewable diesel as drop-in fuels compatible with existing infrastructure, significantly reducing carbon emissions in maritime transportation. Leblanc et al. (2022) emphasize bioenergy's potential to reduce GHG emissions in transport, especially when BECCS (Biomass energy with carbon capture and storage) technology is not feasible. The life cycle assessment (LCA) of biofuel production is a comprehensive process that addresses key issues from environmental compatibility to policy implications. As shown in Figure 20, this process begins with defining the goals and scope, focusing on the selection of environmentally compatible biomass resources such as energy crops and agricultural waste. It then moves through various stages including technology selection, inventory analysis where greenhouse gases (GHGs) like CO₂, CH₄, and N₂O are evaluated, and energy indicators like non-renewable primary energy consumption are considered. Each stage of the LCA is critical in ensuring that the biofuels produced are truly beneficial for the environment and can contribute effectively to the decarbonization of sectors such as maritime and road transport.

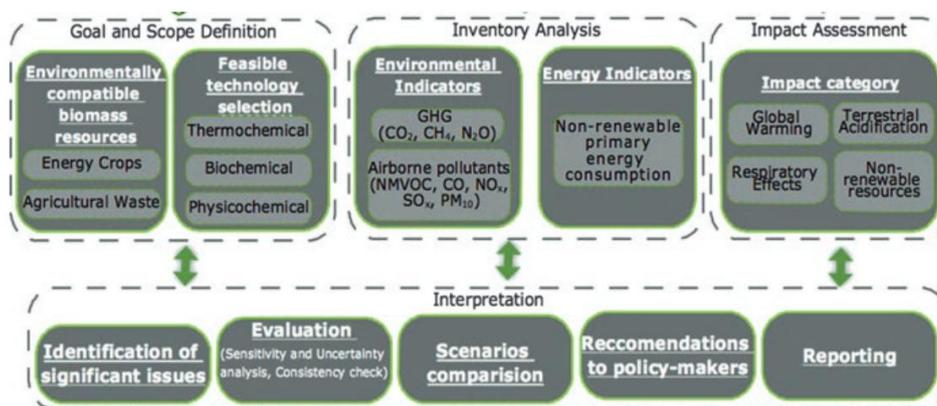


Figure 20: Key issues in each step of the LCA of biofuel (source: Hanaki et al., 2018)

5.1.3 Synthetic Fuels

Synthetic fuels, also known as e-fuels, are produced using carbon-neutral processes. They are praised for their potential to decarbonize sectors where direct electrification is challenging. Prussi et al. (2022) highlight e-fuels' greenhouse gas savings when produced with low-carbon-intensity electricity. However, the production of synthetic fuels is energy-intensive and currently lacks scalability at a commercial level.

The integration of synthetic diesel into the fuel market brings forth a unique opportunity to address the pressing issue of emissions from diesel engines, which are difficult to decarbonize. Synthetic fuels, including synthetic diesel, are produced through carbon-neutral processes and have been identified as a potential solution for sectors where direct electrification poses challenges (Prussi et al., 2022).

Wang et al. (2020) offers a detailed comparison of key characteristics of the U.S. EPA #2 diesel, Greyrock synthetic diesel (GD), and a 20% blend of GD with #2 diesel, showcasing the superior qualities of synthetic diesel in various aspects (Table 7).

Table 7: Comparison of key characteristics of US EPA #2D, Greyrock synthetic diesel (GD), and a 20% blend of GD with #2D

Fuel specifications (ASTM test #)	ASTM D975 specification	EPA #2 diesel (#2D)	Greyrock diesel (GD)	20% GD/80% #2D blend
Cetane index (D 976)	≥40	40	70	53
Fuel energy content (MJ/L)	NA	35.87	34.42	35.56
Density (g/mL @ 20 °C)	NA	0.84	0.76	0.82
Lubricity (µm @ 50 °C) (D 6079)	≤520	520	371	404
Viscosity (mm ² /s @ 40 °C) (D 445)	1.9–4.1	2.6	2.0	2.4
Oxidative stability (mg per 100 mL) (D 2274)	NA	1.5	0.1	1.2
Sulfur (ppmw)	≤15	15	<0.1	12
Aromatics (%)	≤35	20	<0.3	16
Benzene (%)	NA	<0.1	<0.1	<0.1
Olefins (%)	NA	13	6	12
Oxygen content (%)	NA	ND	0.21	ND
Residue (%)	NA	1.00	0.50	1.00

Results in bold font denote key synthetic diesel parameters that are better than EPA #2 diesel fuel (NA: not available; ND: not determined).

For example, the cetane index of Greyrock synthetic diesel stands at 70, a marked improvement over the ASTM D975 specification of 40, indicating a better combustion quality. The energy content of Greyrock diesel at 34.42 MJ/L is slightly less than the 35.87 MJ/L of #2 diesel but still within a competitive range. When it comes to density, Greyrock diesel exhibits a lower value (0.76 g/mL) compared to the standard (0.84 g/mL), which could influence fuel efficiency positively.

Moreover, the lubricity and viscosity of Greyrock diesel are within optimal ranges, at 371 µm and 2.1 mm²/s respectively, which can enhance the engine's performance and longevity. Significantly, the sulphur content of Greyrock diesel is less than 0.1 parts per million by weight (ppmw), a considerable reduction from the 15 ppmw specified by ASTM. Aromatics are also drastically reduced in Greyrock diesel to less than 0.3%, with benzene at less than 0.1%, suggesting a potential for fewer harmful emissions. The 20% GD/#2D blend also demonstrates improved characteristics, such as reduced aromatics and residue, compared to standard diesel.

The promise of synthetic diesel in reducing emissions is further supported by the findings of Wang et al. (2020), who reported that synthetic diesel blends can reduce emissions by significant margins—24% for carbon monoxide, 30% for total hydrocarbons, 5.5% for nitrogen oxides, and 19% for PM2.5. Notably, a complete switch to 100% synthetic diesel could enhance these reductions even further, with decreases in emissions by 36% for carbon monoxide, 48% for total hydrocarbons, and 10% for nitrogen oxides.

In the broader context of synthetic fuels' impact on emissions, Gössling et al. (2021) suggest that the production of synthetic fuels, if powered by 14–20 EJ of photovoltaic energy, could eliminate the need for fossil fuels and prevent up to 26.5 Gt of CO₂ emissions from 2022 to 2050. This highlights the significant role that synthetic diesel, as a type of synthetic fuel, could play in the global effort to reduce carbon emissions and combat climate change. The figures presented in Table 7, especially those in bold, denote the areas where synthetic diesel outperforms traditional EPA #2 diesel, underscoring its potential as a cleaner alternative fuel.

5.1.4 Hydrogen

Hydrogen, when produced through sustainable methods, is recognized as an environmentally friendly fuel that boasts a high energy density and versatility across different transportation sectors. Despite its benefits, the adoption of hydrogen fuel faces hurdles such as storage and transport logistics, alongside the substantial initial investments required for fuel cell technologies (Carlisle et al., 2023). Yet, the potential environmental advantages are significant. For instance, blending hydrogen with

natural gas can considerably curtail greenhouse gas emissions, predominantly by reducing CO₂ emissions from combustion (Neacsu et al., 2022).

Figure 21 illustrates various green pathways for hydrogen production. These include the conversion of diverse feedstocks like natural gas, coal, biomass, and water into hydrogen. Techniques such as natural gas reforming, coal gasification, biomass gasification, and various water-splitting methods including electrolysis, photolysis, and biological processes, are outlined. An intermediate product in many of these processes is synthesis gas (syngas), which can subsequently be transformed into hydrogen, an energy carrier with wide-ranging applications.

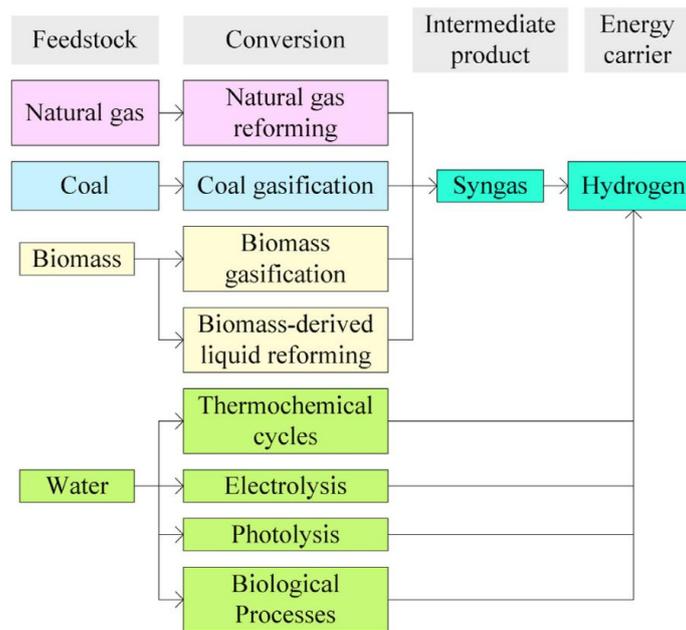


Figure 21: Processes outline for hydrogen production (source: Xing et al, 2021)

The environmental benefits of hydrogen as a fuel are further emphasized by research indicating that GHG emissions could be reduced by 61 to 68% when hydrogen is used in certain scenarios, leading to considerable enhancements in urban air quality (Stephens-Romero et al., 2009). This aligns with the objectives of nations such as Malaysia, which aims to reduce the GHG emission intensity of its GDP by 45% by the year 2030. Adopting hydrogen fuel cell (HFC) technology is a strategic move for Malaysia to diversify its energy mix and meet its climate targets (Azni et al., 2021).

In this context, the public's growing approval of hydrogen as an alternative fuel, particularly for shipping, plays a crucial role in mitigating global GHG emissions and fostering a more sustainable energy future (Carlisle et al., 2023). Figure 21 from Xing et al. (2021) provides a visual representation of the processes that can facilitate the green production of hydrogen, reinforcing the narrative that hydrogen, when produced and used appropriately, holds a key to unlocking a low-carbon economy.

5.1.5 Ammonia

Green ammonia emerges as a noteworthy alternative fuel, especially for the shipping industry, which is actively seeking carbon-free options. Produced using renewable energy, green ammonia promises to significantly reduce the carbon footprint of maritime transportation. Lindstad (2020) emphasizes its

potential, highlighting that, unlike conventional fuels, green ammonia does not emit CO₂ during combustion, though it does produce nitrogen oxides.

According to Al-Alboosi et al. (2021), renewable ammonia could slash greenhouse gas emissions by as much as 80% when compared to traditional maritime fuels. Ankathi et al. (2022) further the argument, suggesting that green ammonia could cut well-to-hull global GHG emissions from crude transportation by 50% relative to conventional ammonia. This showcases green ammonia's capacity to play role in the decarbonization efforts of the shipping industry.

5.1.6 Electricity (Production of Energy from Renewable Sources)

Electric vehicles, powered by renewable energy, offer significant potential to reduce GHG emissions, especially in urban distribution and short-haul transport.

Sathre et al. (2023) find that electric trucks with bioelectricity have lower climate impacts and primary energy use compared to diesel and DME-based pathways. However, the availability of charging infrastructure and the lifecycle environmental impact of batteries are pertinent concerns.

5.1.7 Electrofuels or E-fuels

Electrofuels, or e-fuels, represent a class of synthetic fuels that can be generated from renewable energy sources, including wind and solar power. These fuels are considered a potential avenue for reducing carbon emissions within the shipping industry, which is responsible for approximately 3% of global GHG emissions (Brynnolf et al., 2018). The production of e-fuels involves converting renewable electricity into chemical energy, which can then be used as fuel for various modes of transportation.

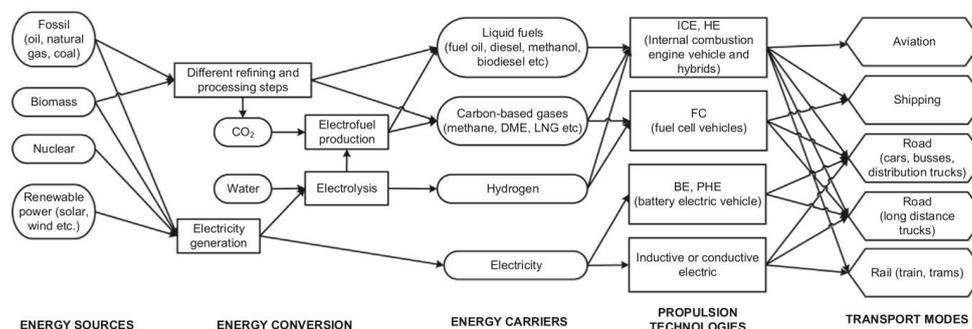


Figure 22: Simplified schematic of primary energy sources, energy conversion technologies, and energy carriers for different transport modes (source: Brynnolf et al., 2018)

Figure 22 provides a simplified schematic of energy sources, energy conversion technologies, and energy carriers for different transport modes. It illustrates how primary energy sources such as fossil fuels, biomass, nuclear, and renewables are converted into energy carriers like liquid fuels, hydrogen, and electricity. These carriers are then used to power various propulsion technologies across different transportation modes including aviation, shipping, and ground transportation.

While e-fuels offer promise in the shift towards a low-carbon economy, their production and use are not without environmental implications. The process of generating e-fuels is energy-intensive and could demand significant land use, potentially leading to competition with food production. Moreover, there are uncertainties regarding the full lifecycle emissions of e-fuels, which include considerations

from production to end-use. Consequently, the deployment of e-fuels should be approached as a part of a broader set of decarbonization strategies. This suite of strategies may encompass improvements in energy efficiency, the electrification of transport systems, and the integration of biofuels into the energy mix. The integration of these strategies aims to create a more sustainable and comprehensive approach to reducing emissions from transportation, in alignment with global climate targets.

Figure 23, as delineated by Brynolf et al. (2018), maps the production process of electrofuels, illustrating a flow from power generation to the final fuel product. The diagram begins with electricity—preferably from renewable sources—powering the electrolysis of water to yield hydrogen, a clean fuel. This hydrogen, along with CO₂ sourced from the air, seawater, or combustion processes, enters a synthesis reactor. Here, it is transformed into various types of electrofuels, such as methane (CH₄), dimethyl ether (DME, CH₃OCH₃), higher hydrocarbons like gasoline (C₈H₁₈), and alcohols like ethanol (C₂H₅OH). It is interesting to note that Figure 23 emphasizes the potential of integrating electrofuel production with biofuel processes, indicating a complementary relationship where CO₂ from biofuel combustion can feed into the production of additional electrofuels, creating a more sustainable and circular energy system.

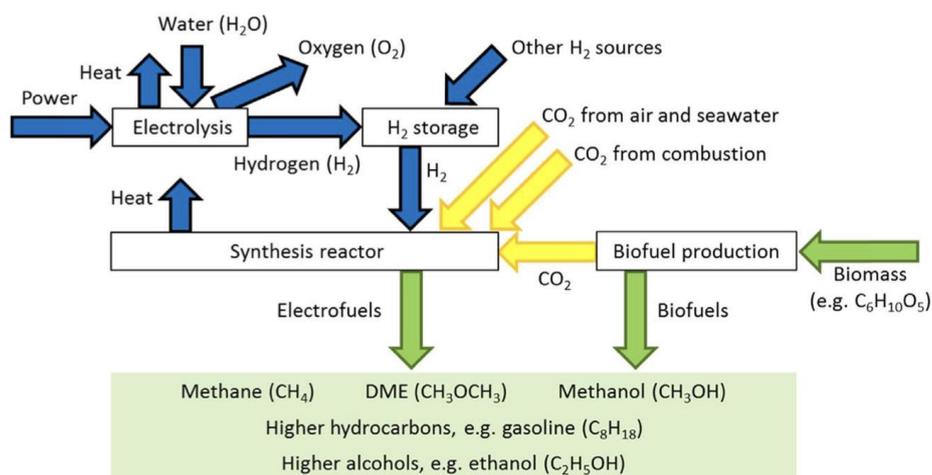


Figure 23: Process steps in the production of electrofuels (source: Brynolf et al., 2018)

Ueckerdt et al. (2021) offer a comprehensive view of the economic and environmental aspects of e-fuels. Figure 24 provides a detailed breakdown of the levelized costs of e-methane and e-gasoline, highlighting the potential future cost reductions in these fuels due to advancements in electrolysis and direct air capture (DAC) technologies. It also compares these costs with the prices of natural gas and gasoline, showing the trend towards cost competitiveness over time.

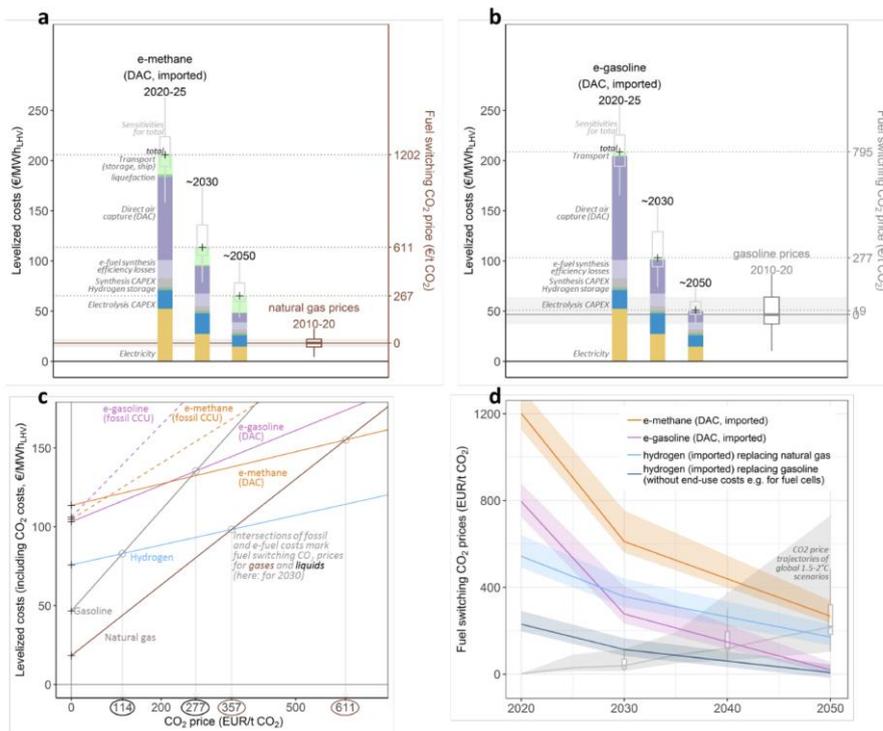


Figure 24: Cost and fuel switching CO₂ prices of e-fuels (source: Ueckerdt et al., 2021)

Figure 25 illustrates the life-cycle greenhouse gas (GHG) emissions of different fuels across various transport applications. It emphasizes the crucial role of the carbon intensity of electricity used in the production of e-fuels and for battery charging. The data demonstrates how renewable energy's share in electricity generation significantly impacts the emissions of e-fuels, suggesting that the environmental benefits of e-fuels are maximized when coupled with low-carbon electricity sources.

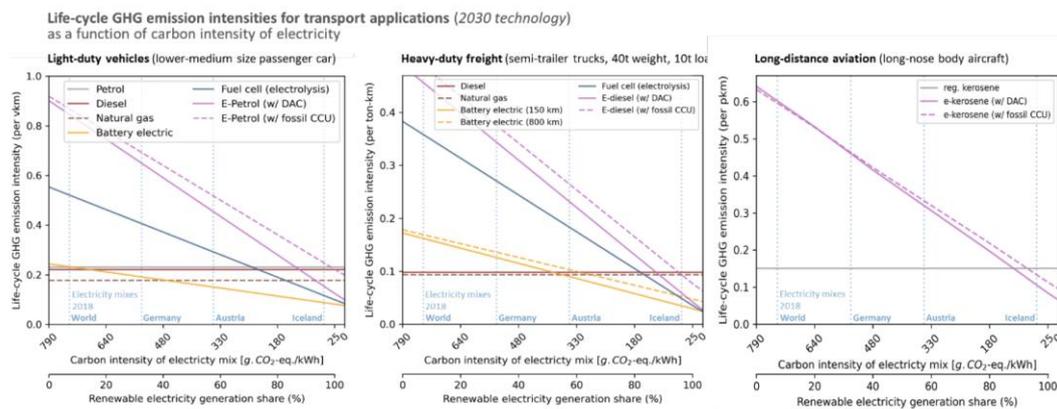


Figure 25: Life-cycle GHG emissions for different fuels and transport applications, as a function of the life-cycle carbon intensities of electricity used for battery charging, hydrogen and e-fuel productions (source: Ueckerdt et al., 2021)

Therefore, it's important of continuing to improve the efficiency and cost-effectiveness of e-fuel production technologies while also decarbonizing the electricity grid to ensure the full climate benefits of these synthetic fuels are realized. Nevertheless, the energy efficiency of a typical E-fuel is not as high as direct electrification, as it can be shown in Figure 26 from Ueckerdt et al. (2021).

Electricity-to-useful energy efficiencies

Black: individual efficiencies
Blue: combined efficiencies

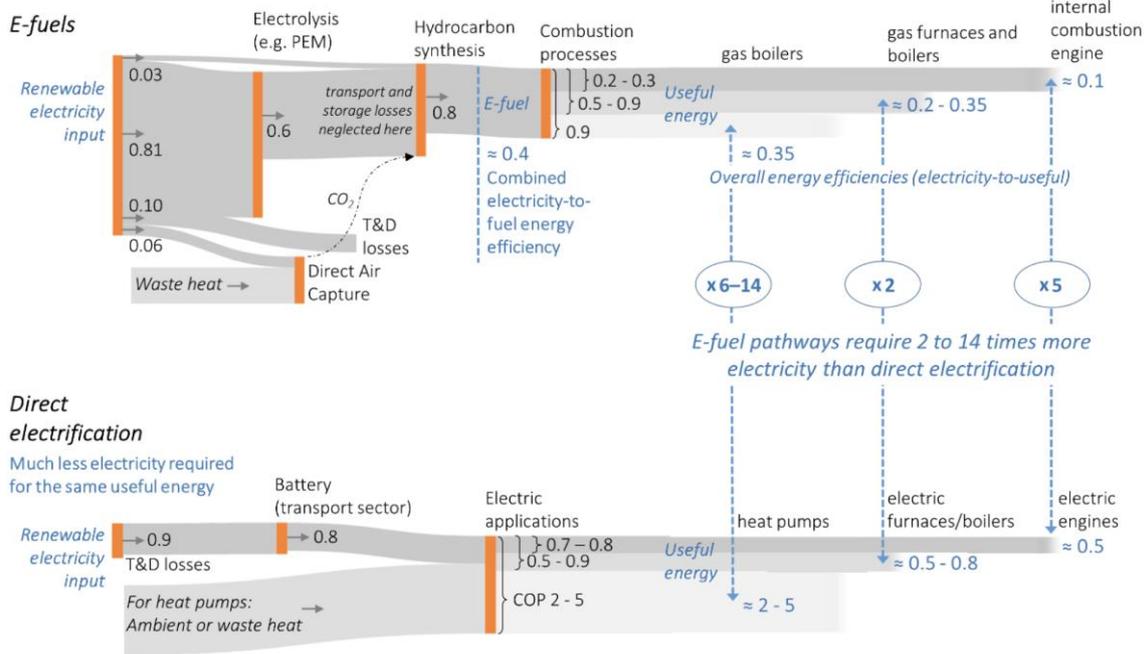


Figure 26: Energy efficiencies for major conversion steps from electricity input to useful energy (source: Ueckerdt et al., 2021)

5.1.8 Lubricant infused fuel

The integration of lubricating oil into fuel, known as lubricant infused fuel, represents an innovative approach to enhancing engine performance and reducing emissions. Wang et al. (2021) found that lubricating oil can shorten the ignition-delay phase during combustion, which not only improves fuel economy but also alters the chemical characteristics of particles, potentially leading to reduced engine emissions. Complementing this, Shao et al. (2022) have demonstrated that when formulated correctly, lubricant additives can positively affect particulate emissions without adversely affecting the performance of particulate filters. Moreover, Zare et al. (2020) provide evidence that adding as little as 5% waste lubricating oil to diesel fuel can diminish particulate matter emissions in both cold start and hot start engine operations. This not only suggests a reduction in environmental impact but also signifies an enhancement in overall engine performance. These studies collectively suggest that optimized lubricant infusion in fuels could be a viable path to achieving more efficient and cleaner combustion in engines.

5.1.9 Compressed Natural Gas

The transition to alternative fuels like Compressed Natural Gas (CNG) for road freight transportation is a critical step towards sustainability. Dörr Heinz et al. (2016) emphasize the importance of powertrain innovation for enhancing energy efficiency and minimizing CO₂ equivalent emissions in freight transport. In line with this, recent studies reveal the tangible benefits of switching to CNG.

As depicted in Figure 27 from Gialos et al. (2022), the switch from single fuel (diesel) to dual-fuel (CNG – Diesel) systems offers significant advantages, including a 24.9% reduction in fuel costs per 100 km

and a notable 21.9% decrease in well-to-wheel (WTW) GHG emissions for the same distance. Gialos et al. (2022) further support this by quantifying the reduction in CO₂e emissions and operational costs when CNG is adopted as an alternative fuel in road freight transport, indicating its potential for mitigating the sector's impact on global warming.

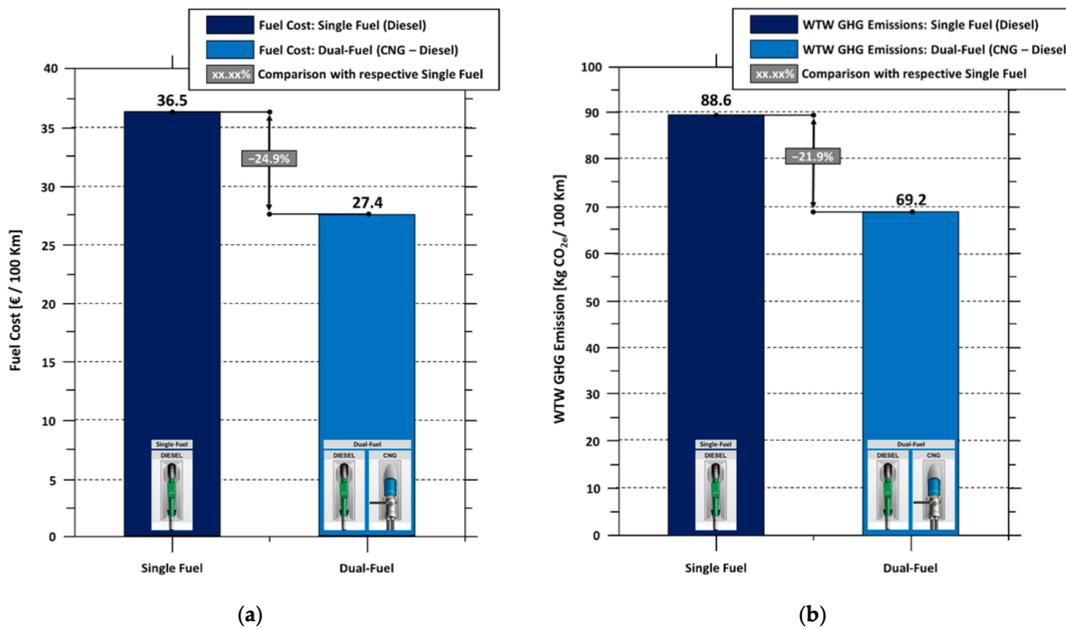


Figure 27: (a) Comparison of fuel cost, single vs. dual fuel for 100 km (b) Comparison of WTW GHG emissions, single vs. dual fuel for 100 km (source: Gialos et al., 2022)

5.1.10 Summary evaluation and KPI's for Marine alternative fuel adoption:

The maritime industry is actively exploring various pathways to achieve the International Maritime Organization's (IMO) goals for reducing emissions. Song (2021) identifies Maersk's proposition of biodiesel, methanol, ammonia, and lignin fuels as potential solutions for net-zero emissions in shipping.

According to the data presented by Song (2021), the projected fuel mix for the industry by 2030, 2040, and 2050 includes a transition from predominantly using very low sulphur fuel oil/marine gas oil (VLSFO/MGO) and heavy fuel oil to a more diverse array of energy sources. By 2050, the expectation is to see significant shifts towards e-fuels like e-methanol and e-ammonia, alongside a substantial increase in the use of bio-LNG, as shown in Table 8.

Table 8: A pathway of maritime fuel mix towards IMO goals (source: Song, 2021)

% of Energy	2030	2040	2050
VLSFO/MGO	46%	12%	1%
LNG	25%	48%	19%
Heavy fuel oil	17%	10%	0%
e-MGO	10%	10%	23%
e-LNG	2%	3%	3%
e-ammonia	0%	10%	40%
bio-LNG	0%	5%	11%
e-methanol	0%	2%	3%

The described changes are influenced by a variety of factors as illustrated in Table 9, including economic performance, energy density, compatibility with existing marine engines, and environmental considerations such as life cycle CO₂ emissions. The strategic fuel choice determinants for container ships will revolve around compliance with regulations, operational measures, and logistics considerations, all of which will guide the industry towards a more sustainable future.

Table 9: Characteristics of fuel types and choice determinants for container ships (source: Song, 2021)

Low-carbon fuels	Petroleum-based fuels with carbon capture and sequestration systems; LNG; LPG; Methanol; Ethanol; Biofuel
Carbon-neutral fuels	Bio-MGO; e-MGO; Bio-LNG; e-LNG; Synthetic fuels by hydrogenating carbon dioxide; Biofuels through photosynthesis; Renewable natural gas; Renewable diesel fuel
Zero-carbon fuels	Hydrogen; e-ammonia; Bio-methanol; e-methanol; Fuels produced from renewable electricity, biomass and natural gas with CCS
Fuel choice determinants	<p>Economic performance: Commercial interest of stakeholders; Future price of energy sources (renewable electricity, natural gas and biomass); Future fuel prices; Energy density; Compatibility with conventional marine engines</p> <p>Environmental considerations: CO₂ emission; other emissions (SO_x/NO_x, particulate matters); life cycle emission</p> <p>Regulations and policies: International, regional, national and even port-based emission regulations and policies; Safety regulations; Market-based measures; Entering into force over short and medium term;</p> <p>Technology considerations: Technology readiness level; Safety and security; Ship design technology; Technology for generating power; Engine technologies;</p> <p>Operational measures: Ship types and sizes; Trade routes; Digitalization to reduce GHG; Transport modal shift; Ability to comply with regulations;</p> <p>Logistics considerations: Fuel supply infrastructure; Fuel availability; Fuel storage and transport; Ship re-fuelling</p>

Figure 28 delves into the environmental implications and decision-making criteria for choosing alternative marine fuels. The GWP data suggest a move away from traditional high-GWP fuels like heavy fuel oil towards lower-GWP alternatives such as biofuels and hydrogen could significantly reduce maritime emissions.

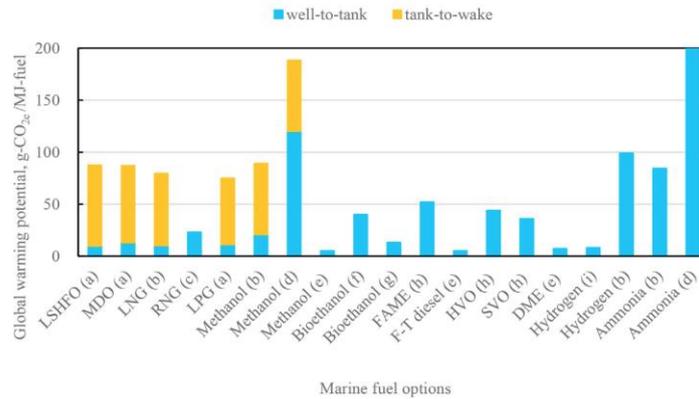


Figure 28: GWP for different marine options (source: Xing et al., 2021)

Table 10 and Table 11 outline a structured approach to evaluate alternative fuels, considering their entire life-cycle from well-to-tank, tank-to-wake, encompassing technical, environmental, and social factors. These criteria are crucial for maritime stakeholders to meet regulatory demands, societal expectations for cleaner shipping, and industry goals for reducing greenhouse gas emissions in line with IMO targets.

Table 10: Possible evaluation criteria for alternative marine fuel options (source: Xing et al., 2021)

Sources	DNV GL (2019)	Hansson et al. (2019)	Ren and Liang (2017)	Deniz and Zincir (2016)
Criteria	<p>Applicability:</p> <ul style="list-style-type: none"> energy density technological maturity flammability and toxicity regulations and guidelines <p>Economics:</p> <ul style="list-style-type: none"> energy costs capital costs <p>Environment:</p> <ul style="list-style-type: none"> climate change air pollution <p>Scalability:</p> <ul style="list-style-type: none"> main current usages availability global production capacity and locations 	<p>Technical:</p> <ul style="list-style-type: none"> available infrastructure reliable supply of fuel <p>Economic:</p> <ul style="list-style-type: none"> investment cost for propulsion operational cost fuel price <p>Environmental:</p> <ul style="list-style-type: none"> acidification health impact climate change <p>Social:</p> <ul style="list-style-type: none"> safety upcoming legislation 	<p>Technological:</p> <ul style="list-style-type: none"> maturity reliability capacity <p>Economic:</p> <ul style="list-style-type: none"> capital cost operational cost <p>Environmental:</p> <ul style="list-style-type: none"> CO₂ emissions NO_x emissions SO_x emissions PM emissions <p>Social:</p> <ul style="list-style-type: none"> compliance with regulations social acceptance 	<ul style="list-style-type: none"> ship safety global availability bunker capability durability adaptability compliance with regulations engine performance engine emissions engine components commercial issues costs

Table 11: Decision making framework for alternative marine fuel options on a life-cycle pathway (source: Xing et al., 2021)

Criteria	Well-to-tank				Tank-to-wake	
	Feedstock	Transportation	Production	Distribution, storage and bunkering	On board storage	End use
						ICE FC
Technical availability	✓	✓	✓	✓	✓	✓ ✓
Safety	✓	✓	✓	✓	✓	✓ ✓
Available infrastructure	–	✓	✓	✓	–	– –
Reliable supply of fuel	✓	–	–	–	–	– –
Investment cost for infrastructure	✓	✓	✓	✓	–	– –
Investment cost for plants	–	–	–	–	✓	✓ ✓
Operational cost	✓	✓	✓	✓	–	✓ ✓
Climate change	✓	✓	✓	✓	–**	✓ ✓
Air pollution *	–	–	–	–	–**	✓ ✓

Notes: ✓ applicable; – not applicable; * well-to-tank air pollution is neglected supposing effective land-based abatement measures available; ** environmental impact has been covered in end uses.

Table 12 from IRENA et al. (2021) outlines the readiness level of various shipping fuels, examining their technological maturity, market readiness, GHG reduction potential, and associated engine technology. It offers a detailed comparison across different fuel types such as Fuel Oil, LNG, Advanced Liquid Biofuels, Renewable Gaseous Fuels, Hydrogen, Ammonia, and Methanol. For each fuel type, the table

lists advantages and challenges, providing insights into the practicality of their use in the shipping industry. For instance, while fuel oil is widely used with established infrastructure, it faces challenges like high carbon and particulate emissions. On the other hand, hydrogen offers nearly zero carbon emissions and is versatile but is hindered by high production and storage costs. This evaluation aids stakeholders in making informed decisions regarding fuel strategies for shipping, balancing efficiency, environmental impact, and readiness for implementation.

The literature suggests a strategic shift towards fuels with a lower carbon footprint, such as LNG and advanced biofuels, and an eventual transition to zero-carbon fuels like hydrogen and ammonia. However, each alternative fuel presents its own set of challenges, such as economic cost, technological readiness, and infrastructure requirements. The maritime industry must navigate these factors to meet IMO's emission reduction goals, suggesting a gradual and mixed-method approach to adopting new fuel technologies.

Table 12: Readiness level of shipping fuels (source: IRENA et al., 2021)

4 Readiness level of shipping fuels (● High - ● Medium - ● Low)

	FUEL TECHNOLOGICAL READINESS	ENGINE TECHNOLOGICAL READINESS	SCALABILITY & TIME TO MARKET	ENERGY DENSITY	GHG REDUCTION	ENGINE TECHNOLOGY	ADVANTAGES	CHALLENGES
Fuel Oil	High	High	High	High	Low	ICE	Already used globally, has high efficiency and is low cost in comparison to alternative fuels.	HFO has high carbon emissions and particulate emissions from production and use in vessels.
LNG	High	High	Medium	High	Low	ICE	Well-established supply infrastructure, high energy density and is currently used in vessels globally. Has a lower sulphur content than HFO.	LNG has fewer emissions compared with HFO but still significantly more emissions than low-carbon alternative fuels. Uses non-renewable resources.
Advanced Liquid Biofuels	High	High	Low	High	Medium	ICE	Biofuels have an established infrastructure due to use in multiple sectors. Easy integration into current engines. Can be used as a drop-in fuel.	Growth of feedstock used in biofuel production may affect land use, which could impact global food security. High demand from multiple sectors makes scaling difficult.
Renewable Gaseous Fuels	High	High	Low	High	Medium	ICE	Bunkering in ports can use LNG infrastructure, making implementation cheaper. Ships that use LNG can switch to liquefied biogas (LBG) as a drop-in fuel.	Limitations with storage capacity required for LBG. Can only be considered for short-distance vessels. Long-distance vessels would require large storage capacity.
Hydrogen	Low	Low	Medium	High	High	ICE FCs	Employing green H ₂ would lead to nearly zero carbon emissions. A main option as an energy carrier in FCs. Multiple applications across sectors, which can increase the rate of research.	H ₂ production and storage is costly, requiring cryogenic storage. Still an immature technology in the shipping sector but has high potential as an alternative fuel.
Ammonia	High	Low	Medium	High	High	ICE FCs	Ammonia has existing production and transport infrastructure due to the agricultural industry. Green ammonia is carbon neutral and has one of the highest efficiencies when compared to alternative fuels.	Global demand for ammonia across multiple sectors can cause scalability issues. Ammonia has a high production cost and is highly toxic, requiring special storage and safety measures.
Methanol	High	High	High	High	Medium	ICE FCs	Currently used in a multitude of sectors and can be implemented within the shipping sector with relative ease. Using e-methanol and bio-methanol is 100% renewable.	Difficulties in acquiring sustainable and cost-effective carbon sources. Green methanol has high production costs.

Issa et al. (2022) also contributes to the weighting of Advantages and Disadvantages of the alternative fuels (Table 13). For instance, it highlights that while LNG has competitive pricing and available infrastructure, it falls short of the 50% CO₂ reduction target. Hydrogen offers zero-emission potential but is limited by high costs and storage challenges. Ammonia's toxicity and biofuels' price and volume constraints are mentioned, alongside the efficiency of electricity but with caveats on energy density and capital expenditure.

Table 13: Benefits and drawbacks of shipping fuels (source: Issa et al., 2022)

Alternative Fuels	Advantages	Disadvantages
LNG	<ul style="list-style-type: none"> Prices are competitive Infrastructure technology that are available 	<ul style="list-style-type: none"> Insulated tanks are necessary for storage Unable to meet the 50% CO₂ reduction target
Hydrogen	<ul style="list-style-type: none"> Enable the zero-emission option with fuel-cell Can be made from electrolysis near ports 	<ul style="list-style-type: none"> Fuel prices are extremely high There is not a piston engine or infrastructure available Very low storage temperature
Ammonia	<ul style="list-style-type: none"> Can be employed for engines and fuel cells. Can be stored at a high temperature and low pressure. 	<ul style="list-style-type: none"> Toxicity and environmental impact when leaked When utilized in internal combustion engines, hydrogen must be added.
Biofuels	<ul style="list-style-type: none"> It is possible to be carbon-free Compatibility with existing engine 	<ul style="list-style-type: none"> Price Narrow product volume
Electricity stored in batteries	<ul style="list-style-type: none"> Efficiency Enable zero-emission 	<ul style="list-style-type: none"> Small energy density of mass and volumetric density Prohibitive CapEx

Ankathi et al. (2022) provide a complementary detailed comparison of direct and well-to-tank greenhouse gas (GHG) emissions factors for various marine fuels, spanning conventional fossil fuels to alternative and renewable options. It compares traditional heavy fuel oil (HFO) and newer options like green ammonia. It indicates that biofuels, hydrogen from renewable power, and green ammonia offer significantly lower well-to-tank GHG emissions compared to conventional fuels. These data are essential for maritime stakeholders aiming to reduce their carbon footprint and for informing policy and investment decisions in line with environmental targets.

Additionally, we may also take into consideration specific information regarding Flammability, auto-ignition and combustion emissions trade-offs. Table 15 from Xing et al. (2021) shows that conventional fuels like HFO (Heavy Fuel Oil) and MDO (Marine Diesel Oil) typically have higher levels of emissions, including CO₂, SO_x, NO_x, and PM. The trade-off with these fuels is that they are often cheaper and more readily available with established supply chains. Alternative fuels such as LNG (Liquefied Natural Gas), DME (Dimethyl Ether), and biofuels like FAME (Fatty Acid Methyl Ester) generally result in lower SO_x and PM emissions but may still contribute to CO₂ and NO_x emissions. LNG, in particular, is noted for significantly lower SO_x emissions. Hydrogen and ammonia are often highlighted for their potential to significantly reduce or even eliminate CO₂ emissions, especially when produced from renewable sources. However, hydrogen can contribute to NO_x emissions when combusted in ICE without adequate after-treatment technologies. Biofuels can offer reduced CO₂ emissions, especially if they are produced sustainably. However, the NO_x and PM emissions can vary based on the specific type of biofuel and the engine technology used.

Table 14: Direct and WTH GHG emissions for marine fuels, gCO₂e/MJ (source: Ankathi et al., 2022)

Marine fuel	Production pathway	Direct GHG EF	WTH GHG EF	Ref.
HFO	Crude oil/processing/HFO (0.5% S)	81.74	95.40	b
Methanol	Natural gas/methanol synthesis/methanol	69.49	92.02	b
MDO	Crude oil/processing/MDO (0.5%)	78.63	91.87	b
MGO	Crude oil/processing/MDO (0.5%)	74.08	91.67	b
LNG	NG/liquefaction/LNG	75.18	87.96	b
LPG	NG/liquefaction/LPG	64.40	73.00	c
LBG ^a	Biogas/liquefaction/LBG	54.53	20.00	c
Biodiesel (Soy oil)	Soybean oil/transesterification/biodiesel	76.88	31.36	b
RD(YG)	Yellow grease/hydro processing/RD	73.68	14.26	d
SVO(HP)	Bio-oil/hydro processing/SVO	77.94	13.96	b
Biooil (Pyrolysis)	Biomass/pyrolysis/bio-oil	101.67	10.79	b
Diesel (Biomass)	Biomass/FT synthesis/FT-diesel	73.38	6.08	d
Bio methanol	Biomass/methanol synthesis/bio methanol	69.49	5.74	d
H ₂ (SMR)	SMR W/O carbon capture and storage	0	91.58	d
H ₂ (SMR with CCS)	SMR W carbon capture and storage	0	23.66	d
H ₂ Renewable power	Electrolysis from 100% renewable power	0	0.71	d
H ₂ SD Electricity mix	Electrolysis from US grid mix of SD scenario	0	23.00	d
Conventional ammonia	Electric-based Haber-Bosch process	0	137.10	e
Low carbon grey ammonia	N ₂ from cryogenic distillation and H ₂ from low-temperature electrolysis using renewable electricity	0	97.85	e
Green ammonia	Steam cracker for H ₂ and PSA for N ₂	0	11.82	e

Table 15: Typical physicochemical properties and emissions performance of marine fuels (source: Xing et al., 2021)

Fuels	Chemical formula	Density at 15 °C, kg/m ³	Cetane number	Boiling point, °C	Auto-ignition temperature in air, °C	Flammability limits in air, vol%	Combustion emissions in ICE			
							CO ₂	SO _x	NO _x	PM
LSHFO	C ₈ -C ₂₅	975-1010	>20	>180	230	0.6-7.5	high	medium	high	medium
MDO	C ₁₀ -C ₁₅	796-841	>35	>180	210	0.6-7.5	high	low	high	low
NG	CH ₄	0.78	130 *	-162	540	5.0-15.0	medium	low	medium	low
PG	C ₃ H ₈ &C ₄ H ₁₀	1.90	94-112*	-42	450	2.1-9.5	medium	low	medium	low
Methanol	CH ₃ OH	792	<5	65	464	6.7-36.0	medium	low	medium	low
Ethanol	C ₂ H ₅ OH	789	5-15	78	365	3.3-19.0	medium	low	medium	low
DME	CH ₃ OCH ₃	665	55-65	-25	350	3.4-27.0	medium	low	medium	low
Hydrogen	H ₂	0.09	>130 *	-253	585	4.0-75.0	low	low	high	low
Ammonia	NH ₃	0.73	120 *	-33	651	15.0-28.0	low	low	high	low
SVO	C ₁₄ -C ₂₂	900-960	30-45	>180	424	0.6-7.5	high	low	high	low
FAME	C ₁₆ -C ₁₈	860-900	45-55	>180	261	0.6-7.5	high	low	high	low
HVO	C ₁₅ -C ₁₈	770-790	>70	>180	204	0.6-7.5	high	low	high	low
F-T diesel	C ₁₅ -C ₁₈	774-782	74-80	>180	204	0.6-7.5	high	low	high	low

Note: *-octane number. PG-Petroleum gas.

Based on such information, Xing et al. (2021) show priority levels for different marine fuels across various types of marine operations (inland/domestic, coastal/domestic, short sea/international, deep sea/international), suggests that renewable methanol, ammonia, hydrogen (both compressed and liquefied), and biofuels like biodiesel and bioethanol are given higher priority for adoption in maritime activities. These fuels are likely rated based on their environmental performance and potential to reduce greenhouse gas emissions, which are critical considerations for the maritime industry as it moves towards decarbonization.

Xing et al. (2021) developed a qualitative evaluation approach with ranks various marine fuels based on multiple criteria such as technical availability, safety, availability of infrastructure, and so on (Figure 29). The ranking seems to range from I (best) to IV (worst). Additionally, there is a numerical scoring

for climate change impact, suggesting an attempt to quantify the potential contribution of each fuel to global warming.

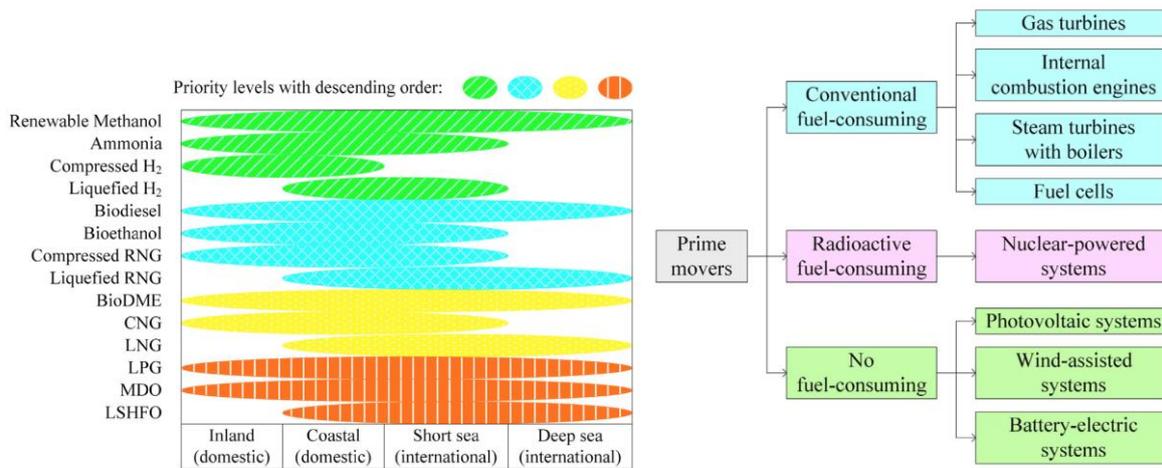


Figure 29: Priority levels and potential applications of different marine fuels and Possible power sources for ship propulsion (source: Xing et al., 2021)

Figure 29 and Table 16 show that renewable methanol and ammonia, especially when used in fuel cells (FC) have a high rank, suggesting that they are seen as promising alternatives for future marine fuel, likely because they can offer significant reductions in GHG emissions when produced from renewable sources. Compressed and liquefied hydrogen also score highly, reflecting their potential as zero-carbon fuels. However, their practical use will depend on the development of suitable infrastructure and technologies for safe handling and storage. Traditional fuels such as Low Sulphur Heavy Fuel Oil (LSHFO) and Marine Diesel Oil (MDO) rank lowest in priority, likely due to their higher GHG emission profiles and increasing regulatory pressure to reduce emissions from shipping operations. The best fuel types appear to be those that offer a balance between lower environmental impact and practical feasibility for use in the maritime sector. This includes not just the GHG emissions but also factors like technical availability, safety, and the cost of fuel and infrastructure.

Table 16: Qualitative evaluation on different potential marine fuels based on selected decision-making framework (source: Xing et al., 2021)

Criteria	LSHFO/ MDO + ICE	Hydrogen + ICE	Hydrogen + FC	Ammonia + ICE	Ammonia + FC	RNG + ICE	Renewable Methanol + ICE	Renewable methanol + FC	Bioethanol + ICE	BioDME + ICE	Biodiesel + ICE
Technical availability	IV	II	III	II	I	III	III	II	III	II	III
Safety	IV	I	I	I	I	III	II	II	III	III	IV
Available infrastructure	IV	I	I	III	III	II	III	III	III	II	III
Reliable supply of fuel	IV	IV	IV	IV	IV	III	III	III	I	II	I
Investment cost for infrastructure	IV	I	I	II	II	II	III	III	III	II	III
Investment cost for propulsion	IV	II	II	II	I	III	III	I	III	II	III
Operational cost	IV	II	I	III	I	II	III	I	III	III	III
Climate change *	I	IV	IV	III	III	III	III	III	III	III	III
Air pollution	I	II	IV	II	III	III	III	IV	III	III	I
$\bar{x} \pm S^{**}$	3.3 ± 1.3	2.1 ± 1.2	2.3 ± 1.4	2.4 ± 0.9	2.1 ± 1.2	2.7 ± 0.5	2.9 ± 0.3	2.4 ± 1.0	2.8 ± 0.7	2.4 ± 0.5	2.7 ± 1.0

Notes: I to IV-ranking from the worst to the best; * supposing the world energy mix in 2050 is hybrid fossil energy and non-fossil energy; ** mean value and standard deviation, supposing the scores 1–4 are assigned to the ranking levels I-IV and equal weightings are assigned to each criterion.

5.1.11 Summary evaluation and KPI's for Road alternative fuel adoption

The work of Haase et al. (2022) is relevant for understanding the evaluation necessary for the transition to alternative fuels in road transport. Figure 30 and Table 17 illustrate a framework for assessing vehicle production, economic viability, and environmental impacts across different fuel types, offering a forecast into the future performance of these fuels. Vehicles powered by internal combustion engines (ICEVs) running on fossil fuels are being re-evaluated in favour of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), which promise lower emissions and a smaller environmental footprint. Table 17 illustrates the move away from the traditional Otto engine and gasoline tanks to more sustainable systems like electric motors with batteries and fuel cells with hydrogen storage. This shift is not just about adopting new technologies but also aligning with broader sustainability goals and regulatory requirements. The cost implications vary, with some alternative fuel vehicles like FCEVs showing lower costs in certain areas compared to ICEVs.

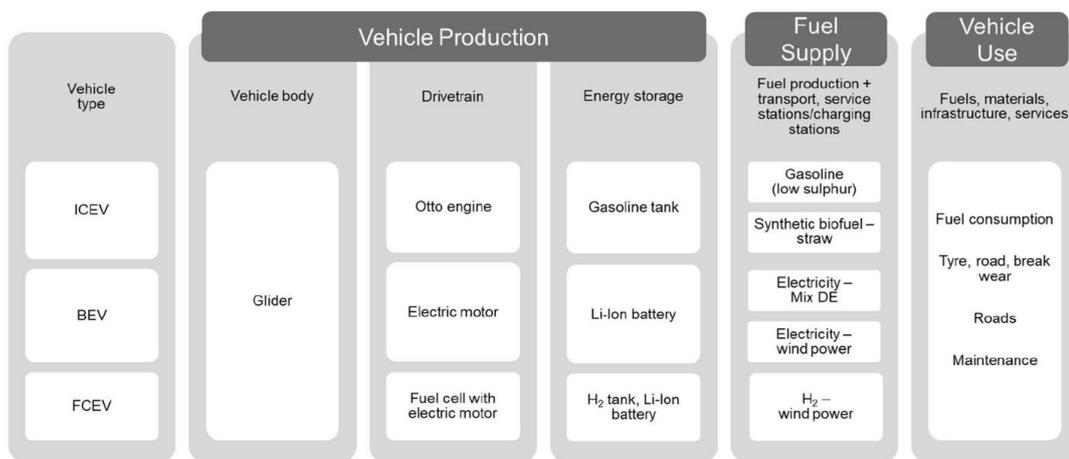


Figure 30: Characterisation of alternative fuels for road transport (source: Haase et al., 2022)

Table 17: Input data for economic assessment, year 2050 (source: Haase et al., 2022)

Vehicle Type	Fuel type	Vehicle production	Fuel supply			Vehicle use		
		Car acquisition	Fuel production	Fuel transport/distribution, margin, storage, service/charging stations		Maintenance and repairs	Insurance	
ICEV	Gasoline (fossil)	23.210 €	96.3 (46.3)	€cent/l	14.4	€cent/l	797 €	876 €
	Synthetic biofuel		120.2 (149.4)	€cent/l				
BEV	Electricity: wind power		4.7 (6.11)	€cent/kWh	29.3** (36.6)*	€cent/kWh	368 € (484)	876 € (785)
	Electricity: production mix DE		10.2 (4.91)	€cent/kWh	29.3** (36.5)*	€cent/kWh		
FCEV	Hydrogen from wind power		4.3 (7.4)	€/kg	2.6 (5.7)	€/kg	482 € (787)	876 € (1496)

Values in parentheses refer to the differing values for the base year 2020

**Thereof 10.8 €Cent/kWh for charging

*Thereof 16.8 €Cent/kWh for charging

Table 18 highlights the technical specifications of the vehicles, including power, weight, fuel consumption, and battery characteristics. This information is crucial for understanding the performance and efficiency of each vehicle type.

Table 18: Technical characterization of vehicles in 2050 (source: Haase et al., 2022)

Vehicle Type	Power kW	Vehicle weight without battery kg	Fuel consumption		Source	Battery		
						Type	Density Wh/kg	Weight kg
ICEV	100	1315	6	l/100 km	ADAC (2021a)	n.a	n.a	n.a
BEV		1376	16	kWh/100 km	ADAC (2021b)	LFP (NCM)	180 (150)	199 (239)
FCEV		1582 (1823)	0.58 (0.76)	kg H ₂ /100 km	Grube et al. (2021), Robinius (2015)	LFP	180 (52)	8 (26)

Values in parentheses refer to the differing values for the base year 2020

NCM lithium nickel cobalt manganese oxide, LFP lithium iron phosphate, ICEV internal combustion engine vehicle, BEV battery electric vehicle, FCEV fuel cell electric vehicle

Table 19 provides a per-kilometer assessment of different vehicles' contributions to various environmental issues. It gives a clear indication of which vehicle and fuel type combinations offer the most significant benefits in terms of reducing emissions and minimizing ecological footprints. BEV-wind, for instance, stands out for its lower climate change impact, indicating the potential of renewable energy-powered electric vehicles in achieving climate goals.

Table 19: Indicator results per km driving distance, year 2050 (source: Haase et al., 2022)

Indicator	Unit	ICEV -straw	BEV -Mix_DE	FCEV -wind	ICEV -fossil	BEV -wind
Electricity Mix based on Pregger et al. 2020						
Acid	molc H ⁺ eq	5.63E-04	5.10E-04	6.90E-04	7.00E-04	4.30E-04
CC	kg CO ₂ eq	5.95E-02	8.20E-02	8.02E-02	2.24E-01	5.68E-02
Ecotox-fw	CTUe	4.54E+00	5.39E+00	3.78E+00	4.17E+00	5.42E+00
Eutr-fw	kg P eq	4.32E-05	6.05E-05	5.42E-05	3.19E-05	5.69E-05
HT-c	CTUh	1.41E-08	1.61E-08	1.56E-08	1.14E-08	1.63E-08
HT-nc	CTUh	9.20E-08	9.91E-08	8.78E-08	5.32E-08	9.31E-08
IR-hh	kBq U235 eq	6.57E-03	6.03E-03	7.22E-03	1.69E-02	5.30E-03
Eutr-mar	kg N eq	1.25E-04	8.93E-05	1.10E-04	1.00E-04	7.16E-05
OD	kg CFC-11 eq	5.07E-09	3.70E-08	1.93E-08	3.72E-08	3.22E-08
PM	kg PM2.5 eq	9.96E-05	8.98E-05	1.00E-04	1.10E-04	8.21E-05
POF	kg NMVOC eq	5.39E-04	3.40E-04	3.90E-04	5.30E-04	2.80E-04
RD	kg Sb eq	5.05E-05	2.26E-05	1.99E-05	4.29E-05	2.22E-05
Eutr-ter	molc N eq	1.33E-03	9.30E-04	1.18E-03	1.10E-03	7.20E-04
Costs	€cent	3.00E+01	2.57E+01	2.39E+01	2.86E+01	2.48E+01
Domestic value-added	%	6.92E+01	6.19E+01	6.29E+01	6.77E+01	6.91E+01

Haase et al. (2022) indicate that by the year 2050, ICEV-straw and BEV-wind might generate the highest domestic value-added. However, the costs are notably higher for ICEV-straw. BEV-wind shows the lowest environmental impacts for climate change amongst the considered alternatives and performs best for most environmental indicators. Conversely, ICEV-fossil has the lowest impacts for freshwater

eutrophication and human toxicity (both carcinogenic and non-carcinogenic). FCEV-wind scores best in freshwater ecotoxicity and resource depletion, while ICEV-straw leads in ozone depletion reduction.

De Angelis et al. (2021) analyse the shift in electricity production sources mix and their potential to reduce air pollution. Figure 31 displays the percentage electricity production distribution over the sources for selected scenarios. It shows a bar chart with three different scenarios (scen 19, scen 20, and scen 8) and the corresponding mix of electricity production sources. These sources include natural gas, coal, liquid fossil fuels, biomass, biogas, biofuels, waste, photovoltaic, and hydroelectric. The chart suggests that each scenario proposes a different energy mix, which likely reflects varying degrees of reliance on renewable sources versus fossil fuels.

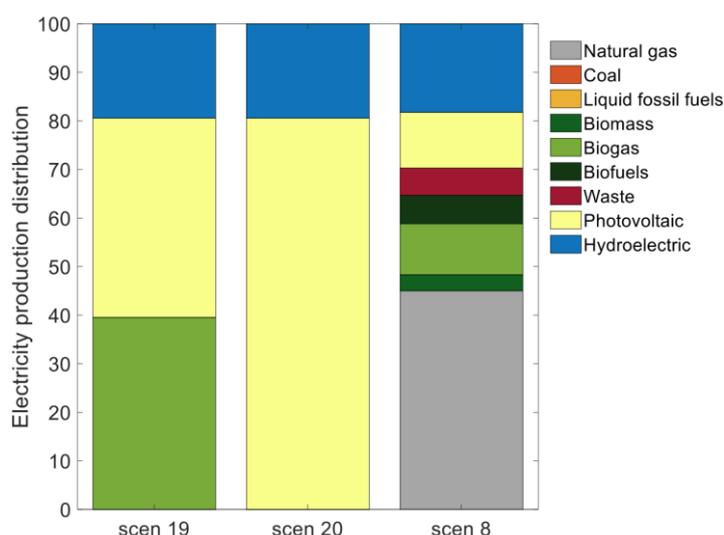


Figure 31: Percentage electricity production distribution over the sources for scenarios (source: De Angelis et al., 2021)

Table 20 presents the air pollution precursors percentage emission reduction with respect to the base-case for the year 2018 for the selected scenarios. It lists the scenarios (scen 8, scen 19, and scen 20) alongside the reduction percentages for various pollutants, including nitrogen oxides (NO_x), volatile organic compounds (VOC), ammonia (NH₃), particulate matter (PM₁₀ and PM_{2.5}), and sulphur dioxide (SO₂). The reductions are given in percentage terms, suggesting improvements in air quality relative to a base year, presumably due to changes in the electricity production mix indicated in the scenarios above.

Table 20: Indicator results per km driving distance, year 2050 (source: De Angelis et al., 2021)

AIR POLLUTION PRECURSORS PERCENTAGE EMISSION REDUCTION WITH RESPECT TO THE BASE-CASE 2018 FOR THE SELECTED SCENARIOS

Scenario	NO _x	VOC	NH ₃	PPM ₁₀	PPM _{2,5}	SO ₂
scen 8	-46.8%	-1.8%	-0.5%	-4.7%	-5.8%	-15.2%
scen 19	-53.4%	-3.4%	-0.6%	-6.1%	-7.3%	-21.8%
scen 20	-55.0%	-3.4%	-0.6%	-6.1%	-7.4%	-22.0%

According to Liu et al. (2021), the adoption of fuel cell vehicles (FCVs) could significantly reduce greenhouse gas (GHG) emissions from the heavy-duty truck fleet by 2050, with the Aggressive scenario aiming for a 63% reduction, the Moderate scenario a 30% reduction, and the Conservative scenario a 12% reduction, assuming that a higher proportion of fuel cell HDTs results in lower GHG emissions due to the cleaner nature of hydrogen fuel. The stocks are categorized by fuel types: hydrogen, diesel, and natural gas, with sales projections for fuel cell heavy-duty trucks (HDTs) in 2030, 2040, and 2050 under three scenarios: Aggressive (30%, 70%, 100%), Moderate (12.5%, 30%, 50%), and Conservative (5%, 12%, 20%). The Aggressive scenario predicts a full transition to hydrogen fuel cell trucks by 2050, while the Moderate and Conservative scenarios expect a partial transition. Machado et al. (2021) also highlight the potential for significant environmental benefits through the adoption of alternative fuel technologies in the transportation sector. Specifically, they point out that biogas or fuel-cell hydrogen trucks present higher chances of reducing greenhouse gas (GHG) emissions. Furthermore, the study notes that trucks powered by fuel-cell hydrogen or natural gas are capable of lowering emissions of particulate matter (PM_{2.5}) and nitrogen oxides (NO_x), indicating a dual advantage in terms of both climate change mitigation and air quality improvement.

5.2 Selective Emissions Reductors

Selective Emissions Reductors reviewed in this section include main technological solutions to reduce emissions from harmful pollutants that put at risk sustainable development, including sulphur oxides, nitrogen oxides, hydrocarbons, carbon monoxide, particulate matter and the capture, utilize and storage of carbon emissions.

5.2.1 SO_x Scrubbing System

Kim et al. (2019) describe SO_x Scrubbing Systems also as Exhaust Gas Cleaning Systems (EGCS). These are vital technologies for reducing sulphur oxides (SO_x) from ship exhaust gases, which are significant contributors to air pollution, particularly in coastal regions. These systems use either seawater or fresh water combined with an alkaline substance to neutralize and extract SO_x, aligning with the International Maritime Organization's (IMO) sulphur emission regulations. This contributes markedly to mitigating acid rain and preventing respiratory issues by ensuring compliance with environmental standards.

Further expanding on the environmental benefits of these systems, Wilailak et al. (2021) provide a detailed analysis revealing that wet SO_x scrubber systems can decrease greenhouse gas (GHG) emissions by 31.72% in open-loop systems and by an impressive 51.17% in closed-loop systems. These figures emphasize the potential of SO_x scrubbing technology in significantly reducing the carbon footprint of maritime operations.

Additionally, Tran (2017) and Ni et al. (2020) present findings on the efficacy of these scrubbing systems in curtailing emissions, demonstrating that SO_x gas emission reductions can achieve up to 95%, while the efficiency in reducing Particulate Matter (PM) can reach 60%. This high level of emission control further illustrates the critical role of SO_x scrubbing systems in enhancing air quality and protecting environmental and human health. Together, these studies show the benefits of adopting exhaust gas cleaning systems aboard ships, from meeting stringent international regulations to significantly lowering the environmental impact of the shipping industry.

5.2.2 Selective Catalytic Converter

Selective Catalytic Converter or Reduction (SCR) technology plays a crucial role in mitigating air pollution by effectively reducing harmful emissions from vehicles and industrial sources. This technology targets nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO), transforming them into less harmful substances, thereby significantly enhancing air quality and curtailing smog formation.

Athrashalil et al. (2014) emphasize the effectiveness of SCR technology in vehicles, indicating that it can achieve over 55% NO_x conversion, a substantial reduction that emphasizes its importance in environmental protection efforts. Further emphasizing the versatility and efficiency of SCR technology, Han et al. (2019) identify NH₃-SCR as the leading method for curtailing NO_x emissions not just in diesel engines but also in coal-fired industries, highlighting its broad applicability and potential impact on a wide range of emission sources.

However, despite its effectiveness, SCR technology does face challenges, particularly in terms of its performance across different temperature ranges. Barreau et al. (2020) point out that while SCR is a potent process for removing NO_x from diesel exhaust, its activity diminishes in lower temperature ranges, specifically achieving only 50–60% efficiency between 200°C and 300°C. This limitation highlights an area for potential improvement and further research to enhance the technology's overall efficacy.

5.2.3 Carbon Capture, Utilization, and Storage

Carbon Capture, Utilization, and Storage (CCUS) is an approach to managing carbon dioxide (CO₂) emissions, a significant contributor to global warming. Figure 32 shows that CCUS encompasses various technologies and methods for capturing CO₂ from sources such as fossil fuel power generation, natural CO₂ wells, and industrial processes. Once captured, the CO₂ can be either used in applications like chemical synthesis and energy production or stored in geological formations to prevent its release into the atmosphere.

The efficacy of CCUS is evident in its potential to reduce the carbon footprint of fossil fuels, thus enabling continued use while mitigating environmental impacts. Volkart et al. (2013) provide a quantitative assessment of CCUS's benefits, indicating that the implementation of Carbon Capture and Storage can lead to life cycle greenhouse gas (GHG) emission reductions of 68-92% for fossil power generation and 39-78% for cement production. These numbers emphasize the significant role that Carbon Capture and Store can play in transitioning to more sustainable industrial processes.

Furthermore, He et al. (2021) examine the benefits of CO₂ utilization, particularly through the reverse water-gas shift reaction, which converts CO₂ into syngas. This syngas can then be used for producing liquid fuel and power, achieving an energy savings of 18.19% and a life-cycle carbon emission reduction rate of 46.87% when compared to conventional natural gas combined cycle (NGCC) and gas-to-liquids (GTL) standalone production systems. These statistics highlight the dual benefit of CCUS technologies in reducing emissions and enhancing energy efficiency.

The integration of capture, utilization, and storage in the CCUS model by Taipa et al. (Figure 32), provide a comprehensive strategy for addressing CO₂ emissions. By capturing emissions at their source,

employing them in beneficial applications, and securely storing any excess, CCUS technologies offer a pathway to significantly reduce the carbon footprint of industrial activities and contribute to global efforts to combat climate change.

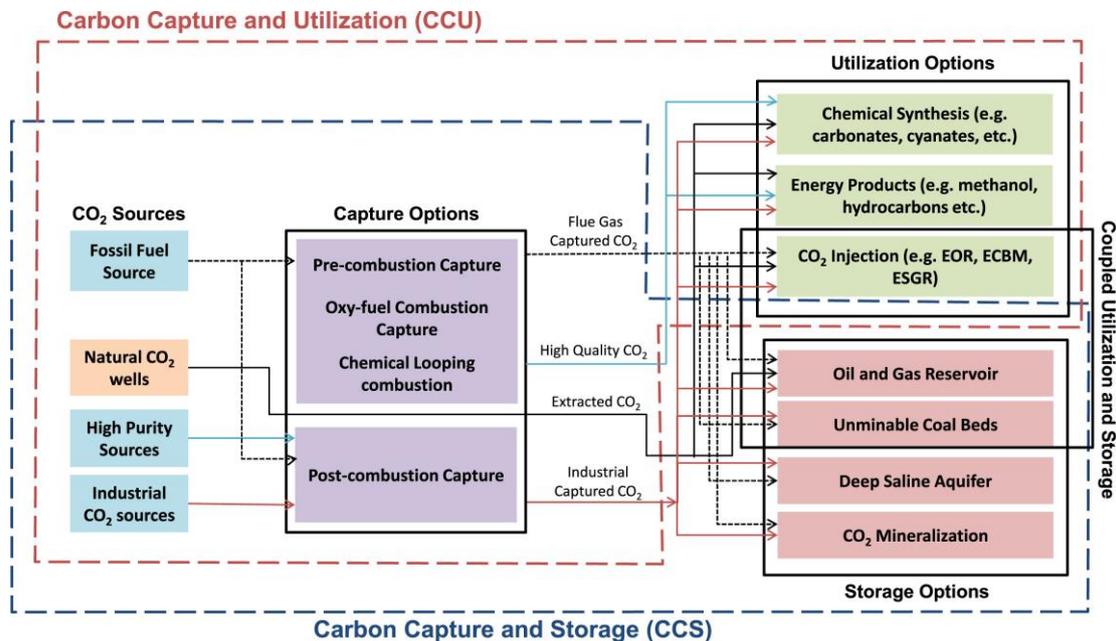
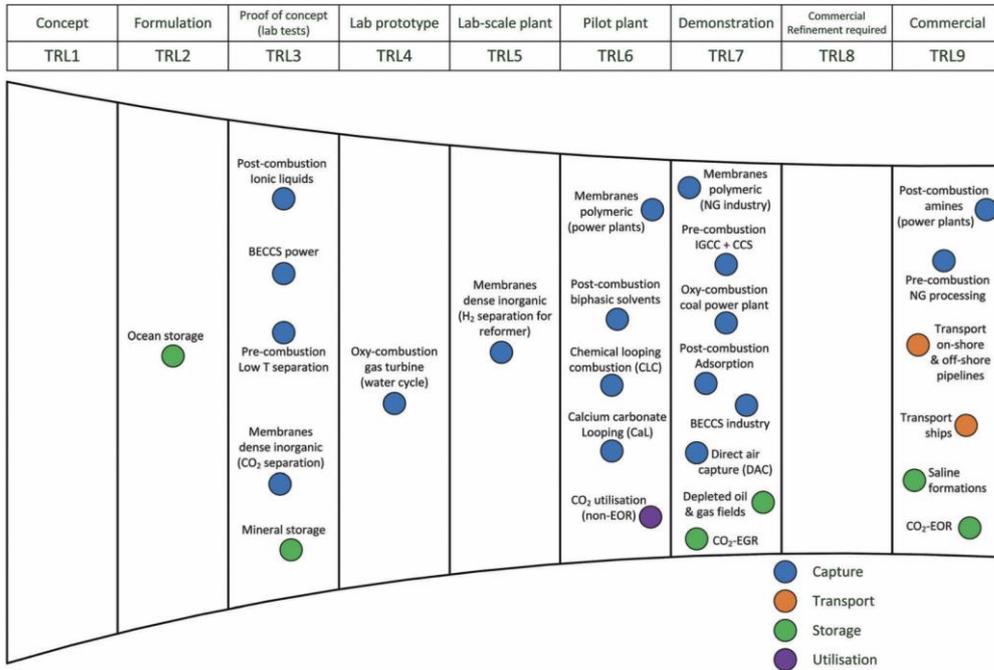


Figure 32: Carbon Capture, Utilization, and Storage (source: Taipa et al., 2018)

The work of Bui et al. (2018) delivers a comprehensive understanding of the current landscape and future needs of Carbon Capture, Utilization and Storage (CCUS) technologies. These visuals collectively highlight the stages of technology readiness, global deployment of commercial-scale projects, and key research and development (R&D) needs in the short term for bioenergy with carbon capture and storage. Claiming not to be exhaustive, these works provide a list a range of negative emissions technologies: a) Direct Air Capture – it provides a mechanical solution with chemical aids; b) Soil Carbon Sequestration – it leverages agricultural practices; c) – Biochar - it uses waste biomass; c) Enhanced Weathering (EW) – it manipulates natural mineral processes; d) Ocean Fertilization (OF) - it enhances biological sequestration in oceans, and e) Indirect ocean capture - it uses chemical processes to increase the ocean's natural absorption capacity. These methods are at various stages of research, development, and deployment, and they present promising avenues for reducing global CO₂ levels, which is critical in the fight against climate change.

The technology readiness levels (TRL) depicted in Figure 33 illustrates the progression of various CCUS technologies from concept to commercial deployment. Technologies like post-combustion ionic liquids, membranes for power plants, and oxy-combustion gas turbine (water cycle) are in varying stages of development, with some reaching pilot plant stages and others still requiring demonstration and refinement. Notably, post-combustion adsorption and pre-combustion integrated gasification combined cycle (IGCC) + CCS have advanced further, moving closer to commercial reality.



Current development progress of carbon capture, storage and utilization technologies in terms of technology readiness level (TRL). BECCS = bioenergy with CCS, IGCC = integrated gasification combined cycle, EGR = enhanced gas recovery, EOR = enhanced oil recovery, NG = natural gas. Note: CO₂ utilisation (non-EOR) reflects a wide range of technologies, most of which have been demonstrated conceptually at the lab scale. The list of technologies is not intended to be exhaustive.

Figure 33: Technology Readiness Levels of carbon capture, storage, and utilization technologies (source: Bui et al., 2018)

Regarding the CO₂ capture capacity of commercial-scale CCS projects worldwide, with clear worldwide leaders emerging. The United States stands out with a significant number of projects in operation, while regions like Australia, New Zealand, and Asia are actively evaluating and defining projects, indicating a global recognition of the importance of CCS in mitigating climate change (Figure 34).

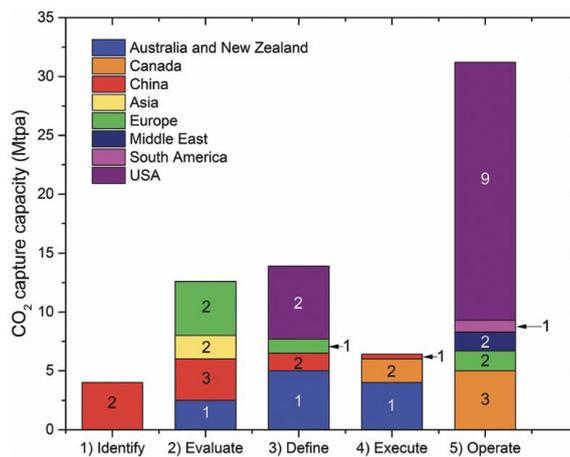


Fig. 2 The CO₂ capture capacity of commercial-scale CCS projects worldwide. The number labelled on each proportion of capture capacity corresponds to the number of projects. Data from the Global CCS Institute.⁴

Figure 34: CO₂ capture capacity of commercial-scale CCS projects worldwide, n° of projects (source: Bui et al., 2018; data from the Global CCS Institute)

Bui et al. (2018) also identified key R&D needs to ensure the technology's viability and sustainability. It includes the need for sustainable biomass feedstocks, the development of technical innovations to increase efficiency and reduce emissions, the assessment of less mature technologies, and the consideration of economic and policy frameworks to encourage its deployment. Public perception is also noted as a key area, suggesting a need for increased engagement and collaboration among stakeholders to foster broader acceptance and implementation of CCS technologies.

The Sixth Assessment Report (AR6) by the Intergovernmental Panel on Climate Change (IPCC, 2023) provides critical insights into the role of negative emissions technologies (NETs) in climate mitigation strategies. According to AR6, the extent of the overshoot in global temperature levels directly correlates with the magnitude of net negative CO₂ emissions required to revert to specific warming thresholds. Specifically, achieving a reduction in global temperature necessitates net negative emissions of approximately 220 gigatonnes (Gt) of CO₂ for every 0.1°C decrease, based on a best estimate, with the potential range lying between 160 and 370 gigatonnes (IPCC, 2021). This requirement emphasizes the significance of modelled pathways that aim to cap warming at 1.5°C above pre-industrial levels with minimal or no overshoot, which project median cumulative net negative emissions of 220 gigatonnes by the century's end. Conversely, pathways that aim to return to the 1.5°C threshold following a significant overshoot are estimated to require median net negative emissions of around 360 Gt. Furthermore, the report emphasizes the importance of swift reductions in CO₂ and non-CO₂ emissions, particularly methane, to mitigate peak warming levels effectively. Such actions not only limit the extent of overshoot but also diminish the reliance on net negative emissions and carbon dioxide removal (CDR) technologies. By doing so, potential feasibility, sustainability issues, and social and environmental risks associated with extensive use of NETs and CDR can be significantly reduced, ensuring a more viable path towards achieving long-term climate goals (IPCC, 2023).

5.2.4 Cold Ironing in shipping or onshore power supply from renewable energy (shore-to-ship power)

Onshore power supply (OPS), also known as cold ironing, is a transformative approach for reducing emissions from ships while docked. It involves connecting ships to the local electricity grid, allowing them to power down their engines, thereby significantly decreasing emissions at ports. Voldsund et al. (2023) have indicated that OPS can lead to emission reductions of over 95% when the ships are supplied with low greenhouse gas (GHG) electric power. Nonetheless, as Olaniyi et al. (2022) argue, the effectiveness of OPS in cutting CO₂ emissions—estimated at about 25% directly from the vessels—is heavily dependent on the use of green electricity. The current lack of green electricity in all cruise ports worldwide limits the full environmental potential of OPS. In addition to environmental considerations, factors such as infrastructure costs and ship compatibility with OPS technology are critical. Moreover, there is the risk of merely shifting emissions from ships to power plants if the electricity used is not from low-carbon sources, a concern that must be addressed to ensure that OPS contributes genuinely to ecological improvements.

Ballini et al. (2015) emphasize the importance of OPS in improving air quality and reducing health risks for residents in port cities by cutting emissions of NO_x, SO_x, CO, and particulate matter from ships. Furthermore, Lee et al. (2021) provide detailed metrics on the potential emission reductions achievable through the application of cold ironing in shipping, including decreases in CO₂ by 30%, NO_x

by 30%, SO_x by 93%, particulate matter (PM₁₀ and PM_{2.5}) by 64%, volatile organic compounds (VOC) by 28%, ammonia (NH₃) by 30%, and carbon monoxide (CO) by 30%. These figures emphasize the efficacy of OPS as a strategy for making maritime transportation more environmentally friendly, albeit with the caveat that its success hinges on the carbon intensity of the local electricity grid and the infrastructure's compatibility with different ship designs.

5.2.5 Electrostatic precipitators

Electrostatic Precipitators (ESPs) are advanced filtration devices designed to capture fine particles, such as dust and smoke, from flowing gases by leveraging the power of an induced electrostatic charge. These devices are important in mitigating particulate emissions in various settings, including power plants and diverse industrial and manufacturing processes. Their operation is not only crucial for air quality control but also for enhancing the performance and efficiency of engines and other machinery within these environments.

Samuel et al. (2019) highlight the significant impact of integrating an electrostatic precipitator with a diesel particulate filter, showcasing a remarkable reduction in particulate matter (PM) and lead emissions by 98%. This integration not only boosts the collection efficiency of particulate matter but also enhances engine efficiency, offering a dual benefit of environmental protection and improved machinery performance. On a related note, Jaworek et al. (2018) emphasize the capability of two-stage electrostatic precipitators to curtail PM_{2.5} particle emissions by up to 99%. However, they also note a limitation in their efficiency when dealing with ultrafine particles smaller than 1 micron, suggesting an area for potential improvement in ESP technology. While ESPs demonstrate high efficiency in filtering particulate emissions, the noted decrease in performance with particles smaller than 1 micron points to an opportunity for technological advancements. Enhancing the capability of ESPs to efficiently capture these ultrafine particles could further solidify their position as a cornerstone technology in pollution control and air purification efforts.

5.2.6 Low-NO_x burners and overfire air systems

Low-NO_x burners and Overfire Air (OFA) systems represent critical technologies aimed at minimizing nitrogen oxide (NO_x) emissions from industrial boilers, furnaces, and other combustion units. These technologies address the environmental challenge of NO_x pollution by optimizing the combustion process to reduce the formation of these harmful gases. Low-NO_x burners achieve this through precise management of the combustion environment, whereas OFA systems enhance the efficiency of combustion, contributing to further reductions in NO_x emissions.

Recent advancements in this field have shown promising results in decreasing NO_x emissions across various types of combustion systems. Ma et al. (2020) reported that a novel combustion system utilizing separated over-fire air (SOFA) technology could cut NO_x emissions by over 50% in down-fired boilers, indicating a significant leap in performance and environmental impact mitigation. Similarly, Archan et al. (2021) explored the efficacy of novel small-scale multi-fuel biomass grate furnace technology, documenting a notable reduction in NO_x emissions—39% for wood chips, 40% for wood pellets, and 45% for miscanthus briquettes—when compared to conventional small-scale furnaces.

Furthermore, Yan et al. (2021) demonstrated that the strategic adoption of middle flue gas recirculation combined with top supplementary burnout air in a Circulating Fluidized Bed (CFB)

combustor led to a NO_x reduction rate of 46.15%. This innovative approach emphasizes the potential for significant environmental benefits through the thoughtful integration of combustion technologies. Zhu et al. (2021) highlighted another profound achievement, where the implementation of close-coupled over-fire air and separated over-fire air systems resulted in a substantial NO_x reduction of 70.2%, achieving emission levels as low as 217 mg/m³.

5.2.7 Thermal oxidizers

Thermal oxidizers, also known as thermal incinerators, are critical systems designed to address pollution by treating exhaust streams laden with volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). These systems operate on the principle of heating pollutants to a high temperature, which facilitates the breakdown of toxic compounds into less harmful byproducts such as CO₂ and water vapor. This process is instrumental in mitigating the environmental impact of industrial activities by ensuring cleaner air emissions.

Sarjito et al. (2021) highlight the efficiency of thermal oxidizers in managing nitrogen oxide (NO_x) emissions, noting that these systems can eliminate up to 50% of nitrogen oxide, thereby contributing to the reduction of greenhouse gas emissions in the atmosphere. This capability emphasizes the importance of thermal oxidizers in combating air pollution and climate change. In parallel, Rogalev et al. (2021) introduce the Allam cycle as a novel approach to reducing CO₂ emissions. This closed thermodynamic cycle uses oxy-fuel combustion to achieve a remarkable net efficiency of 51.4%. The integration of such cycles in industrial processes can significantly enhance the efficiency of emission reduction efforts, marking an advancement in environmental technology. Moreover, Suratwala et al. (2022) propose improvements to after treatment systems to achieve even greater efficiencies, suggesting that it is possible to extract 90% or more efficiency from these systems. Their review outlines several pollutant reduction methods, including exhaust gas recirculation (EGR), lean NO_x trap (LNT), diesel oxidation catalyst (DOC), diesel particulate filter (DPF), and selective catalytic reduction (SCR). Each of these methods plays a crucial role in minimizing emissions from industrial processes, offering a comprehensive suite of solutions for environmental pollution control.

5.3 Energy Efficiency

This section outlines thirteen “energy efficient solutions” (Subsection 5.3.1), and seven other measures designated as “sustainability through collaboration” across road, rail and maritime transport (Subsection 5.3.2), the latter requiring further cooperation of stakeholders, transport modes, sharing of resources or use of common digital methods to achieve the common goal of energy efficiency.

Brenna et al. (2020) provides a previous review on energy efficiency in transportation covering railways, road and maritime modes, the latter focusing on the electrification of propulsion systems and electrically driven equipment (e.g., pumps, cranes, etc.). More recently, Rigogiannis et al. (2023) presents a review of green technologies for GHG reduction that are applicable to road transportation.

5.3.1 Energy efficient solutions

Dynamic wireless power transfer & inductive charging roads

The emergence of Dynamic Wireless Power Transfer (DWPT) and Inductive Charging Roads (ICR) stands out as a beacon of innovative technology. These cutting-edge solutions are not just theoretical concepts but are relevant in the shift towards more sustainable and efficient transportation models. By integrating DWPT and ICR into our transportation infrastructure, we can significantly diminish CO₂ emissions while concurrently boosting the energy efficiency of vehicle operations.

Bi et al. (2019) emphasize the environmental and operational efficiencies afforded by dynamic wireless charging technology. Their research suggests that this technology can curtail greenhouse gas emissions and energy usage by as much as 9.0% and 6.8% respectively. Moreover, it presents an opportunity to reduce electric vehicle (EV) battery capacity requirements by up to 48%, which could lead to significant advancements in EV design and utility. This is a crucial development in the automotive industry, promising to make EVs more accessible and environmentally friendly.

Further emphasizing the potential of renewable energy integration into this innovative charging infrastructure, Mou et al. (2019) demonstrate that an adaptive dynamic wireless charging system, when powered by renewable wind energy, can slash carbon emissions by an impressive 63.7%. This system not only facilitates a significant reduction in emissions but also maintains fast demand prediction and supply response, showcasing a symbiotic relationship between renewable energy sources and advanced vehicle charging technologies.

Shimizu et al. (2020) add to the discourse by illustrating the substantial environmental benefits of DWPT systems in electric vehicles. According to their findings, these systems have the potential to reduce CO₂ emissions by up to 62% in comparison to traditional internal combustion vehicles. This reduction is a testament to the sustainability and consumer appeal of DWPT-equipped passenger vehicles, marking a significant step forward in the pursuit of a more sustainable future.

Energy harvesting shock absorbers and thermoelectric generators

The integration of energy harvesting technologies such as shock absorbers and thermoelectric generators (TEGs) into modern systems presents a ground-breaking approach to enhancing vehicle efficiency and reducing environmental impact. These innovations capitalize on otherwise wasted energy—be it from vehicle vibrations or temperature differentials—to generate electricity, offering a sustainable solution to reliance on fossil fuels.

Thermoelectric generators have emerged as a cornerstone in the quest for green energy production. Zaferani et al. (2021) detail the capabilities of TEGs in capturing and recycling waste heat, which not only mitigates greenhouse gas emissions but also advances thermal management across various industries. The ability of TEGs to effectively recycle waste heat emphasizes the potential for significant environmental benefits and efficiency improvements in energy use.

Building on the environmental and operational merits of TEGs, Jouhara et al. (2021) highlight the promising aspects of these devices as a green power production alternative. TEGs are lauded for their environmentally safe, quiet, and durable characteristics. Additionally, their ability to convert thermal

energy into electric power through the Seebeck effect presents a clean, efficient method of electricity generation that complements the global shift towards sustainability.

Kinetic energy recovery systems (KERS) & regenerative braking systems in trains and electric vehicles

Kinetic energy recovery systems (KERS) are designed to capture and store kinetic energy during vehicle deceleration, offer a promising avenue for enhancing energy efficiency and reducing reliance on fossil fuels across various modes of transportation. Raju et al. (2020) show the impact of kinetic energy recovery braking systems on fully electric vehicles, emphasizing their potential to extend driving ranges significantly. By recovering energy that would otherwise be lost during braking, these systems not only reduce the need for frequent recharging but also contribute to a decrease in the overall dependence on fossil fuels. This innovation is important in the quest for more sustainable electric vehicle operations, showcasing the tangible benefits of integrating KERS into modern automotive designs.

In the context of internal combustion engine vehicles, Pipitone et al. (2020) introduce an electric to 20%, despite a marginal increase in vehicle weight (+2%). This system's readiness for implementation in current vehicle production emphasizes the feasibility of retrofitting existing vehicles with energy-saving technologies, presenting a scalable solution for enhancing fuel efficiency and reducing emissions in the short term. Furthermore, Cutrignelli et al. (2023) extend the application of regenerative braking technology to the railway sector, demonstrating its effectiveness in diesel-powered rail vehicles. Their findings reveal that regenerative braking can lead to a 20% reduction in fuel consumption and a significant 22.3 kg CO₂ emissions reduction per vehicle compared to traditional diesel operations. This evidence highlights the versatility and environmental benefits of regenerative braking systems, proving their value across different transportation mediums.

Energy-efficient refrigeration for transport cooling

Maiorino et al. (2021) emphasize the potential benefits of optimizing refrigerated transport systems. Their research sheds light on how modern technologies and strategies can significantly lower energy consumption, reduce greenhouse gas emissions, and enhance overall system efficiency. The study presents a comprehensive overview of the current state of refrigerated transport, identifying technical issues, innovations, and challenges that lie in the path towards achieving sustainability in this critical sector. By adopting energy-efficient refrigeration systems, the transport industry can make substantial strides in improving its sustainability profile. The focus on leveraging advanced insulation and compressor technologies not only supports the reduction of energy usage but also contributes to the global efforts in combating climate change. Through such optimizations, the sector can ensure the continued, efficient delivery of perishable goods across vast distances while simultaneously embracing a more sustainable operational model.

Eco-driving

Eco-driving involves the adoption of efficient driving behaviours, such as smoother acceleration and deceleration, which not only enhance vehicle efficiency but also diminish environmental impact through optimized fuel use and minimized carbon emissions. Barth, M., & Boriboonsomsin, K. (2009) delve into the concept of dynamic eco-driving, which leverages real-time traffic sensing and telematics. Their research indicates that such an approach can result in approximately 10-20% fuel savings and

lower CO₂ emissions, without a significant increase in travel time. This approach exemplifies how technology can facilitate eco-driving in real-world conditions, adjusting driving patterns dynamically in response to traffic conditions to maximize fuel efficiency.

Massar et al. (2021) present a compelling case for eco-driving and platooning, which together can lead to a reduction in greenhouse gas (GHG) emissions by up to 35%. This significant decrease emphasizes the effectiveness of combining driving behaviour modification with technological advancements in vehicular coordination and traffic management.

Coloma et al. (2017) provide previous evidence of the benefits of eco-driving, noting CO₂ savings of 17% for gasoline engines and an even greater reduction of 21% for diesel engines. They also acknowledge a modest increase in travel times by an average of 7.5%, suggesting that while eco-driving is beneficial for the environment, it may slightly impact travel efficiency.

De-speeding trucks

The implementation of de-speeding strategies for trucks is becoming increasingly recognized as an effective measure to reduce fuel consumption and emissions, thereby contributing to environmental sustainability and public health. De-speeding involves lowering the maximum allowed speeds for heavy-duty vehicles, and this practice yields multiple benefits across different spheres of impact. Panis et al. (2011) have noted that while speed management policies in Europe may not substantially affect the emissions of most classic pollutants, they have a consistent and positive effect on reducing CO₂ emissions and fuel consumption for trucks. This highlights the potential of regulatory speed limits as a straightforward means of contributing to environmental goals.

Further emphasizing the impact of de-speeding, Wu et al. (2015) found that reducing the average speed of diesel buses and trucks from 30 km/h to 20 km/h can lead to a significant 26% reduction in CO₂ emissions and an even more substantial 43% decrease in NO_x emissions. These reductions can contribute to better air quality and lower the overall environmental impact of freight transport.

Osorio-Tejada et al. (2018) outline the quantitative details of how de-speeding can influence energy consumption and emissions. They suggest that de-speeding trucks can reduce energy consumption and emissions by up to 145%, with the extent of these reductions depending on factors such as vehicle speed, load, and road gradient. This indicates a nuanced relationship between de-speeding and fuel efficiency, which can vary with operational conditions. Pan et al. (2019) provide a broader perspective on the benefits of de-speeding, linking it to public health and economic advantages. According to their research, de-speeding trucks can reduce PM_{2.5} emissions by 20%, which could prevent 3600 premature deaths and yield \$38 billion in economic benefits, showcasing the profound societal benefits of such environmental policies. Ferreira et al. (2020) quantify the environmental and resource consumption impact of de-speeding, reporting an average of 6.50% impact reduction for resource consumption, human health, and global warming potential. Furthermore, they note a substantial reduction in diesel consumption by up to 5000 liters per year for each truck, which translates into a significant decrease in the environmental footprint of freight transport.

Route optimization

Route optimization is a critical component in the push towards more sustainable transportation systems. By leveraging advanced algorithms and tools, transportation can be made more efficient, significantly reducing fuel consumption and the emissions associated with vehicular travel. Torres-Machí et al. (2017) describe a tool designed to optimize sustainable maintenance programs. Their research shows that such a tool can increase the condition of the transportation network by up to 22% while concurrently reducing greenhouse gas (GHG) emissions by 12%. This demonstrates that route optimization not only benefits the environment but also improves the overall quality of transportation infrastructure. The study by Bandeira et al. (2013) brings a nuanced perspective to the discussion, pointing out that while faster intercity routes can reduce fuel use and CO₂ emissions, they might lead to increases in other pollutants such as carbon monoxide, nitrous oxides, and hydrocarbons by up to 150%. This highlights the complex trade-offs that must be considered when optimizing routes for speed and efficiency. Schröder et al. (2019) examine the concept of eco-friendly routes, noting that these can result in substantial fuel and emission savings of up to 20% in tested scenarios. However, they also acknowledge that such routes may incur increased expenses, suggesting that economic factors must be balanced against environmental benefits in route optimization. Further emphasizing the potential of intelligent systems, Nguyen et al. (2021) present a swarm intelligence-based traffic optimization framework. Their findings indicate that this framework can reduce average fuel consumption and emissions by 13-19% and cut down average trip duration by 19-28%, showcasing the significant impact of advanced computational techniques in transportation. Macedo et al. (2020) contribute to the research field by discussing a multi-objective traffic assignment approach that yields savings in distance travelled (2.6%) and emissions (1.3% for CO₂ and 1.1% for NO_x). However, they note a trade-off, as this approach penalizes travel time by 3%, resulting in an average increase of 20 seconds per vehicle. This emphasizes the importance of balancing various objectives in route optimization to achieve the best overall outcomes to achieve sustainability.

Slow steaming

The shipping industry has been actively seeking strategies to mitigate environmental impacts and adhere to international targets for reducing greenhouse gas emissions. Studies have shown that various factors including engine types, operational conditions, and fuel sulphur content significantly influence the emissions from ships. Emission factors for different engine types show that, for main engines (ME), slow-speed diesel (SSD) emits 620 g/kWh of CO₂, while high-speed diesel (HSD) emits 686 g/kWh. Auxiliary engines (AE) and boilers exhibit higher CO₂ emissions, with AEs at 683 g/kWh and boilers at a considerable 970 g/kWh (Weng et al., 2020). The correction factors for different fuel types based on their sulphur content further indicate that using fuels with lower sulphur content can reduce SO₂ emissions. For instance, residual oil (RO) with 1.50% sulphur content has a correction factor for SO₂ emissions of 0.56, while marine distillates (MD) with only 0.10% sulphur content can reduce SO₂ correction factors to as low as 0.04 (Weng et al., 2020).

A promising approach to reduce emissions is slow steaming, a practice that involves operating vessels at lower speeds. This technique not only reduces fuel consumption but also diminishes emissions of CO₂, CH₄, N₂O, and Black Carbon (BC), contributing to a better ship's Carbon Intensity Indicator (CII) rating. It shall be noted that the CII is a rating system for ships developed by the IMO. Through slow

steaming, the shipping industry aims to achieve CO₂ reduction targets of 40% by 2030 and 50% by 2050 (Zincir, 2023).

Table 21 presents the four different scenario cases for the voyage data of a case ship in the study of Zincir (2023). The scenarios range from S1, with a main engine load of 75% and a ship speed of 11 knots resulting in a voyage duration of 65.3 days, to S4, where the main engine load is reduced to 19%, the ship speed is 6.3 knots, and the voyage lasts for 114.5 days. This table effectively demonstrates the principle of slow steaming, where reducing engine load and speed leads to longer voyage durations. Figure 35 from the same study shows the emissions and Global Warming Potential (GWP) comparison across the case study scenarios. As the scenarios progress from S1 to S4, there is a noticeable decrease in emissions of CO₂, N₂O, CH₄, and BC, aligning with the reduction in engine load and ship speed.

Table 21: Voyage data for shipping scenarios in the study of Zincir (2023)

Scenario cases	Main engine load [%]	Ship speed [knots]	Voyage duration [days]
S1	75%	11	65.3
S2	38%	8.3	84.9
S3	27%	7.3	98.8
S4	19%	6.3	114.5

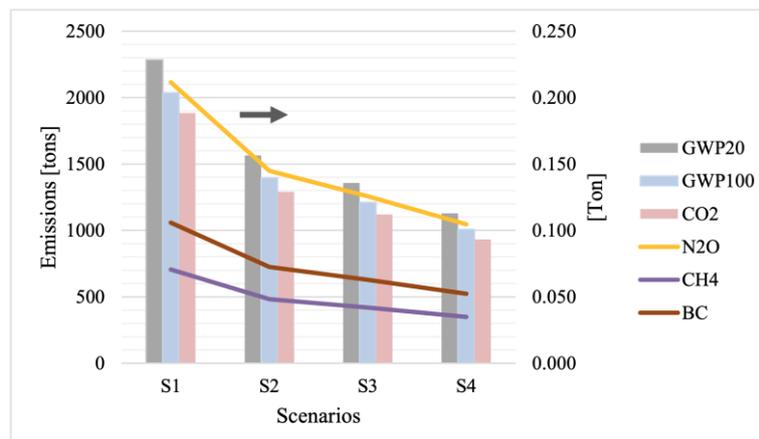


Figure 35: Emission and GWP comparison of the case study scenarios (source: Zincir, 2023)

Furthermore, the cumulative percentage of ship emissions under different operating conditions and engine emissions highlights the impact of operational strategies and engine selection on overall emissions. Berthing, anchoring, manoeuvring, slow-steaming, and normal cruising contribute variably to emissions of different pollutants like CO₂, CO, HC, NO_x, and SO₂. Similarly, the type of engine (ME, AE, or Boiler) also determines the cumulative emissions profile (Weng et al., 2020), as illustrated in Tables 22, 34 and Figure 36.

Table 22: Emissions factors for different engine types, g/KWh (source: Weng et al., 2020)

Machine type	Engine type	CO ₂	CO	HC	NO _x	SO ₂
ME	SSD	620.00	1.40	0.60	17.00	10.50
ME	MSD	683.00	1.10	0.50	13.00	11.50
ME	HSD	686.00	1.10	0.50	12.70	11.31
AE	MSD	683.00	1.10	0.40	13.00	12.30
Boiler		970.00	0.20	0.10	2.10	16.50

Note: ME is main engine, AE is auxiliary, SSD is slow-speed diesel, MSD is medium-speed diesel and HSD is high-speed diesel.

Table 23: Correction factors for different fuel types (source: Weng et al., 2020)

Table 5

Correction factors of different fuel types.

Fuel type	Sulfur content/%	CO ₂	CO	HC	NO _x	SO ₂
RO	1.50	1	1	1	1	0.56
MD	1.50	1	1	1	0.90	0.56
MD	0.50	1	1	1	0.94	0.18
MD	0.20	1	1	1	0.94	0.07
MD	0.10	1	1	1	0.94	0.04

Note: RO is residual oil, MD is marine distillates.

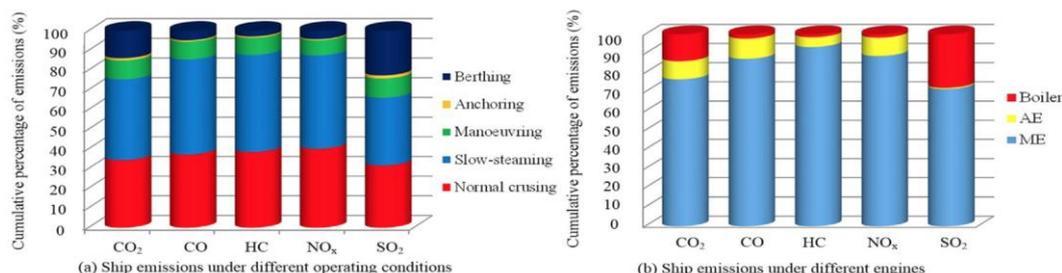


Figure 36: Cumulative percentage of ship emissions under each (a) different operating conditions and (b) different engine emissions (source: Weng et al., 2020)

To complement operational strategies like slow steaming, the industry also uses indices such as the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operating Index (EEOI) and considers Market-Based Measures (MBMs) like emissions trading schemes and carbon tax proposals. These measures are designed to promote greener shipping by incentivizing the design and operation of more energy-efficient vessels.

The interaction of various measures impacting shipping emissions has been conceptualized by Fan et al. (2021), who provided a structural analysis (Figure 37) of the connections between different variables in the maritime industry. Their study delineated how these measures interact and influence each other, as well as their collective impact on shipping emissions and environmental quality.

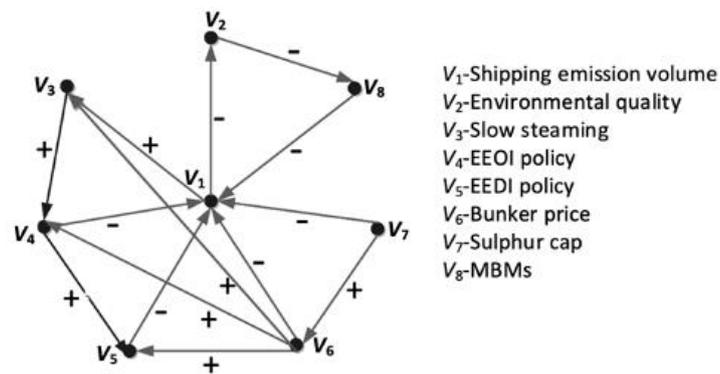


Figure 37: Structural connections of measures impacting shipping emissions (source: Fan et al., 2021)

In their framework, as it can be seen in Figure 37, the variable V1 represents the shipping emission volume, which is directly affected by slow steaming (V3), EEDI policy (V5), and bunker price (V6). Slow steaming (V3) is shown to have a positive effect on environmental quality (V2), which suggests that reducing ship speeds leads to improved environmental outcomes. This aligns with the practice's intent to decrease fuel consumption and emissions, as evidenced by the CO₂ reduction targets set for the industry. EEDI policy (V5) and EEOI policy (V4) are both crucial in defining the design and operational efficiency of ships. The EEDI influences ship design to ensure that new vessels meet certain energy efficiency criteria, while the EEOI assesses the operational efficiency of existing ships. These policies are interconnected, as indicated by a bidirectional positive relationship. The bunker price (V6) influences shipping emissions (V1) and is also impacted by Market-Based Measures (MBMs, V8), such as carbon pricing schemes, which can make fuel costs more variable and potentially higher. The sulphur cap (V7), representing the limits on fuel sulphur content, directly affects the bunker price due to the need for cleaner, often more expensive, fuels. MBMs (V8) are also connected to EEOI policy (V4) and the shipping emission volume (V1), showcasing how market mechanisms can incentivize reductions in emissions through economic signals.

Wind power for energy production

Wind power, as a sustainable and renewable energy source, is instrumental in the global shift towards cleaner energy production. The utilization of wind turbines for electricity generation is not only a viable alternative to fossil fuels but also a significant contributor to reducing carbon emissions from transportation and energy production sectors.

Amin et al. (2020) have established that an uptick in renewable energy consumption can cut CO₂ emissions from transportation by an estimated 12 percent, underlining the critical role of renewables in achieving carbon reduction targets. Research by Li, H. et al. (2020) compared the life cycle emissions of wind and coal power, revealing that wind power projects boast a low carbon intensity of only 4.429 g/kWh. The potential for emission reductions throughout their life cycle is substantial, amounting to 2.0416 million tons when juxtaposed with traditional coal-fired stations. Complementing this finding, Li, J. et al. (2020) noted that for every kilowatt-hour generated, wind power is responsible for merely 4% of the total carbon dioxide emissions and environmental costs associated with coal power.

It is also important to consider the indirect emissions associated with wind power, specifically those arising from the manufacturing of turbines and their components. Detailed material lists for wind turbines, such as those for a 1.5 MW unit (Table 24), reveal substantial quantities of steel, iron, fiberglass, copper, and other materials required for their construction (Li, J. et al., 2020). Table 25 shows the energy and pollutant emission intensity associated with these raw materials, as well as the construction and Table 27 the inputs and outputs for the life-cycle analysis for wind power. Figure 38 shows that SO_x, NO_x, CO and PM emissions are orders of magnitude higher compared to coal power lifecycle.

Table 24: List of materials for 1.5 MW wind turbine and its components (source: Li, J. et al., 2020)

Equipment	Main component	Subcomponent	Materials	Quantity/tons		
Wind turbine	Rotors	Rotors blade(Three)	Fiberglass	19.2		
		Blade hub	Steel and iron	10		
		Pitch bearing(Three)	Steel and iron	3.6		
	Nacelle	Pitch drive	Pitch drive	Steel and iron	2.4	
			Nacelle cover	Fiberglass	0.8	
		Main shaft	Main shaft	Resin	1.2	
			Gearbox	Steel and iron	14	
		Generator	Gearbox	Steel and iron	25	
				Copper	1.85	
				Steel and iron	3.96	
		Nose-cone	Yaw system	Generator	Silicon	0.18
				others	Steel and iron	3
			Tower connector	Yaw system	Steel and iron	3.5
				others	Steel and iron	2.5
others	Steel and iron			12		
Flange	Tower	Basic ring	Steel and iron	10		
		Tower	Steel and iron	160		
		Footing	Concrete	300 (m ²)		
Foundations	Foundation	Reinforcement	Steel and iron	35		
		Box-type Transformer (30)	Copper	78		
Station and cables	Inside	Cables (150 mm)	Steel and iron	312		
			Copper	95.44		
		Overhead cables (14 km)	Aluminum	49		
			Copper	72		
	Outside	Large transformer(8)	Steel and iron	288		
			Aluminum	280		
		Overhead cables(20 km)	Aluminum	280		
			Cable tower(40)	Steel and iron	2400	

Table 25: Energy and pollutant emission intensity of wind farm raw materials (source: Li, J. et al., 2020)

Materials	Energy intensity (kgce/t)	CO ₂ (kg/kg)	SO ₂ (kg/kg)	NO _x (kg/kg)	CO(kg/kg)	PM(kg/kg)	Reference
Steel and iron	1379.8	2061.88	2.01	5.77	3.15	0.39	Wang and Zhang (2012)
Copper	3656.2	10 909.29	31.87	27.69	—	—	(Ruan et al., 2010)
Cement	228.8	604.00	0.372	1.92	—	0.341	Xu et al. (2013)
Silicon	5050	20 510	139	42	556	435	Ye (2007)
Fiberglass	5778	1128.9	3.5	4.25	—	—	Zhao et al. (2018)
Resin	1103	690	4.16	2.8	91.07	—	Li et al. (2009)
Aluminum	527.4	8566.00	34.20	14.00	3.08	0.88	(Liu and Müller, 2012)

Table 26: Inputs and outputs of LCI for wind power (source: Li, J. et al., 2020)

Inputs	Quantity (t)	Outputs				
		CO ₂ (g/kWh)	SO ₂ (g/kWh)	NO _x (g/kWh)	CO (g/kWh)	PM (g/kWh)
Steel and iron	22794.65	22.87	0.02	0.06	0.03	0.00
Copper	421.20	2.24	0.01	0.01	0.00	0.00
Cement	7391.52	2.17	0.00	0.01	0.00	0.00
Silicon	7.43	0.07	0.00	0.00	0.00	0.00
Fireglass	890.47	0.49	0.00	0.00	0.00	0.00
Resin	49.50	0.02	0.00	0.00	0.00	0.00
Aluminium	495.06	2.06	0.01	0.00	0.00	0.00
Diesel	169.43	0.26	0.00	0.00	0.00	0.00
Gasoline	4.90	0.00	0.00	0.00	0.00	0.00
Purchased Electricity	2675.7 (MWh)	1.14	0.03	0.02	0.00	0.31
Total		31.32	0.08	0.10	0.04	0.32

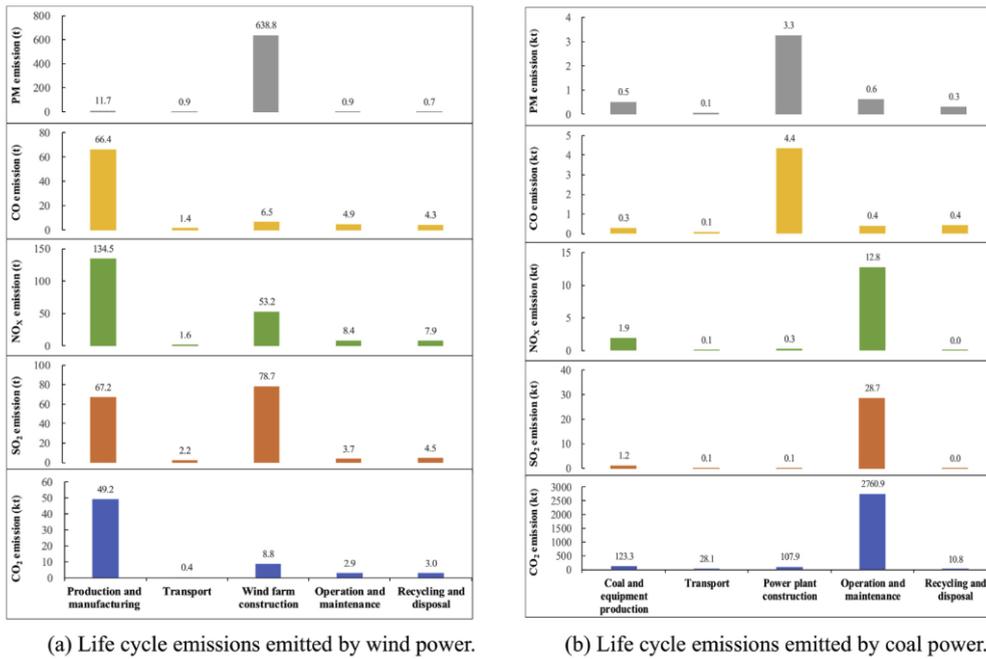


Figure 38: Life cycle emissions emitted by wind power (a) and (b) coal power (source: Li, J. et al., 2020)

The life cycle assessment of wind power, which includes production, transportation, construction, operation, maintenance, and recycling stages, offers an extensive view of its environmental footprint is illustrated in Figure 39 by from Li et al. (2020). The energy flow and emissions throughout the wind power life cycle, shows that while the operation and maintenance phase represent relatively low emissions, the production and manufacturing phase can be quite resource intensive.

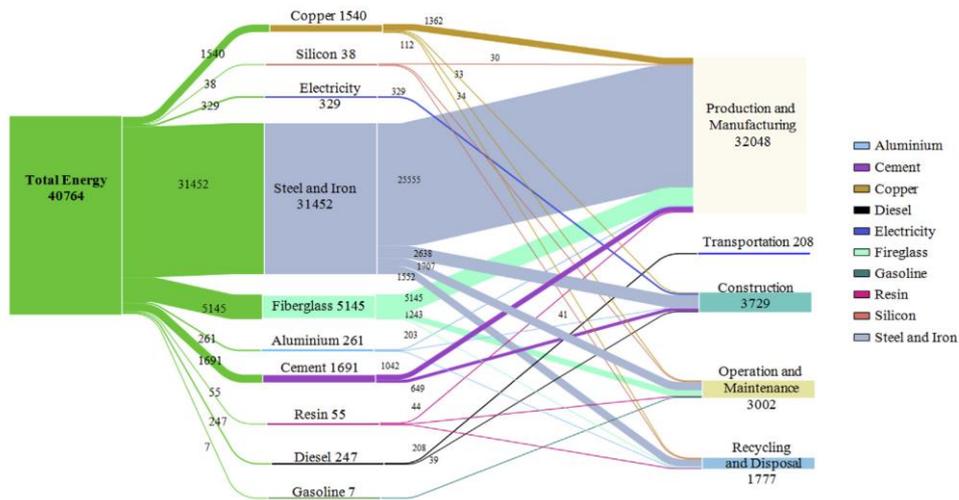


Figure 39: Energy flow of wind power in entire life cycle (source: Li et al., 2020)

Comparatively, the emissions from wind power across its life cycle are significantly lower than those from coal power, highlighting wind power's environmental advantage. Life cycle emissions figures for both wind and coal power illustrate the stark contrast in pollution levels, with wind power's emissions

being just a fraction of coal's across all stages, from raw material acquisition to disposal (Li, H. et al., 2020; Li, J. et al., 2020).

Solar Power for energy production:

Solar power, a pillar of renewable energy, leverages the vast and clean resource of solar energy to generate electricity. Its role in the sustainable energy transition is relevant due to its ability to reduce greenhouse gas emissions and the dependency on fossil fuels. The utilization of solar power aligns with the findings of Akram et al. (2020), who determined that energy efficiency and renewable energy significantly contribute to reducing carbon emissions in developing countries, particularly at higher quantiles of carbon emission levels.

In the marine industry, the potential of integrating renewable energy technologies, including solar power, has been evaluated with promising prospects. According to Issa et al. (2022), various innovative renewable energy technologies have been assessed for their applicability in different ship classes, ranging from vessels less than 400 tons to those exceeding 50,000 tons (Table 27). The assessment covers a range of technologies such as soft sails, fixed wings, rotors, kites, turbines, and solar photovoltaics.

Table 27: Renewable energy technologies and their potential to be applied in the marine industry (source: Issa et al., 2022)

Renewable Energy description		Retrofit or New Built	vessel < 400 T	400 ≤ 10,000 T	10,000 ≤ 50,000 T	Vessel > 50,000 T
Wind	Soft sails	Retrofit	●●●	●●●	●●●	●●●
		New built	●●●	●●●	●●●	●●
	Fixed wings	Retrofit	●●	●●	●●	●
		New built	●●	●●●	●●●	●●
	Rotors	Retrofit	●●	●●	●●	●●
		New built	●●●	●●●	●●●	●●
	Kites	Retrofit or new built	●●	●●	●●	●
	Turbines	Retrofit or new built	●	●	●	●
Solar photovoltaics	Main propulsion	Retrofit	N/A	N/A	N/A	N/A
		New built	●	N/A	N/A	N/A
	Auxiliary propulsion	Retrofit	●●	N/A	●	N/A
		New built	●●	N/A	●	N/A
Ancillary power	Retrofit or new built	●●	N/A	●	N/A	
Biofuels	First generation	Retrofit	●●	●●	●●	●
		New built	●●	●●	●●	●
	2nd generation	Retrofit	N/A	N/A	N/A	N/A
		New built	●●●	●●●	●●●	●●
	3rd generation	Retrofit	N/A	N/A	N/A	N/A
		New built	●●●	●●●	●●●	●●

■ Concept ; ■ Design ; ■ In commercial use ; ■ Proven ; ■ Proof of concept ; □ Uncertain .

●●●: High potential ; ●● : Medium potential; ●: Limited ; N/A : not available.

Table 28 systematically rates the potential of each renewable technology using a color-coded system, indicating whether the technology is still a concept, under design, proven, or in commercial use. Technologies like wind rotors and kites are shown to have high potential for both retrofit and new build applications, especially in smaller vessels. In contrast, solar photovoltaics display medium potential across various ship sizes and applications, indicating that while the technology is viable, its

effectiveness may be subject to limitations such as space for panels and efficiency under different operating conditions. The potential for these technologies varies with the vessel size and whether the technology is applied to new builds or as a retrofit. For instance, solar photovoltaics show a medium to high potential for both retrofit and new build applications across all vessel sizes, though the exact potential depends on the specific application, whether it be main propulsion, auxiliary propulsion, or ancillary power. This evaluation, set against the backdrop of the Royal Academy of Engineering's exploration of alternative methods of ship propulsion (Royal Academy of Engineering, 2013), indicates a clear trend towards diversifying energy sources in shipping. The move towards renewable options is not only a response to environmental concerns but also a strategic shift to future-proof the industry against the volatility of fossil fuel markets and the tightening of global emissions regulations.

Waste Heat recovery systems

Waste Heat Recovery (WHR) systems are relevant in the pursuit of enhanced energy efficiency and sustainability, capturing and utilizing waste heat from various sources to reduce overall energy consumption and environmental impact. Among the technologies employed for WHR, Thermal Energy Storage (TES), and Organic Rankine Cycles (ORC) are notable for their application in industrial waste heat (IWH) recovery. Miró, Gasia, & Cabeza (2016) provides a categorisation of IWH technologies (Figure 40).

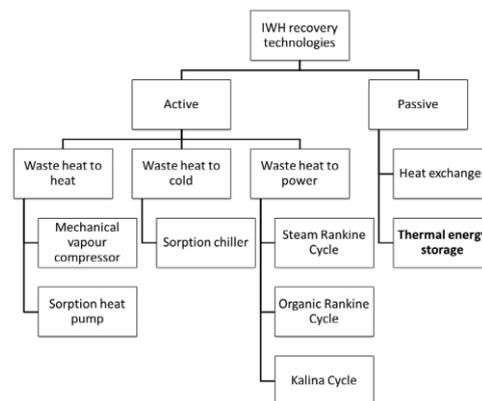


Figure 40: Categorization of IWH recovery technologies (source: Miró et al., 2016)

The categorization of IWH recovery technologies outlined by Miró, Gasia, & Cabeza (2016), distinguishes between active and passive systems. Active systems, such as mechanical vapor compressors, sorption chillers, and various cycles like Steam Rankine, Organic Rankine, and Kalina, actively convert waste heat into power or cooling. Passive systems, like heat exchangers and thermal energy storage, rely on the thermal gradient created by waste heat to function. TES systems are particularly effective in managing the temporal mismatch between waste heat generation and demand. The review by Miró et al. (2016) provides a comprehensive analysis of different TES systems and their applications in various countries. For instance, TES systems utilizing Phase Change Materials (PCM) and Thermochemical Materials (TCM), such as Zeolite, have been implemented in aluminium factories, steelworks, and sludge incinerators. These systems have proven to be effective in storing waste heat for later use, achieving significant savings in energy costs, and reducing CO₂ emissions by as much as 93%.

Ramadhani et al. (2020) showed that the proposed heat recovery system could reduce carbon emissions by 31.60% and 30.32% compared to a basic heat recovery system and a separated system, respectively. This indicates the high potential of advanced WHR systems in contributing to carbon reduction in industrial applications. Similarly, ORC systems have found their place in the automotive industry. Ramli et al. (2020) reported that ORC waste heat recovery systems in hybrid electric vehicles could lead to fuel economy improvements of 1.0% and 1.2%, respectively. These improvements, while seemingly modest, are significant in the context of large-scale automotive fleets and can contribute meaningfully to the reduction of fossil fuel consumption and emissions over time.

Coating to reduce drag and other aerodynamic modifications

Coating to reduce drag along with other aerodynamic modifications is a key strategy to enhance the sustainability of transport vehicles by optimizing performance and reducing energy consumption. The application of specialized coatings or surface treatments to vehicles and vessels plays a critical role in improving fuel efficiency and reducing emissions, a topic thoroughly investigated by Uherek et al. (2010). Their study encompasses the broad impacts of land transport on the atmosphere and climate, illustrating how innovative technologies can mitigate these effects by reducing aerodynamic drag. In the maritime industry, one such innovative technology is air lubrication, which has been shown to have a substantial impact on the operational efficiency of commercial ships. Fotopoulos et al. (2020) conducted a computational analysis of air lubrication systems and found that they can reduce fuel consumption by up to 8% and CO₂ emissions by a similar percentage. This reduction in energy use and emissions is not only beneficial for the environment but can also translate into significant economic savings, potentially amounting to up to 8000 EUR per travelling day for shipping companies.

Platooning

Platooning represents a transformative approach in highway transportation, where vehicles, particularly heavy-duty trucks, are electronically linked to travel in close formation. This technique can enhance efficiency and sustainability by optimizing traffic flow and fuel economy while reducing emissions. The systematic arrangement in platooning allows vehicles to reduce air resistance through drafting, where the leading truck experiences increased base pressure, and the trailing truck benefits from reduced drag due to the yaw changes, as detailed by Törnell et al. (2021).

The system architecture for look-ahead heavy-duty vehicle platooning, as conceptualized by Turri et al. (2016), as shown in Figure 41, encapsulates a platoon coordinator that manages the dynamics between individual vehicle controllers. This advanced control system ensures that vehicles maintain optimal inter-vehicle distances (IVD) for fuel efficiency while adhering to safety regulations. Such technological integration is vital in addressing safety concerns that arise from the reduced spacing between trucks.

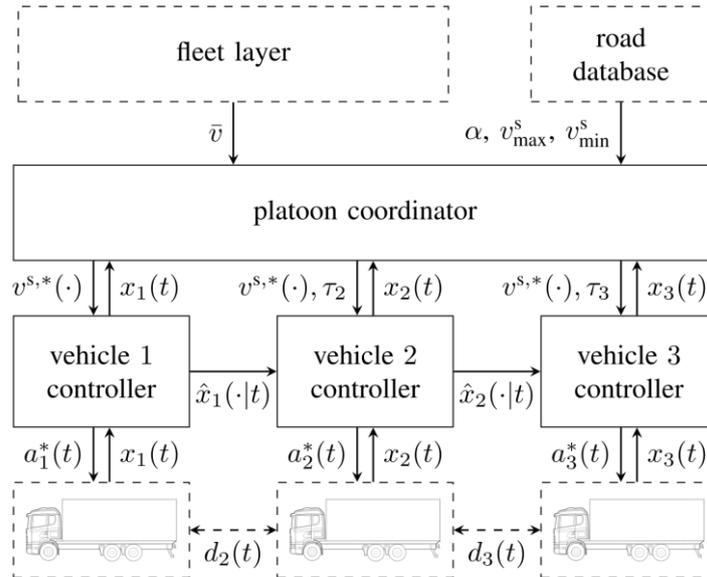


Fig. 6. System architecture for look-ahead heavy-duty vehicle platooning.

Figure 41: System architecture for look-ahead heavy-duty vehicle platooning (source: Turri et al., 2016)

In the context of vehicle aerodynamics, important metrics such as the Coefficient of Pressure (C_p) and Coefficient of Drag (C_D) are crucial in evaluating the effectiveness of platooning. The C_p affects the base pressure experienced by the lead vehicle, while the C_D determines the resistance faced by the trailing vehicle. The reduction in C_D is especially noteworthy, as Liang et al. (2016) observed that platooning could reduce overall fuel consumption by up to 20% for the trailing vehicle, underscoring the importance of aerodynamic considerations in platooning configurations.

Empirical studies have demonstrated the tangible benefits of truck platooning. Han et al. (2022) quantified the fuel savings rate at 5.7% due to platooning, which directly translates to a reduction in carbon emissions. Further, Brummitt et al. (2022) projected that platooning could potentially reduce CO_2 emissions by 37.9 million metric tons between 2022 and 2026, showcasing its significant environmental impact.

5.3.2 Sustainability through collaboration

Maritime emissions trading system

The Maritime Emissions Trading System (METS) has been identified as a central mechanism for encouraging the maritime industry to adopt more energy-efficient and carbon-efficient shipping practices. Zhu et al. (2018) delve into the potential impacts of METS on fleet deployment and the broader goal of mitigating CO_2 emissions within the maritime sector. Their research suggests that METS serves as a significant incentive for operators to transition towards utilizing ships that are more efficient in terms of energy and carbon usage. This shift is particularly pronounced in scenarios where bunker fuel prices are elevated, highlighting the economic leverage METS can exert on operational decisions in shipping.

Vessel sharing

Vessel sharing emerges as a strategic collaboration among maritime carriers, designed to optimize space usage and enhance operational efficiencies within the shipping industry. This arrangement, as detailed by Qiu et al. (2018), allows multiple carriers to allocate space among themselves, aiming to better meet demand and improve overall maritime operations. Such partnerships are particularly significant in contexts like the Maritime Silk Road, where optimizing logistical and environmental efficiency is crucial for sustainable development.

Further exploration into the impacts of vessel sharing reveals its potential to significantly reduce maritime emissions, alongside boosting operational efficiency. Park et al. (2022) provide quantitative insights into these benefits, noting an average reduction in maritime emissions by 5%. This decrease emphasizes the environmental advantage of adopting collaborative strategies in maritime logistics, contributing to the broader goal of sustainable shipping practices. However, it's important to acknowledge the trade-offs involved, as the study also identifies a slight increase in lead time associated with vessel sharing arrangements. This factor suggests a complexity in balancing operational efficiency with speed of delivery, necessitating careful planning and coordination among participating carriers.

Reverse logistics

Reverse logistics stands as an integral component in the sustainable management of resources within the supply chain, focusing on the recovery and proper disposition of products and materials post-consumer use. This process promotes the reuse, recycling, or repurposing of products and materials, contributing to the significant reduction of waste and the environmental footprint of logistics operations. Hashemi et al. (2021) highlight the application of reverse logistics in the sustainable management of municipal waste. Their approach encompasses the entire spectrum of waste handling, from collection and recycling to reuse, with a strong emphasis on reducing emissions throughout the process. This application of reverse logistics demonstrates its potential to enhance environmental sustainability at the municipal level.

Huang et al. (2022) delve into the specific impacts of an integrated system on reverse logistics, examining the Waste Recycling Facility Support System (WRFSS), which combines Building Information Modeling (BIM), Warehouse Management Systems (WMS), and an API plug-in. Their study reveals that the WRFSS can decrease transportation distance by 30.6 km and carbon dioxide emissions by 0.0259 tons. This indicates a significant stride towards achieving sustainable development within the reverse logistics supply chain by leveraging technology to optimize the return flow of materials.

In this topic, it is particularly important to take an integrated approach of polluting processes. The comprehensive analysis by Ding et al. (2023) focus into the intricate relationship between Forward Logistics (FL) and Reverse Logistics (RL) operations within the context of Circular Economy (CE) in construction. Their work presents a Circular Logistics Integration (CLI) framework that is designed to optimize logistics processes, enhance material recycling, and reuse, and improve overall sustainability in the construction industry. Figure 42 shows the developed framework that integrates various industry actors from manufacturing, Architecture, Engineering, and Construction (AEC), waste management, and logistics intermediaries, each playing a role in the lifecycle of construction materials. Forward Logistics covers the traditional flow of materials from design and procurement (F1) to

operations (F4), while Reverse Logistics encompasses the processes from end-of-use (R1) to material reprocessing (R4), thus closing the loop in a circular economy. During the design phase (F1), incorporating logistics planning based on Life Cycle Assessment (LCA) can lead to greener procurement practices. The manufacturing phase (F2) benefits from waste management optimization, which directly feeds into the construction phase (F3) where onsite waste reduction and efficient logistics contribute to reduced environmental impact. The operations phase (F4) further leverages logistics coordination, which is crucial for lifecycle planning and ultimately feeds into the deconstruction phase (R1). The reverse flow starts with waste tracking and deconstruction project planning (R1), leading to the reuse of products (R2) and optimization of distribution networks (R3). Finally, material reprocessing (R4) ensures that recycled and remanufactured building products are reintegrated into the forward logistics phases, thus completing the circular loop.

Circular logistics integration is elaborated through sub-topics such as vertical and lateral integration, circular channel creation, circular networks integration, and circular inventory management. These sub-topics address both established practices, such as marketing for secondary markets, and innovative practices, like the utilization of Geographic Information Systems (GIS) and Internet of Things (IoT) for material inventory tracking.

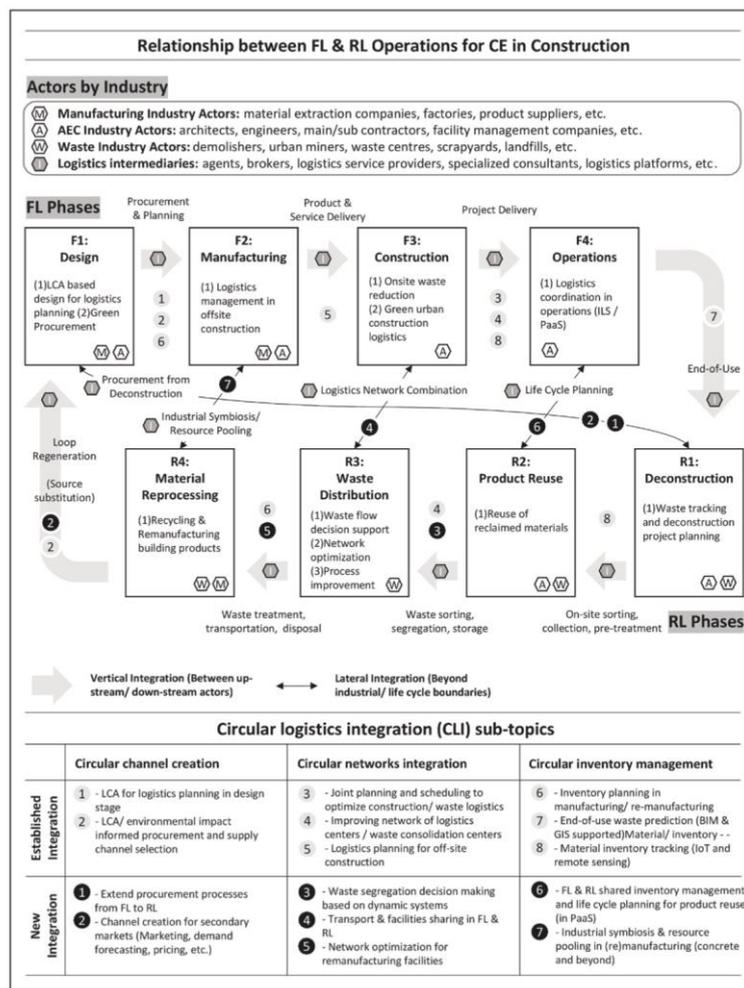


Figure 42: Circular logistics integration framework for Forward (FL) and Reverse Logistics (RL) operations (source: Ding et al., 2023)

Mode choice optimization

The optimization of mode choice in transportation is a critical factor in reducing environmental impacts and promoting sustainability. Tattini et al. (2018) emphasize the importance of encouraging the selection of transportation modes with lower environmental impacts, such as rail or sea freight over road transport, through improved representation in bottom-up optimization energy system models. This approach not only supports the environment but also offers a practical solution for producers. Hoen, K., Tan, T., Fransoo, J., & Houtum, G. (2014) highlight that switching transport modes can lead to a significant reduction in carbon emissions—by as much as 10%—with a relatively minor increase in total logistics cost for producers of bulk liquids, approximately 0.7%. This evidence points to the tangible benefits of re-evaluating transportation methods to meet voluntary carbon emission targets, as detailed in their study in the journal *Transportation Science*. Further expanding on the subject, Maggi, E., & Vallino, E. (2020) investigate the effectiveness of combining price-based and preference-based policies in urban commuting. Their research shows that such a combination yields the best outcomes for sustainable urban commuting, significantly reducing particulate matter (PM) emissions. This approach emphasizes the need to consider a range of factors, including cost, time, and environmental considerations, in making transportation choices. By adopting more sustainable transportation options, significant reductions in carbon emissions and energy consumption can be achieved, thereby contributing to the broader goals of environmental sustainability and energy efficiency.

Cargo sharing for last-mile logistics

The integration of cargo sharing strategies in last-mile logistics offers a promising approach to enhancing the efficiency and sustainability of urban delivery systems. By consolidating multiple deliveries into single trips, it is possible to reduce the number of vehicles on the roads, thereby minimizing both emissions and congestion within urban districts. According to Assmann et al. (2020), the utilization of cargo bikes and urban transshipment points (UTPs) can lead to a substantial decrease in greenhouse gas emissions, as well as particulate matter and nitrogen oxides, contributing to cleaner urban environments. Assmann et al. (2020) describe various scenarios to optimize the use of small urban transshipment points (UTPs) in coordination with logistics service providers (LSPs) and courier, express, and parcel (CEP) services. One such scenario is U-C, where a central urban transshipment point (cUTP) is stationed at the main approach to a district, covering a delivery zone of 2 km². Another scenario, U-Q, involves two cUTPs located in the center of a quarter, each serving a 1 km² delivery zone. The S-o strategy employs semi-stationary swap bodies and optimizes UTP placement for each CEP provider, with delivery zones ranging from 0.25 to 2 km². In these scenarios, the network vehicle configuration (NVC) is of importance. The conventional system excludes returns, pick-ups, and time windows, focusing on a straightforward delivery process. Highly innovative electric vans (E-vans) have been introduced to complement the fleet of diesel vans and cargo bikes. For the UTP network, parcels are initially transported from the distribution center to the UTP site by heavy 12-ton trucks or vans, depending on the UTP type. Following deliveries, semi-stationary swap body sUTPs are returned to the distribution center each evening. Figure 43 shows the comparison of kilometrage and GHG emissions between conventional delivery and UTP strategy U-C with trucks and vans, showing that UTP strategies tend to result in lower GHG emissions across various population densities and parcel delivery volumes. For instance, at a density of 10,000 residents per km² with 1,800 parcels/day, the emissions from conventional vans are contrasted with those from UTP strategies involving trucks and vans, highlighting

the emissions benefits of the UTP approach. The research also emphasizes the importance of implementing cargo bike transshipment points within urban districts. This model not only improves the efficiency of last-mile delivery processes but also significantly reduces the environmental footprint of urban logistics operations, thus contributing to the broader goals of urban sustainability.

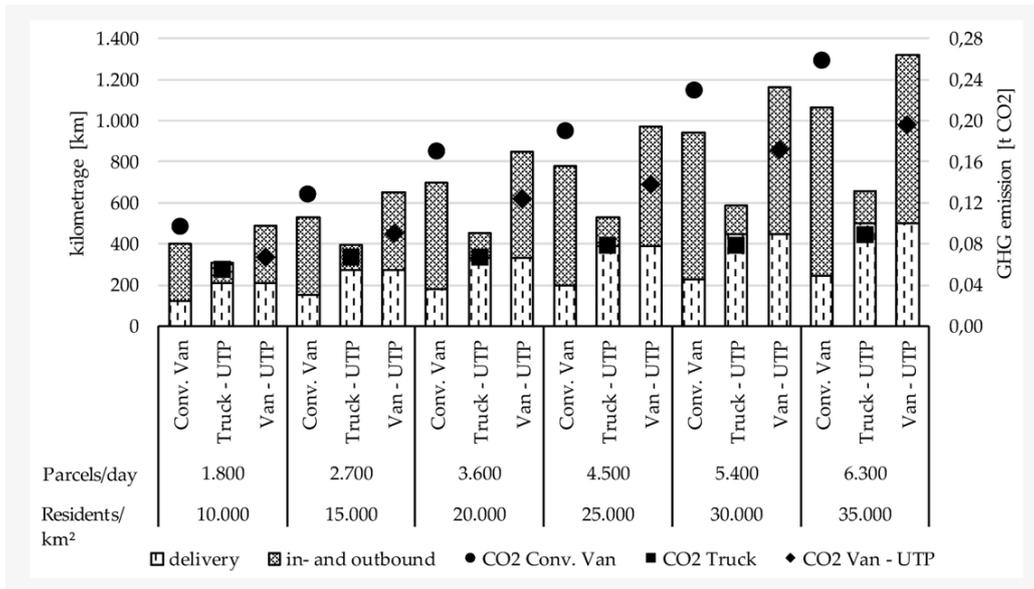


Figure 43: Conventional delivery vs Urban Transshipment Points (UTP) with trucks and vans: Kilometrage and GHG emission (source: Assmann et al., 2020)

Furthermore, Figure 44 from Assmann et al. (2020) provides a sensitivity analysis of GHG emissions, displaying the potential improvements and worsening scenarios under different population densities (10,000 and 35,000 residents per km²). This analysis considers various configurations, including electric vans and trucks, and illustrates the potential for a 50% improvement or worsening in emissions, emphasizing the impact of vehicle and network choices on environmental performance.

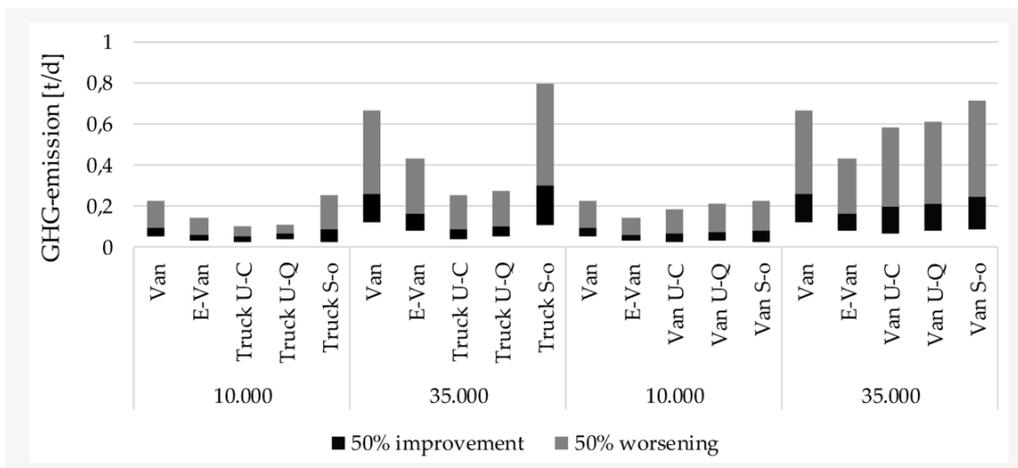


Figure 44: Sensitivity analysis of GHG emissions, for different population densities (source: Assmann et al., 2020)

Optimization of cargo load

The meticulous optimization of cargo loading processes within rail-truck intermodal terminals is essential for advancing sustainability and efficiency in freight transportation. The model developed by Wang et al. (2019) meticulously targets the minimization of total handling time, container reshuffling, and energy consumption. This is achieved by evaluating various factors such as the energy consumed by loading cranes moving containers to rail vehicles, the consumption by empty cranes between operations, and the reshuffling of containers during the loading process, as depicted in their Table 28 outlines the mentioned factors contributing to the overall energy use and optimizing these can significantly enhance operational efficiency.

Table 28: Energy consumption by loading/empty/reshuffling cranes moving containers to rail vehicles (source: Wang et al., 2019)

Energy consumption	Description
Loading crane energy consumption	This aspect is generated by the loading crane moving from the container yard or trucks to rail vehicles. Because all outbound containers have specific handling positions, the loading crane energy consumption is a fixed value in one handling task. In general, this kind of energy consumption is determined and never changed after the handling task is generated.
Empty crane energy consumption	This aspect is generated by the empty crane moving between two outbound container loading operations. This energy consumption is determined by the outbound container handling sequence. Different handling sequences have a great influence on empty crane energy consumption, so optimizing the handling sequence can directly reduce this kind of energy consumption and improve energy efficiency of outbound container loading operations.
Reshuffling crane energy consumption	This aspect is generated by container reshuffling operations in the loading process. According to the different status of the upper container, reshuffling crane energy consumption can be divided into two types. In the first type, the upper container does not belong to the same handling task, so it must be reshuffled to ensure the handling task can go on smoothly. This type of energy consumption is unavoidable. The other type is caused by the overlapping of containers in the same handling task, and this type of energy consumption can be reduced or avoided by optimizing the handling sequence.

In recent years, a significant emphasis has been placed on optimizing logistics and transportation processes within intermodal terminals to enhance sustainability and efficiency. A study by Wang and Zhu (2019) introduced an optimization model aimed at minimizing the total handling time, container reshuffling, and energy consumption in rail-truck intermodal terminals. This model not only streamlines operations but also contributes to the broader objective of maximizing the utilization of vehicle capacity. By optimizing cargo loads, the model effectively reduces the number of trips required for transporting goods, thereby lowering fuel consumption and emissions per unit of cargo (Wang & Zhu, 2019). However, the challenge of optimizing cargo for sustainability extends beyond simply reducing greenhouse gas (GHG) emissions. Fan et al. (2018) highlighted that while optimizing cargo load for sustainability necessitates a consideration of both GHG and air pollutants, a transport method with lower GHG emissions does not invariably result in lower particulate matter (PM) and sulphur oxides (SOx) emissions. This distinction emphasizes the complexity of achieving true sustainability in logistics, where multiple environmental factors must be balanced. Further research by Li et al. (2020) demonstrated that an integrated approach, combining operation planning optimization with pricing strategies, can significantly shift transport modalities from road to rail. Their findings suggest a potential 39.27% modal shift, accompanied by a 37.09% reduction in carbon emissions, highlighting

the substantial environmental benefits that can be realized through strategic operational changes (Li et al., 2020).

Lim et al. (2020) explored the impact of optimizing in-situ production quantities, revealing that such measures could result in considerable savings in both CO₂ emissions (7557 t-CO₂) and costs (6,966,000 USD), amounting to reductions of 14.58% and 10.533%, respectively. This study indicates the significant potential for optimization strategies to contribute to environmental sustainability and economic efficiency simultaneously.

Korotkiy et al. (2021) introduced an innovative approach using smart automated containers-transformers, which has the potential to revolutionize logistics services. Their research found that these advanced containers can reduce the time for loading/unloading by up to 30%, decrease empty runs by up to 25%, and lower logistics costs for transporting empty containers by up to 75%. Such advancements not only enhance urban mobility but also have a profound positive impact on the environment by optimizing the logistics chain's efficiency.

Sustainable supply chain management

Supply chain management is a critical component of modern business practices, focusing on the strategic coordination and optimization of activities within the supply chain to bolster sustainability. This management process is not merely about logistics and efficiency. It encompasses a comprehensive approach to minimizing waste, emissions, and overall environmental impact. By improving resource efficiency, supply chain management plays a vital role in reducing the carbon footprint of businesses and encouraging ethical and responsible practices throughout the entire supply chain.

Sustainable supply chain management (SSCM) is a concept that extends beyond traditional business goals to include the management of environmental, social, and economic impacts. Ghosh et al. (2020) define SSCM as an integrative approach that emphasizes the importance of cooperation among supply chain partners to address sustainability objectives effectively. It's a holistic framework that accounts for the interconnectedness of various supply chain activities and their collective impact on the planet and society.

The benefits of implementing SSCM are several. For instance, Yadav et al. (2021) have identified that adjustments to production rate, batch size, shipments, and preservation investments can reduce waste and carbon emissions by 20%. This not only supports environmental stewardship but also proves to be a financially profitable strategy for businesses, demonstrating the alignment of ecological and economic goals. Similarly, Mishra et al. (2023) highlights the financial and environmental advantages of integrating credit sales, flexible production, and quality improvements in an energy supply chain model. Their research presents a compelling case where such integrations can result in a profit increase of 28.64% and a reduction in carbon emissions by up to 4.01%. These figures emphasize the potential of SSCM practices to drive profit while also contributing to the global effort to mitigate climate change.

5.4 Digitalization and Monitoring

Digitalization and monitoring solutions include main digital transformative platforms/tools to data management and operations such as the Single Logistic Window, smart technologies, digital tools for cargo planning, carbon calculators, on-line customer services, community collaboration, and real-time and fleet/emissions monitoring in transport.

Song et al. (2022) provides a review of digital technologies from the perspective of the infrastructure (e.g., communication and computer devices), enabling mechanisms (e.g., IoT, cloud computing) and algorithms (e.g., routing), along with their potential applications for low-carbon energy transport systems. Table 29 summarizes their review of mechanisms, algorithms along with their applications.

Table 29: Summary of algorithms as enabler of digital technologies and their applications (source: Song et al., 2022)

Mechanism	Reference	Algorithms	Algorithm category	Application
IoT	ref. [79]	Adaboost	Traditional machine learning	Transportation safety
	ref. [89]	BN-SARIMA	Time-series analysis	Traffic prediction
	ref. [90]	Hidden Markov Model	Traditional machine learning	Judging vehicle motion trajectories
	ref. [91]	SVM, MRF	Traditional machine learning	Parking system
	ref. [207]	Decision trees	Traditional machine learning	Predicting traffic congestion
	ref. [92]	Regression tree	Traditional machine learning	Predicting traffic circulation
	refs. [93, 94]	Clustering	Traditional machine learning	Traffic data simulation, Road Anomaly detection
Cloud computing	ref. [80]	CNN, deeper CNN	Neural networks	Road condition detection
	ref. [104]	Routing algorithm (Martins and meta-heuristic)	Optimization	Low-carbon transportation
	refs. [208, 209]	PSO algorithm	Optimization	Energy system optimization
	ref. [113]	QCNN algorithm	Neural networks	Low-carbon supply chain
Blockchain	refs. [115, 116]	Reinforcement learning algorithm based on PSD	Reinforcement learning	Intelligent transportation
	ref. [135]	Proof of concept	Distributed optimization	A local energy market simulation model
	ref. [137]	Proof of work	Distributed optimization	Local EVs electricity trading market
	ref. [136]	Proof of stake	Distributed optimization	A P2P energy trade platform involving auction
Data trading	ref. [125]	Proof of stake	Distributed optimization	A secure and private ITS
	ref. [162]	Parametric estimation, non-parametric estimation	Traditional machine learning	Data valuation
	refs. [161, 210]	Genetic algorithm	Optimization	Data pricing
	ref. [211]	Optimal estimation algorithm	Optimization	Data pricing
Digital twin	ref. [212]	Multi objective optimization	Optimization	Data pricing
	ref. [191]	Decision Tree C5.0, the Naive Bayes algorithm	Traditional machine learning	Vehicle intrusion detection
	ref. [192]	Genetic algorithm, logistic regression	Traditional machine learning	Vehicle intrusion detection
	ref. [193]	SVM, RF	Traditional machine learning	Vehicle intrusion detection
	ref. [195]	Auto-encoder	Neural networks	Vehicle intrusion detection
	ref. [197]	CNN, RNN	Neural networks	Vehicle intrusion detection
	ref. [198]	RANet	Neural networks	Vehicle intrusion detection
ref. [199]	Hidden Markov model	Traditional machine learning	Driver intention prediction	
refs. [200, 202]	LSTM	Neural networks	Vehicles trajectory analysis, Driver intention prediction	

5.4.1 Single logistic window

The implementation of a Single Logistic Window (SLW) is a transformative approach to data management and operations within the logistics sector. By centralizing data, SLW systems simplify and streamline processes, reduce administrative overhead, and significantly improve the efficiency and transparency of logistics operations. This leads to better resource allocation, reduced waste, and enhanced coordination and optimization of transport activities, which are critical for achieving sustainability in the logistics industry. A Single Logistic Window serves as a one-stop data hub for all

stakeholders involved in the logistics chain, from customs to transportation companies, enabling smoother operations and less bureaucratic friction. The UNECE (2016) noted the environmental benefits of SWL systems, pointing out that streamlining customs clearance and other regulatory procedures can significantly reduce the time vehicles spend idling at borders or waiting for clearance, thereby decreasing fuel consumption and CO₂ emissions. In Ghana, the implementation of a fully automated pre-arrival assessment reporting system and other features as part of the GNSW has already demonstrated the positive impacts of such systems on efficiency and emissions reduction. Furthermore, Tijan et al. (2019) highlighted the success of the Netherlands Maritime Single Window (MSW) in reducing cargo waiting times at large seaports and airports, leading to more efficient use of natural resources and lower emissions of CO₂ and other pollutants. The minimization of paper documents within the MSW also contributes to reduced logging and deforestation, showcasing the holistic environmental benefits of digitalization in logistics.

The European Maritime Single Window (EMSW) set by the EU Regulation 2019/1239 aims to foster the harmonisation of rules for the provision of information that is required for port calls, by ensuring that the same data sets can be reported to each maritime Single Window in the same way. The existing maritime National Single Window in each Member State (JUL – “Janela Unica Logística”, in the case of Portugal) is mentioned to be maintained as the basis for a technologically neutral and interoperable European Maritime Single Window Environment. Through this initiative, information will be standardized for port management, making it accessible to all relevant stakeholders, thereby optimizing cargo flows and further reducing transport CO₂ emissions and resource use.

Digitalization and interconnectivity are fundamental to reducing the environmental footprints of the port industry. Intelligent transport systems that incorporate such digitalization hold significant potential for CO₂ emission reductions. For instance, seaports in Hong Kong, Singapore, and Taiwan have demonstrated remarkable efficiency, achieving 46 crane moves per hour, which is 43% more efficient than North American ports in unloading cargo (Tijan et al., 2019).

5.4.2 Smart technology for tracking and tracing containers

Smart technology in the context of container logistics represents a paradigm shift toward heightened efficiency and sustainability. The integration of advanced tracking and tracing capabilities not only improves visibility and transparency throughout the supply chain but also significantly reduces the risk of lost or misplaced shipments. By improving asset utilization and curtailing inventory holding times, smart technology minimizes superfluous transportation and associated emissions, which is a substantial step forward in sustainable logistics management.

The proactive management of logistics operations facilitated by these technologies enables a more efficient allocation of resources, thereby reducing the environmental impact of shipping and freight activities. Efimova and Saini (2023) conducted a study that illustrates the tangible benefits of incorporating an automated monitoring system during container transit. According to their findings, the application of smart technology in container logistics has led to a decrease in container cargo travel time from an average of 2.4 hours to 2.3 hours for port to Container Freight Station (CFS) journeys, and from 4.8 hours to 3.7 hours for CFS to port journeys. This reduction in travel time has had a direct and positive impact on carbon emissions: carbon emissions decreased from 113.4 kg CO₂/liter to 106.7 kg CO₂/liter for port to CFS movements, and from 222.4 kg CO₂/liter to 172.1 kg CO₂/liter for CFS to

port movements. These findings indicate a remarkable decrease in carbon emissions by 6% for import journeys and 23% for export journeys of container cargo, showcasing the significant environmental benefits that can be achieved through the adoption of smart logistics technologies.

5.4.3 Cargo planning

Effective cargo planning and terminal layout optimization are essential components in mitigating the environmental impacts, particularly the reduction of CO₂ emissions. Container terminals play a role in the global supply chain, influencing not only the efficiency of cargo movement but also the environmental footprint of maritime transport. The optimization of cargo routing and scheduling is crucial in minimizing unnecessary trips, which directly reduces fuel consumption and emissions. Moreover, improving load efficiency and capacity utilization contributes to fewer vehicles on the road, thereby decreasing congestion and further lowering emissions (Stojaković et al., 2021).

Recent studies have explored the impact of container terminal layouts on CO₂ emissions. It has been determined that both parallel and perpendicular container terminal layouts exhibit relatively similar CO₂ emissions profiles, which supports the notion that either layout can be integrated into the sustainable development plans of future ports (Budiyanto et al., 2021). The typical layouts are shown in Figure 45.

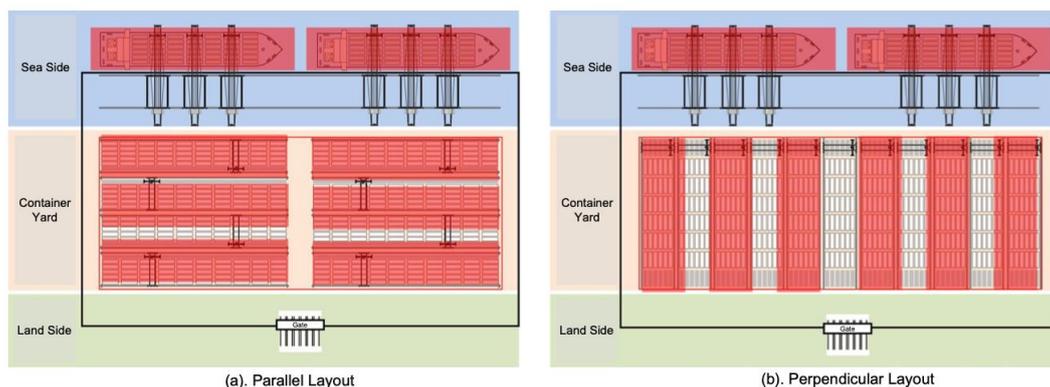


Figure 45: Typical layout of container terminals (source: Budiyanto et al., 2021)

The study by Budiyanto et al. (2021) also highlight significant differences in the primary sources of energy consumption between terminals. For instance, at Terminal A, the rubber-tired gantries (RTGs) accounted for 50% of total energy consumption, whereas Terminal B saw terminal trucks as the main contributor, responsible for 53% of total energy consumption. The breakdown of CO₂ emissions at container terminals is illustrated in Figure 46: in Terminal A, quay/ship to shore cranes were responsible for 36% of emissions, RTGs for 45%, straddle carriers for 1%, reach stackers for 0%, and terminal trucks for 19%. Conversely, Terminal B experienced a different distribution with quay/ship to shore cranes at 28%, RTGs at 24%, straddle carriers at 5%, reach stackers at 9%, and terminal trucks at 34%.

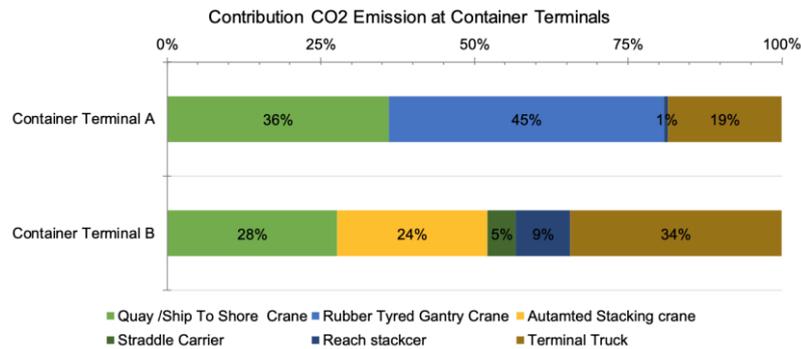


Figure 46: Contribution of each container-handling equipment to the CO₂ emissions at the container terminals (source: Budiyanto et al., 2021)

The energy consumption patterns of each container-handling equipment type have also been documented. Rubber-tired gantry cranes (RTGs) consume 1.32 L/move, straddle carriers (SC) 3.50 L/km and 0.80 L/move, terminal head trucks (TT) 3.23 L/km, automated terminal tractors (ATT) 1.67 L/km, and reach stackers/top picks (RS) 5.00 L/km. When it comes to electricity-powered equipment, quay cranes (QC) consume 6.00 kWh/move and 2.77 L/move, ship to shore cranes (STS) 6.70 kWh/move, and automated stacking cranes (ASC) 5.00 kWh/move (assumptions from Budiyanto et al. (2021)).

5.4.4 Carbon emissions calculator tool

In the context of transport and logistics, the accurate calculation of CO₂ emissions is essential for developing strategies to reduce the environmental impact of transportation activities. Various modes of transport, including road, rail, sea, and air, contribute to the overall carbon footprint of the supply chain.

Emissions calculators for freight transport are tools used for sustainable logistics planning. Tools such as carbon calculators are employed to quantify the carbon footprint of transport activities, thus enabling stakeholders to identify opportunities for emissions reduction and to optimize their carbon management strategies (Aytac, 2023). There exist several approaches that require harmonisation in the context of the recent European Corporate Sustainability Reporting Directive.

Wild (2021) provides a comparative analysis of various methods and standards used to measure and report carbon emissions, such as the ISO standards and the SmartWay program of the US Environmental Protection Agency that helps the freight transportation sector to improve supply chain efficiency. It considers the classification of transport modes, spanning from road freight, identified as full truck load (FTL) and less than truck load (LTL), rail freight that includes block train and single wagon load shipments, and sea freight that can be short or deep sea. Air freight is categorized by direct or indirect flights, and transshipping activities cover terminal operations and warehouse logistics. The cooling chains for cargo that requires temperature control are also considered in the emissions calculations (Table 30).

Table 30: Classification of modes of transport (source: Wild, 2021)

Road freight transport (ROAD)	Full truck load (FTL)
	Less than truck load (LTL)
	Groupage shipment
	Distribution and/or pickup route
Rail freight transport (RAIL)	Block train shipment Single wagon load shipment Intermodal shuttle shipment
Inland waterways freight transport (IWW)	Direct (no intermediate stops)
Short sea freight transport (SEA)	Inland waterways shipment with intermediate stops Direct short sea shipment (no intermediate stops)
Deep sea freight transport (SEA)	Short sea shipment with intermediate stops Direct deep-sea shipment (no intermediate stops)
Freight on a ferry (SEA)	Deep sea shipment with intermediate stops Truck on ferry Train on ferry
Air freight transport (AIR)	Direct air freight shipment (no intermediate stops) Air freight shipment with intermediate stops
Terminals (TRANSSHIPPING)	Maneuvering (including shunting and taxiing)
Warehouses and cross-docking locations (TRANSSHIPPING)	Transshipment (which could be from and to storage or vehicle) or internal transport & shuffle, sort Unload & sort Unconditioned storage Refrigerated storage Deep freeze storage Order picking Preparing for dispatch
Cooling chains (COOL)	(Re)packaging (as Value Added Logistics (VAL) operation) & load Any transport operation which requires cooling

The comparative analysis summary developed by Wild (2021) is presented in Table 31. It highlights the importance of a consistent approach across all transport modes and the need for harmonization in reporting some methods (for example, some use CO_{2e} and others CO₂; some consider WTW analysis but others TTW or both, etc.). Tank-to-Wheel (TTW) refers to the emissions produced by the vehicle from the point of fuel consumption to the wheel's movement, while well-to-wheel (WTW) encompasses the entire energy lifecycle from fuel production to vehicle operation. The distinction between these measures is crucial for understanding the full environmental impact of transport operations.

While ISO standards provide comprehensive guidelines, including vehicle operation system descriptions and allocation units for emissions, gaps in coverage persist, especially in terms of specific allocation units for different transport modes and the energy consumption of auxiliary processes.

Table 31: Comparative analysis of various methods and standards used to measure and report carbon emissions (source: Wild, 2021)

Investigated Aspect	General (all methods or modes)	Variation for specific method's modes
TTW/WTW CO ₂ /CO ₂ e	All use WTW or TTW or both A majority uses CO ₂ e; some CO ₂	
Allocation units in general	EN16258 uses tkm (tonne-kilometers); SmartWay CO ₂ /tsm, CO ₂ /vehicle mile or CO ₂ /cubic foot mile	SEA: CCWG uses CO ₂ /TEU AIR: in general mass and tkm XSHIP: TEU throughput, weight, space use or transported units
Specific allocation units	ISO claims that guidance is missing regarding maintenance, preparation and after-care and cleaning of transport units. For IWW, allocation rules for upstream, downstream transport are missing.	ROAD: tkm based on GCD (great circle distance) SEA: CCWG uses TEU AIR: EN16258 uses mass (passenger converted) ICAO/IATA uses for belly transports passenger + 50 kg for the seat
Energy consumption of auxiliary processes	EN16258 includes on-board processes (not specified).	SEA: CCWG respects reefer data (COOL) AIR: ICAO/IATA include auxiliary processes XSHIP: generally included. Green Logistics is specific as electricity, heating, packaging materials and refrigerants are included. Similarly, ITEC
Processes included	Empty trips included. Most for own fleet; EN16258 also for subcontractors	See above
VOS (vehicle operation system) descriptions	Most standards support the idea of a VOS. However, clear definitions for each mode of transport are required.	SEA: CCWG uses 25 trade lanes. XSHIP: ITEC has defined a certain VOS
Procedure for measured energy consumption data	EN16258 uses specific measured values, transport operator specific measured values and fleet values. SmartWay uses fuel/CO ₂ on measured data.	AIR: ICAO/IATA uses specific fuel measure protocols SEA: CCWG established on process on measured data. IMO uses own process which is vague on transport work done XSHIP: processes are vague
Procedure for absence of measured energy consumption data	EN16258: default data available	SEA: own IMO guidelines for conversions AIR: Default data from ICAO-CAEP or from IATA fuel measurement protocol XSHIP: guidelines are missing
Fuel-based vs. activity-based	Fuel-based	IWW: STREAM uses activity-based on vessel types XSHIP: ITEC uses a mixed approach
Default data	Guidelines in case of absence of measured data are not available	IWW: STREAM uses HBEFA data AIR: BADA & AEM data available SEA: CCWG own sources XSHIP: various options
Specific factors	EN16258 provides comprehensive tables SmartWay uses factors from Argonne Nat. Lab.	IWW: IMO has own factors and STREAM uses Defra factors AIR: IATA/ICAO uses IPCC SEA: IMO uses own factors XSHIP: ITEC uses Europ. Ref. Life Cycle database
Exiting gaps in coverage	More detailed clarification of sub modes in RAIL and SEA is required, as is better distinction between warehousing and transshipping.	
Allocation units Distances calculation	Use of mass/volume and TEU better unified Actual distances (EN16258 uses GCD or shortest distances for allocation)	IWW: EN16258 allows GCD + 95 km for allocation AIR: EN16258/IATA allows GCD + 95 km for allocation. Green Logistics allows GCD + 50 km for allocation ICAO uses GCD + 50/100/125 km depending on distances SEA: CCWG uses direct distances + 15%
Reporting	EN16258 and SmartWay use CO ₂ e on TTW/WTW or CO ₂ /tsm Often not specified	XSHIP: Green Logistics uses size and throughput

The insights provided by carbon footprint calculators are beneficial for users, despite some challenges such as concerns over data safety and the accuracy of emissions estimates. For instance, users of the carbon calculator Svalna demonstrated a willingness to connect their bank accounts for emissions tracking, which indicates a proactive approach towards reducing their carbon footprint, even though they exhibit average trust in the emissions data provided by the tool (Barendregt et al., 2020).

The quantification of emissions from freight transport is a complex process that involves various transport modes and emission categories (scope 1,2 and 3), each with its specific calculation parameters and considerations.

5.4.5 On-line customer service

The integration of online customer service within the logistics sector has brought about significant changes in communication, collaboration, and environmental impact. Such services enable more efficient interactions between customers and logistics providers, often reducing the need for physical

paperwork and travel, thus contributing to a decrease in carbon emissions related to transport. However, the transition to online and on-demand services need to account for all environmental effects. For example, on-demand mobility services, when combined with public transportation, can lower CO₂ emissions, yet they may also increase traffic volume in urban areas due to the use of less bundled vehicles (Dang et al., 2021). The increased traffic congestion resulting from individualized transport services can counteract the benefits of reduced CO₂ emissions, presenting a challenge for urban sustainability.

In the context of freight logistics, online customer service has the potential to enhance the routing of freight orders through an intermodal transportation network. This optimized routing aims to meet specific emission limits set by customers, contributing to a more environmentally friendly supply chain (Heinold & Meisel, 2020). Such optimization can mitigate the environmental impacts of freight transportation by leveraging the most efficient routes and modes of transport.

The shift from private vehicle travel to transportation network companies (TNCs) is another area impacted by the rise of online services. While this shift can lead to a significant reduction in air pollutant emissions, research indicates it may also result in increased fuel consumption and greenhouse gas emissions, as well as elevated traffic congestion costs. A study highlighted that moving private travel to TNCs could reduce air pollutant emission externalities by 50-60%, but at the same time, could lead to a 20% increase in fuel consumption and greenhouse gas emissions (Ward et al., 2021).

Despite these environmental challenges, online customer service positively influences customer satisfaction and loyalty by providing real-time support and responsiveness. This not only fosters more sustainable business relationships but also enhances operational efficiency and resource utilization. Streamlined customer interactions and order management processes that result from effective online service platforms contribute to reduced emissions by avoiding unnecessary transport and promoting more efficient logistics operations.

5.4.6 Digital community for collaboration of various stakeholders

The digitalization within the supply chain ecosystem can significantly foster an environment conducive to collaboration, knowledge sharing, and innovation among various stakeholders. This digital community serves as a platform for the promotion of best practices in sustainability, potentially aiding in transport decarbonization and influencing policy decisions (Tsakalidis et al., 2020). As digital technologies, connectivity, and automation evolve, they transform traditional mobility services and offer opportunities for reducing the carbon footprint of transport activities. However, the relationship between the digital economy and CO₂ emissions is complex. According to Li et al. (2021), this relationship initially follows an inverted U-shaped curve in line with the environmental Kuznets curve hypothesis. At the onset of digitalization, an increase in CO₂ emissions may be observed due to the expansion of digital infrastructure and activities. As such, governments are encouraged to implement hedging policies to counteract any adverse environmental impacts during this initial stage. As the digital economy matures, it has the potential to significantly alleviate CO₂ emissions, underscoring the importance for countries at all income levels to develop and harness digital capabilities for environmental protection. High-income countries are well-positioned to leverage the digital economy

to reduce emissions, while lower-income countries must be vigilant and adopt suitable policies to mitigate any negative effects.

Intelligent Transportation Systems (ITS) applications exemplify the benefits of digitalization in logistics, particularly in road freight transport. ITS applications can improve customer service by enhancing energy efficiency, reducing the environmental impact, and increasing connectivity and comfort (Kadłubek et al., 2022). By integrating such systems, logistics providers can streamline operations, cut down on emissions, and offer better service to their customers.

Furthermore, the collective efforts of stakeholders to address common sustainability challenges can lead to more coordinated and effective initiatives. A digital community strengthens relationships and builds trust among its members, fostering a culture of collective responsibility towards sustainability. For instance, the involvement of stakeholders and crew in defining clear goals and working cooperatively is crucial for the Ship Energy Efficiency Management Plan (SEEMP) to be an effective tool for energy-efficient vessel operations (Hansen et al., 2020).

5.4.7 Real-time monitoring of shipping

Maritime transport emissions significantly affect air quality along Europe's coastlines, noting that various studies highlight the contributions of different pollutants to the atmospheric composition. Shipping emissions are known to influence particulate matter concentrations, particularly PM₁₀, PM_{2.5}, and PM₁, as well as gases such as SO₂ and NO₂. Real-time monitoring of shipping emissions provides crucial data for managing these emissions, enhancing maritime transport operations through insights into vessel performance, fuel consumption, and emissions (Xiao et al., 2022). This proactive optimization is key for reducing the environmental impacts of shipping, which is responsible for notable percentages of airborne particulate matter across Europe. Table 32 with the study results of Xiao et al. (2022) shows, for example, that oil combustion contributes to 4–6% of PM_{2.5} in Seattle (US) and to 20% of the PM 2.5 in Genoa (Italy), expressed as percentage to the annual mean. Shipping activities add less than 5% to PM_{2.5} and PM₁₀ levels in Los Angeles (US), while in Europe, the contributions range from less than 5% to a maximum of 30% across various cities and particulate sizes. Notably, shipping emissions contribute up to 14% of PM_{2.5} in Melilla (Spain) and 30% of non-sea salt sulphate in Lampedusa (Italy). SO₂ emissions from ships also show a substantial impact, with increases of 280% and 106% above background levels in Sweden and Ireland, respectively. Meanwhile, NO₂ contributions range from 7% to 24% across various European countries.

The ability to detect inefficiencies or anomalies through real-time monitoring enables timely interventions, which are critical for maintaining air quality standards and reducing environmental impacts. This monitoring also enhances maritime safety and compliance, reducing the risk of accidents and environmental incidents. Such measures are essential for controlling ship pollutant emissions, which have the most considerable impact on SO₂ and particulate matter, with a minimal impact on NO_x (Xiao et al., 2022).

Table 32: Shipping contributions to air quality across Europe, % to the annual mean (source: Xiao et al., 2022)

Airborne particles				
Reference	Source	Contribution	Size fraction/PM component	Location
Kim & Hopke	Oil combustion	4–6%	PM _{2.5}	Seattle (US)
Mazzei et al. (2008)	Oil combustion	20%	PM ₁	Genoa (Italy)
Minguillón et al. (2008)	Shipping	<5%	OC	Los Angeles (US)
		<5%	PM _{2.5}	Los Angeles (US)
Viana et al. (2008)	Oil combustion	10–30%	PM ₁₀ and PM _{2.5}	Europe
Amato et al. (2009)	Oil combustion	5%	PM ₁₀	Barcelona (Spain)
		6%	PM _{2.5}	Barcelona (Spain)
		8%	PM ₁	Barcelona (Spain)
Viana et al. (2009)	Shipping	2–4%	PM ₁₀	Melilla (Spain)
		14%	PM _{2.5}	Melilla (Spain)
Hellebust et al. (2010)	Shipping	<1%	PM _{2.5-10} and PM _{0.1-2.5}	Cork (Ireland)
Contini et al. (2011)	Shipping	1–8%	PM ₁₀	Venice (Italy)
		1–8%	PM _{2.5}	Venice (Italy)
Pandolfi et al. (2011)	Shipping	3–7%	PM ₁₀	Algeciras (Spain)
		5–10%	PM _{2.5}	Algeciras (Spain)
Becagli et al. (2012)	Shipping	30%	nss SO ₄ ²⁻	Lampedusa (Italy)
		3.9%	PM ₁₀	Lampedusa (Italy)
		8%	PM _{2.5}	Lampedusa (Italy)
		11%	PM ₁	Lampedusa (Italy)
Hammingh et al. (2012)	Shipping	1–5%	PM _{2.5}	North Sea coastal countries
		5%	PM _{2.5}	The Netherlands
		4%	PM _{2.5}	UK
		3%	PM _{2.5}	Belgium
		3%	PM _{2.5}	Denmark
		2%	PM _{2.5}	France
		2%	PM _{2.5}	Germany
		2%	PM _{2.5}	Luxembourg
		1%	PM _{2.5}	Norway
		1%	PM _{2.5}	Sweden
		1%	PM _{2.5}	Switzerland

Issa et al. (2022) provide an overview of ship-produced gaseous pollutants, their environmental impacts, and the initiatives in place to reduce carbon emissions from ships.

Table 33 outlines the consequences of different gaseous pollutants produced by ships. Sulphur oxides (SO_x) and nitrogen oxides (NO_x) are associated with acid rain, while NO_x also contributes to ozone formation at ground level. CO₂ (carbon dioxide) is recognized for its role in the greenhouse effect. It can be shown that SO_x and NO_x are primarily linked with fuel combustion and incinerators on ships, while CO₂ emissions are associated with fuel combustion, incinerators, and linked to the ship's equipment.

Table 33: Ship-produced gaseous pollutants and their environmental effects (source: Issa et al., 2022)

Consequences	Pollutants		
	SO _x	NO _x	CO ₂
Greenhouse effect	-	-	✓
Ozone-ground level	-	✓	-
Acid rain	✓	✓	-
Linked-up with:			
Fuel combustion	✓	✓	✓
Cargo handling	-	-	-
Ships equipment	-	-	-
Incinerators	✓	✓	✓

Figure 47 presents the timeline of the International Maritime Organization's (IMO) plan for ship enhancements from 2013 to 2050. It highlights the significant milestones and targets set to increase the energy efficiency of the global fleet. In 2013, regulations were introduced to bring over 90% of the world's fleet under mandatory energy efficiency management. By 2015, the Energy Efficiency Design Index (EEDI) was implemented for new ships to adhere to agreed-upon efficiency goals. In 2020, a

target was set for new ships to improve efficiency by 10%, equating to a 20% CO₂ reduction per tonne/km. Looking towards the future, the milestones set for 2025 and 2030 require new ships to improve efficiency by 20% and 30%, respectively. The goal is to achieve a 50% CO₂ reduction per tonne/km by 2050, which aligns with the broader maritime industry's objectives to reduce carbon emissions and combat climate change.

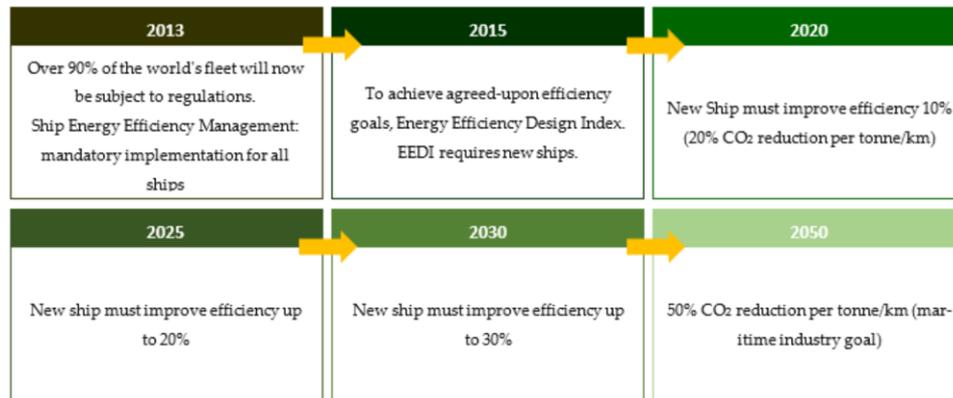


Figure 47: The IMO plan for ship enhancements from 2013 until 2050 (source: Issa et al., 2022)

5.4.8 Real-time monitoring of road cargo

The integration of real-time monitoring into road cargo operations is increasingly recognized as a transformative tool that not only enhances the efficiency of logistics but also contributes significantly to environmental sustainability. By continuously tracking vehicles, shipments, and environmental conditions, real-time monitoring facilitates more informed route planning and resource allocation, which can lead to notable improvements in emission efficiency for trucks (Inkinen & Hämäläinen, 2020). Such efficiency is crucial in urban settings, where on-road remote sensing technology has been instrumental in identifying and rectifying high-emitting vehicle fleets, thus improving urban air quality (Huang et al., 2022).

Moreover, monitoring the carbon footprint of road freight activities in real-time aids in selecting the most effective methods for calculating and reducing greenhouse gas pollution, thereby mitigating its impact on global warming (Tautkevičienė, 2023). This approach becomes particularly relevant when considering that on-road CO₂ concentrations can be twice as high during traffic congestion compared to free-flow conditions (Maness et al., 2015). Real-time monitoring can offer dynamic suggestions for alternative paths, potentially reducing CO₂ emissions by ensuring vehicles operate under less congested conditions.

The significance of real-time monitoring extends beyond roadways to include critical environmental safeguards. For example, remote sensing monitoring of CO₂ storage sites is vital for effective implementation and prevention of harmful effects due to potential leakage, thus protecting the environment and personnel (Zhang et al., 2020). Furthermore, real-time vehicular exhaust emissions data reveal significant variations due to short-term driving events, such as rapid acceleration and braking, which traditional emission models often underestimate by 20-30% (Jaikumar et al., 2017).

5.4.9 Fleet/emissions monitoring along the entire supply chain

Fleet and emissions monitoring within the supply chain is an integral process for evaluating the environmental performance of logistics operations. By tracking vehicles and equipment, companies can pinpoint areas where emissions can be reduced, and operational efficiencies can be achieved. This process is vital for data-driven decision-making and guides investments in cleaner technologies, which are essential for advancing sustainable fleet management practices.

The importance of such monitoring is highlighted considering research indicating that carbon emissions can surge by approximately 18-20% during supply chain disruptions. This increase is largely attributed to the extended travel distances required to fulfil customer backorders (Amiruddin et al., 2021). Additionally, emission factors like the proportion of larger vehicles in the fleet, vehicle speeds, and ambient temperatures have been shown to cause variability in traffic-related pollutant concentrations, which is critical for assessing the environmental impact of transport activities (Wang et al., 2018).

With the implementation of comprehensive emissions monitoring strategies, stakeholders can track their progress towards achieving sustainability goals and demonstrate their commitment to environmental stewardship. Such transparency not only benefits the environment but also strengthens the trust of customers, investors, and regulatory authorities, showcasing the company's dedication to responsible environmental management. This ongoing evaluation and adjustment lead to more resilient supply chains and help mitigate the negative effects of logistical disruptions and traffic-related pollution.

5.5 Connectivity and Automated Systems

Connected and Automated Vehicles (CAVs) incorporate a suite of technologies to perceive their environment, make intelligent decisions, and navigate without human input (Li et al., 2017). Table 34 by Singh et al. (2021) provides a comparative analysis of the autonomous technologies used in both autonomous vehicles (AVs) and autonomous trains (ATs), known as Automated Transportation Systems (ATS).

Table 34: Comparison of autonomous technologies used in AVs and ATs (source: Singh et al., 2021)

a/a	Autonomous Vehicles	Autonomous Trains	Utility of Technology
1	Cameras	Infrared Cameras	Read signage, traffic control devices, lane markings, surrounding environment, etc.
2	Laser Illuminating Detection and Ranging (LIDAR)	Laser Illuminating Detection and Ranging (LIDAR)	Create 3D maps and help detecting potential hazards. Can determine the distance and object profile by bouncing the laser beam off the object surface.
3	Radar	Radar	Accurately measures the speed of nearby vehicles and trains in real time that cannot be adequately achieved by using LIDAR.
4	Sensors	Ultrasonic Sensors	Sensors perform the role of a self-monitoring device to ensure that a vehicle/train is not speeding and monitor the overall vehicle/train functionality. Also, they perform the role of object detection.
5	Dedicated Short-Range Communications (DSRC)	Dedicated Short-Range Communications (DSRC)	The DSRC is a short-range communication system with a reliable two-way high-speed radio service that can be effectively deployed for V2V and V2I communication. It can provide warning at highway-rail grade crossings regarding an approaching AT.
6	Stereo Video	Stereo Video	The stereo video uses two cameras to capture a 3D-environment that forms the basis for various assistance systems in the vehicle/train. It helps in measuring the depth accurately.
7	Human-Machine Interface (HMI)	N/A	It is a combination of systems inside the vehicle, which includes panels and controls for the interaction between the vehicle and its occupants.
8	Domain Controller	Domain Controller	This is the main "brain" of the autonomous driving system that controls the signals and information from LIDAR, sensors, cameras, etc. and determines necessary actions accordingly.
9	Motion Control Systems, Actuators, Mechatronic Units	Motion Control Systems, Actuators, Mechatronic Units	They work in combination with other technologies for execution of different actions that were received from the domain controller.
10	N/A	Positive Train Control (PTC)	It is a GPS-based technology that is used to stop the train, avoid collision, and any unwarranted train movements.

5.5.1 Autonomous road trucks

The integration of autonomous road trucks, or Automated Vehicles (AVs), into the transportation sector is expected to deliver significant advancements in terms of fuel efficiency, emissions reduction, and road safety. The synergy between automated vehicles and on-demand mobility has the potential to substantially decrease energy usage and GHG emissions, as they could enhance the effectiveness of route planning and driving behaviour through advanced sensors and algorithmic optimization (Greenblatt & Shaheen, 2015).

AVs have the potential to reduce greenhouse gas emissions by up to 35% via eco-driving and platooning. Nevertheless, the possibility of inducing easier and faster travel might conversely increase emissions by 41.24% (Massar et al., 2021). Despite this, even a small proportion of AVs on the roads—around 5%—could stabilize traffic flow and mitigate stop-and-go waves, translating to a possible reduction in vehicle emissions of 15% to 73% (Stern et al., 2019).

On a network scale, AVs demonstrate the capability to reduce total CO₂ emissions, with estimations suggesting a 4% reduction with full autonomy (Conlon & Lin, 2019). However, it's important to consider the complete picture. While highly automated vehicles can lead to modest per-kilometer CO₂ emission improvements, the net energy and CO₂ emission balance for AVs might be negative when accounting for the full lifecycle and operational parameters (Annema, 2020). The operational behaviour of CAVs also plays a crucial role in influencing the environmental performance of conventional vehicles. Depending on road types and market penetration rates, network-wide CO₂ savings can vary widely, ranging from an 18% reduction to an increase of 4% (Bandeira et al., 2021).

Beyond emissions, AVs enhance road safety by minimizing human error, which is a leading cause of accidents and traffic congestion. By optimizing resource utilization, AVs pave the way for more efficient and sustainable transportation operations. As such, the potential of AVs extends beyond mere technological innovation; it signifies a step towards a safer and more environmentally responsible future in transportation, as argued by Massar et al. (2021).

5.5.2 Autonomous rail services

The deployment of autonomous rail services is set to significantly enhance the operational efficiency and capacity utilization of rail transport. By leveraging Industrial Internet of Things (IIoT) technologies, autonomous trains can operate with reduced energy consumption and lower emissions per unit of transported freight, contributing to a more sustainable transportation sector. IIoT-enabled technologies encompass a broad range of tools and methods that converge to create intelligent rail systems. Image Processing and Computer Vision technologies, such as object recognition and video analysis, are key for the autonomous navigation of trains. Artificial Intelligence, including machine learning and advanced robotics, supports decision-making and predictive maintenance. Big Data and Data Analytics offer insights for optimizing routes and schedules. Computing advancements like cloud and fog computing enable the processing and analysis of vast amounts of data critical for autonomous operations. Sensors, Modeling and Simulation, and Communication Systems are integral to the real-time monitoring and control required for autonomous trains. Technologies such as RFID, satellite communications, and various types of sensors ensure that trains operate safely and efficiently. These components work synergistically to enable Decentralized Autonomous Train Control (D-ATC) and Driverless Train Operation (DTO), which are central to the concept of fully autonomous rail services (Singh et al., 2021).

Autonomous rail services not only increase the efficiency of rail transport but also enhance safety and reliability through automated control systems, which minimize the risk of accidents and service disruptions (Singh et al., 2021). The modal shift from road to rail, facilitated by these advanced systems, promotes a more sustainable and environmentally friendly freight transportation option. Although high-speed rail operation has been identified as a significant impact factor for regional CO₂ emissions (Gan et al., 2020), the overall implementation of autonomous train technologies is expected to yield a net positive environmental outcome.

The advancements in autonomous rail technologies are projected to optimize energy consumption through intelligent acceleration, traction, and braking procedures. Energy savings are also anticipated through the management of air-conditioning systems and the introduction of LED lighting. Furthermore, the potential integration of renewable energy sources and timely maintenance facilitated by autonomous systems could lead to additional reductions in electric energy consumption.

5.5.3 Automated maritime vessels

Automated maritime vessels, equipped with cutting-edge technology, are at the forefront of this evolution, offering a plethora of benefits that extend well beyond conventional navigation practices. One of the most notable advantages of these automated vessels is their ability to enhance fuel efficiency, thereby substantially reducing emissions. This is a crucial step towards meeting the International Maritime Organization's (IMO) targets for CO₂ emissions reduction, addressing global concerns over climate change. The integration of advanced automation in maritime vessels ensures a more precise and efficient operation, minimizing fuel consumption and, consequently, lowering greenhouse gas emissions. According to Issa et al. (2022), these innovative solutions not only fulfil environmental objectives but also present a viable economic perspective for the maritime industry.

Furthermore, the safety and reliability of maritime transport have significantly improved due to automation. Automated systems are designed to reduce human error, which is often the root cause of maritime accidents such as collisions, groundings, and other mishaps. By leveraging automation, the industry can ensure safer navigation and operation of vessels, ultimately protecting lives, cargo, and marine ecosystems.

In addition to safety and environmental benefits, automated maritime vessels contribute to a more efficient use of maritime infrastructure and resources. This efficiency is crucial for accommodating the growing global trade, which demands more from the existing maritime transport infrastructure. Automation enables the maritime sector to optimize resource allocation and infrastructure usage, ensuring that the industry can meet future demands without compromising sustainability.

Dumitrache, L., Buzbuchi, N., & Faităr, C. (2020) highlight the role of energy efficiency in reducing CO₂ emissions within the maritime sector. By increasing energy efficiency in ship operations, automated maritime vessels significantly contribute to the reduction of pollution emissions. This not only aligns with global efforts to combat climate change but also enhances the overall performance and competitiveness of the maritime industry.

5.5.4 Blockchain and smart contracts

Blockchain technology and smart contracts together facilitate a seamless, automated flow of energy transactions, which significantly enhances the efficiency of energy management systems. By ensuring that transactions are transparent and automatically executed, these technologies reduce the need for intermediaries, thereby cutting down on administrative costs and minimizing waste. This efficient utilization of resources is crucial for reducing environmental impact, as emphasized by Zheng et al. (2019), who highlight the role of smart contracts in improving business process efficiency and reducing risks.

The transformative potential of blockchain-based smart contracts extends beyond administrative efficiency to directly impact environmental sustainability. As noted by Hewa et al. (2021), these technologies revolutionize applications by delivering optimum functionality, which is particularly significant in the context of CO₂ reduction and resource efficiency. The ability to automate and optimize transactions and processes through smart contracts makes it a powerful tool for achieving environmental goals.

Moreover, the application of blockchain and smart contracts in manufacturing supply chains introduces a new dimension of trust and competitiveness. According to Chen et al. (2022), the deployment of these technologies significantly enhances partners' trust, which in turn increases visibility and competitiveness while improving environmental performance. The secure and transparent nature of blockchain, coupled with the automated enforcement of agreements through smart contracts, fosters a collaborative environment. This environment not only supports operational excellence but also promotes sustainability by ensuring that all parties adhere to environmentally responsible practices.

5.5.5 Virtual traffic lights

Developed to optimize traffic flow in real-time, virtual traffic lights (VTLs) operate on the principle of dynamically adjusting signal phases based on the current traffic conditions, without the need for physical traffic light infrastructure. This adaptive approach to traffic management not only enhances the efficiency of urban transport but also significantly contributes to environmental sustainability. Ferreira et al. (2012) emphasizes the potential of VTLs to mitigate carbon emissions, particularly in urban settings characterized by high-density traffic. The research indicates that the implementation of Virtual Traffic Lights can lead to a reduction in CO₂ emissions by nearly 20% in scenarios with heavy traffic congestion. This finding is especially relevant given the growing concerns over urban air quality and the global push towards reducing greenhouse gas emissions. This kind of system may also can reduce fuel consumption by up to 22% for a single vehicle and around 8% in case of more vehicles on the road (Rapelli et al., 2020). The efficacy of VTLs in reducing emissions stems from their ability to decrease idling time and smooth traffic flow, thereby reducing fuel consumption and the associated carbon output. By leveraging wireless communication technology to coordinate signals directly between vehicles, VTLs ensure that traffic moves more fluidly, reducing the stop-and-go patterns that are typical of congested roadways. This not only enhances the overall driving experience but also contributes to a cleaner, more sustainable urban environment.

5.5.6 Advanced driver-assistance systems for fuel efficiency

Advanced Driver-Assistance Systems (ADAS) have emerged as a focal technology in the quest for enhancing fuel efficiency and reducing vehicular emissions. These systems support drivers through a variety of mechanisms, including warnings, automation of control tasks, and relief from manual control, which collectively contribute to more efficient driving patterns and reduced fuel consumption. Piao et al. (2008) emphasize the transition from autonomous to cooperative approaches in ADAS, highlighting their potential in reducing CO₂ emissions and improving efficiency by assisting drivers in maintaining optimal driving behaviours. Building upon this foundation, recent advancements in ADAS technology have led to the development of ECO-ADAS systems, which specifically target the optimization of speed profiles for vehicles approaching intersections.

Marinelli et al. (2023) investigate the impact of Eco-ADAS systems, revealing their capacity to achieve significant reductions in fuel consumption and emissions. In optimal scenarios, savings can reach up to 33%, underscoring the substantial environmental and economic benefits that such systems can offer. This is particularly relevant at signalized intersections, where inefficient stop-and-go driving patterns are prevalent and contribute to excessive fuel use and emissions.

5.5.7 Mooring systems

Mooring systems automate the process of securing vessels to the dock, replacing the traditional manual method of ropes and human strength with advanced mechanisms that can include vacuum pads, magnetic plates, or robotic arms. This automation facilitates a faster, safer, and more reliable mooring process, significantly reducing the time ships spend idling at the port. Piris et al. (2018) conducted a study on the impact of these systems in the port of Santander, revealing a reduction of around 77% in CO₂ emissions. This reduction is attributed to the increased efficiency and reduced operational time associated with automated mooring, which significantly lessens the fuel consumption of vessels during docking procedures.

6 Diagram of technologies across different transport modes: carbon and energy efficiency impacts

6.1.1 Impact assessment

This chapter outlines the diagram of technologies across inland transportation and sea transport, considering the studies reviews in chapter 5 that addressed a wide range of emerging options and the respective performance indicators, focusing on the reduction of carbon emissions and improvements in energy efficiency.

The diagram of technologies across different transport modes represents a former solutions domain - reference of transport modes/evolving technologies and related performance indicators, which form the planned milestone comprising the relevant inputs for the impact assessment framework of solutions (MS3) to be developed in WP 6 – “*Assessment of Solutions and Impact Assessment, task 6.1 Impact assessment framework, KPIs definition and prioritization*”. Examples of most cited technologies during semi-structured interviews with the companies/stakeholders (Chapter 4) are used to build the respective Sustainability Impact cards with positive/negative impact indicators that follow from the literature review (chapter 5). The KPIs found in the review are illustrated for each case. D2.2 is, thus, expected to be important to task 6.1 participants (CTLup, UL, CERTH) that will start on May 2024. The Sustainability Impact cards developed reveal useful information and further KPIs following the evidence found. The comprehensive list of KPIs is at the Annex.

6.1.2 Diagram for Alternative Fuels, Potential Impacts and Sustainability Impact Cards



Figure 48: Diagram for Alternative Fuels and Potential Impacts

Sustainability Impact Cards

These Sustainability Impact Cards consider the set of technological options across transport modes (from now until 2030) that were mentioned by more than one company during the semi-structured interviews previously outlined in chapter 4.



Alternative fuels - Liquefied Natural Gas (LNG)

A transitional low carbon fuel in maritime and haulage sectors
(i.e. IMO based strategy distribution 2030: 25% ;2040: 48% ;2050: 19%)

Carbon neutral variants: e-LNG, Bio-LNG

Source: (Song, 2021) and GEF-UNDP-IMO. Port Emissions Toolkit, Guide No.2



KPIs and Impact:

Decreases the greenhouse gas (GHG), with a drop of 8–20% (and CO2 emissions by 20–30%) compared to HFO (heavy fuel oil) and MDO (marine diesel oil)

More info: (Livaniou et al., 2021) Heraklion Port, which is a port in Greece,




Concerns about methane leakage during the LNG lifecycle warrant attention due to methane's potent greenhouse effect and may not have wide adoption due to that concern

Source: (Gray et al., 2021) (Adamopoulos, 2021)



Hydrogen Fuel for Shipping

Hydrogen used in fuel cells for maritime vessels to reduce greenhouse gas emissions and reliance on fossil fuels.

Variants: Green Hydrogen, Marine Hydrogen Fuel, H2 Shipping Fuel

Source: (Carlisle et al., 2023)



KPIs and Impact:

Helps meet international GHG reduction targets (Azni et al., 2021; IRENA et al., 2021)
It is a zero-carbon fuel. (Song, 2021)
High rate of research (IRENA et al. 2021)
Can be made near Ports through electrolysis (Issa et al., 2022)

Suitable for Inland, Coastal (compressed) and Short sea (liquefied) (Xing et al., 2021)




Substantial initial investments for hydrogen fuel cell infrastructure due to technological immaturity.

Technical and safety challenges in handling hydrogen.

(IRENA et al. 2021)

Ammonia as Marine Fuel



A energy-derived ammonia for use as a carbon-free fuel in shipping, has higher GHG than Oil emissions.

Variants: Grey Ammonia, NH3 Fuel, Zero-Emission Ammonia

Source: (Al-Alboosi et al., 2021)



Suitable for Inland, and Short sea (Xing et al., 2021)

Can be stored at high temperature and low pressure (Issa et al., 2022)

KPIs and Impact:



Indirect GHG emissions 10 times higher than **green** ammonia (Ankathi et al., 2022)

Global demand across sectors can lead to scalability issues (IRENA et al., 2021)

Green Ammonia as Marine Fuel



A renewable energy-derived ammonia for use as a carbon-free fuel in shipping, reducing greenhouse gas emissions.

Variants: Renewable Ammonia, NH3 Fuel, Zero-Emission Ammonia

Source: (Al-Alboosi et al., 2021)



Can reduce maritime GHG emissions by up to 80% compared to traditional fuels (Al-Alboosi et al., 2021).

Has the potential to cut well-to-hull global GHG emissions from crude transportation by 50% relative to **conventional** ammonia (Ankathi et al., 2022).

KPIs and Impact:



Produces nitrogen oxides when combusted (Lindstad, 2020).

Requires development of new infrastructure for wide-scale use and supply.

Hydrogen must be added in internal combustion engines (Issa et al., 2022)

Electrofuels (E-fuels) as Marine Fuel



Synthetic fuels produced from renewable energy sources for use in transportation, aiming to reduce carbon emissions in sectors such as shipping.

Variants: e-methanol, e-LNG, e- MGO e-ammonia, Power-to-liquid fuels

Source: (Brynnolf et al., 2018)



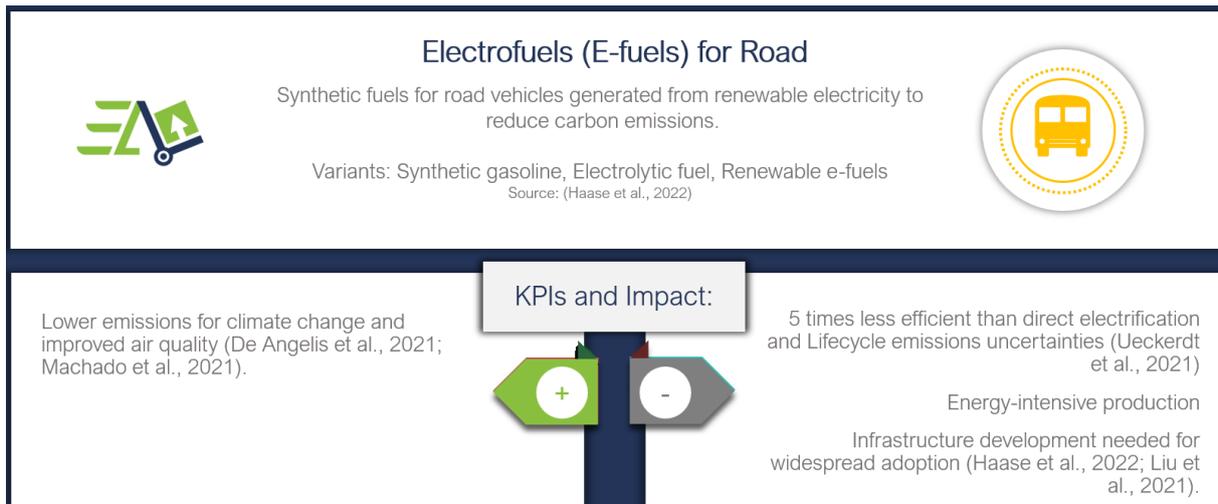
Carbon Neutral (e-MGO, e-LNG) or Zero Carbon (e-ammonia, e-methanol) (Song, 2021)

Promotes decarbonization in transport sectors (Brynnolf et al., 2018).

KPIs and Impact:



5 times less efficient than direct electrification and Lifecycle emissions uncertainties (Ueckerdt et al., 2021)



6.1.3 Diagram for Selective Emissions Reducers, Potential Impacts and Sustainability Impact Cards

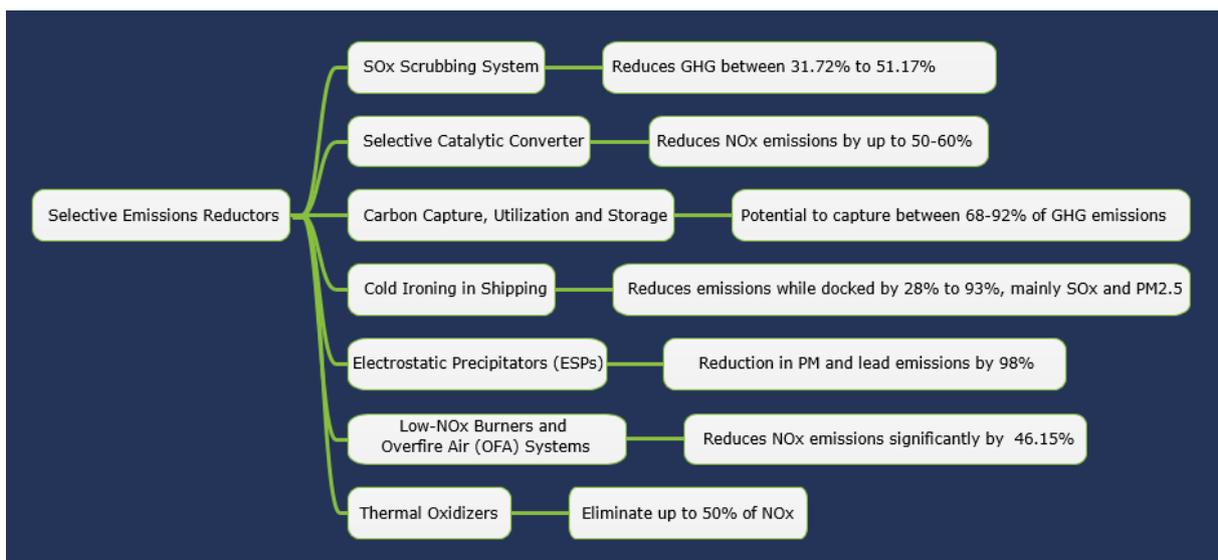


Figure 49: Diagram for Selective Emissions Reducers and Potential Impacts

Sustainability Impact Cards

These Sustainability Impact Cards consider the set of technological options across transport modes (from now until 2030) that were mentioned by more than one company during the semi-structured interviews previously outlined in chapter 4.

SOx Scrubbing Systems

Technologies to reduce sulfur oxides in ship exhaust, ensuring compliance with environmental standards.

Variants: Exhaust Gas Cleaning Systems (EGCS)
Source: (Kim et al., 2019)

Mitigates acid rain and respiratory issues (Kim et al., 2019).

Can decrease GHG emissions by up to 51.17% (Wilailak et al., 2021).

SOx gas emission reductions up to 95% and Particulate Matter (PM) up to 60% (Tran, 2017; Ni et al., 2020)

KPIs and Impact:

Management of scrubbing byproducts can be an issue

Operational costs and maintenance (Tran, 2017; Ni et al., 2020).

Selective Catalytic Reduction (SCR) for Road Transportation

A technology that reduces NOx, HC, and CO emissions in vehicle and industrial exhaust by converting them to nitrogen, water, and CO2.

Variants: NH3-SCR, NOx Reduction/Denitrification Catalyst
Source: (Athrashalil et al., 2014)

Over 55% NOx conversion, reducing smog formation (Athrashalil et al., 2014).

Compliance with stringent emission regulations for road vehicles.

KPIs and Impact:

Reduced efficiency at low temperatures (Barreau et al., 2020).

The need for high-quality urea solution and regular replenishment.

Potential ammonia slip if not properly managed.

Cold Ironing

A technology allowing docked ships to connect to the local grid for power, significantly reducing emissions by using electricity instead of onboard engines

Variants: Onshore Power Supply (OPS), Shore Power, shore-to-ship power
Source: (Voldsund et al., 2023).

Significantly reduces air pollutants and GHG emissions, enhancing air quality and reducing health risks in port cities (Ballini et al., 2015).

Cutting CO2 emissions—estimated at about 25% directly and over 95% when supplied with low (GHG) electric power (Olaniyi et al., 2022; Voldsund et al., 2023)

KPIs and Impact:

Dependency on the availability of green electricity

Infrastructure investment costs

Risk of emissions transfer to electricity generation sources (Olaniyi et al., 2022).

6.1.4 Diagram for Energy Efficiency, Potential Impacts and Sustainability Impact Cards

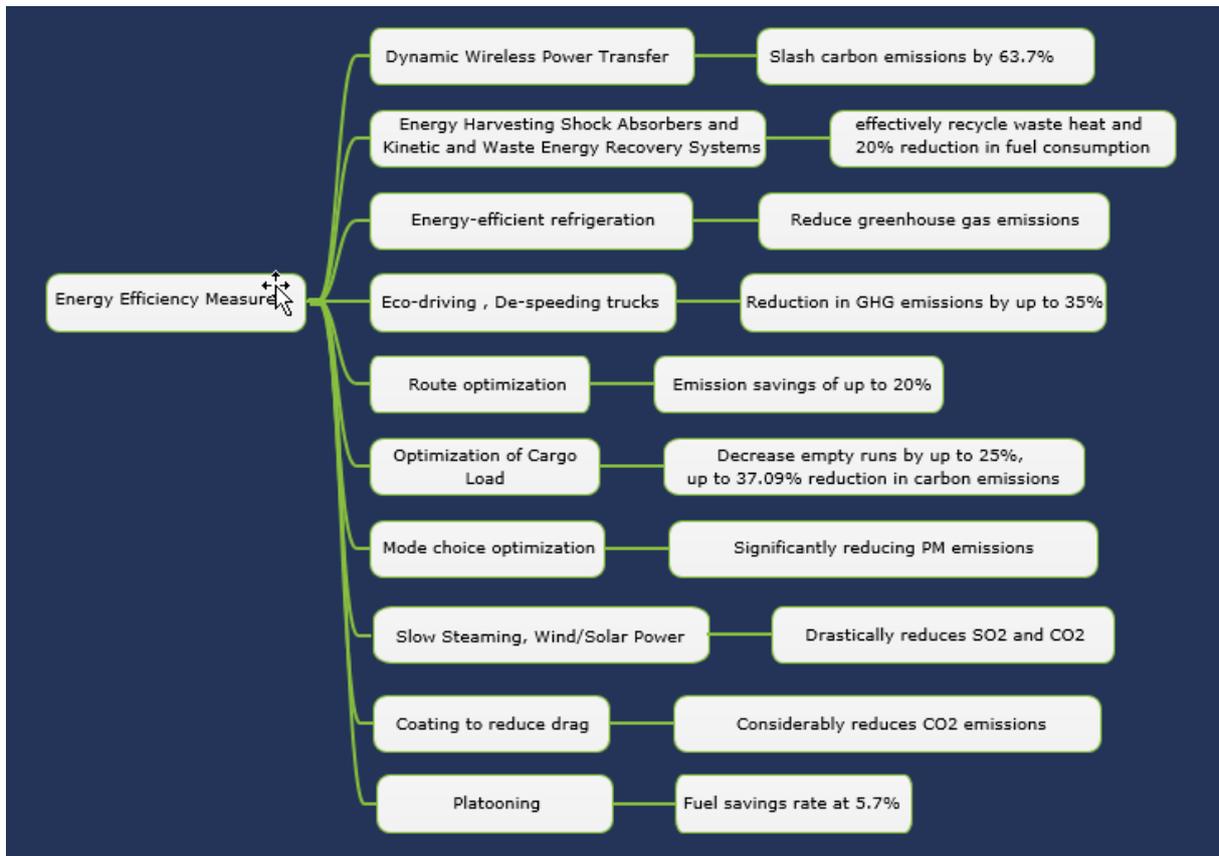


Figure 50: Diagram for Energy Efficiency Measures and Potential Impacts



Figure 51: Diagram for Sustainability through Collaboration Measures and Potential Impacts

Sustainability Impact Cards

These Sustainability Impact Cards consider the set of technological options across transport modes (from now until 2030) that were mentioned by more than one company during the semi-structured interviews previously outlined in chapter 4.



Eco-Driving

Driving practices focused on reducing fuel consumption and minimizing emissions, such as smooth accelerations and decelerations.

Also Known as: Efficient Driving, Green Driving

Source: (Massar et al., 2021)



Eco-driving can lead to up to 35% GHG emissions reduction and significant fuel savings (Massar et al., 2021).

KPIs and Impact:

+

-

May lead to moderate increases in travel times (average of 7.5%), necessitating balance with efficiency (Coloma et al., 2017).



Route Optimization

The application of algorithms and computational methods to determine the most efficient travel routes, reducing fuel consumption and emissions.

Also Known as: Eco-Routing, Intelligent Route Planning

Source: (Nguyen et al., 2021)



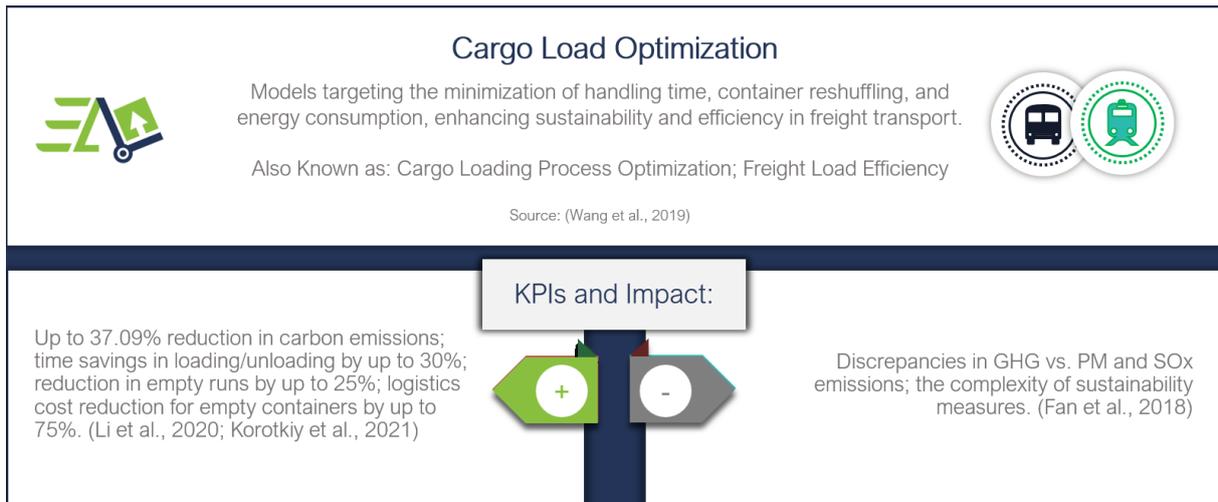
Increases transportation network efficiency and can reduce GHG emissions significantly, with savings in emissions up to 20% (Torres-Machí et al., 2017; Schröder et al., 2019).

KPIs and Impact:

+

-

May increase travel times and operational costs, with complex trade-offs in emission types (Bandeira et al., 2013; Macedo et al., 2020).



6.1.5 Diagram for Digitalization and Monitoring, Potential Impacts and Sustainability Impact Cards

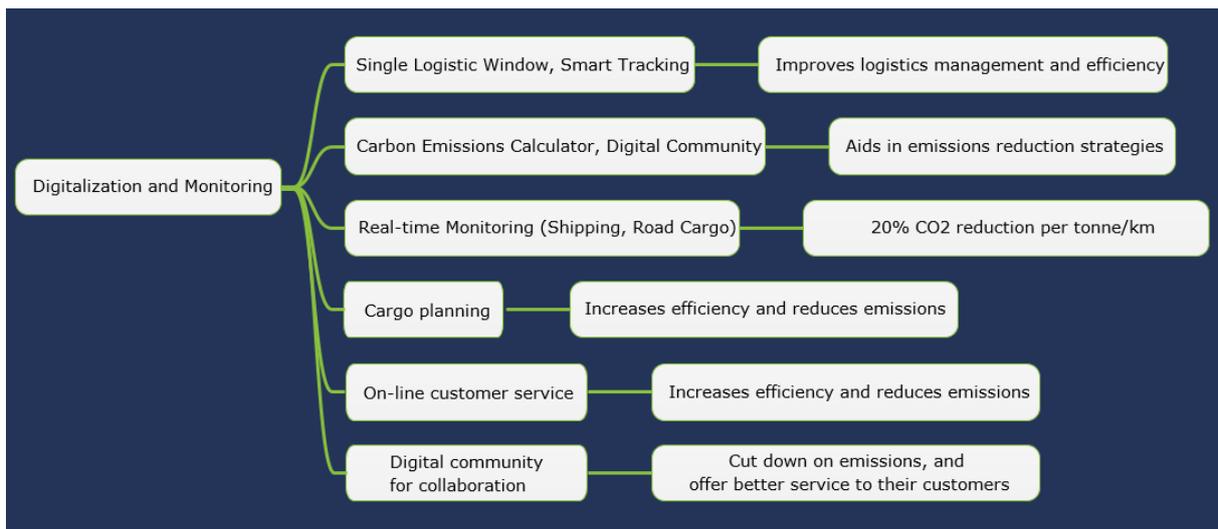


Figure 52: Diagram for Digitalization and Monitoring Measure and Potential Impacts

Sustainability Impact Cards

These Sustainability Impact Cards consider the set of technological options across transport modes (from now until 2030) that were mentioned by more than one company during the semi-structured interviews previously outlined in chapter 4.

Single Logistic Window (SLW)



A centralized data management system designed to streamline logistics operations by consolidating information and processes, reducing administrative work, and enhancing operational transparency..

Source: (UNECE, 2016)



SLWs such as the GNSW in Ghana and the MSW in the Netherlands have demonstrated reductions in cargo waiting times and emissions UNECE (2016). More modern and simplified ports that integrate the entire logistics chain (Projeto JUL, 2019).

KPIs and Impact:



Adoption and standardization challenges across different regions and companies; ensuring data security and privacy. (Tijan et al., 2018; Niculescu et al., 2016)

Smart Container Tracking and Tracing



Smart technology in container logistics enhances supply chain visibility and efficiency by integrating advanced tracking and tracing capabilities, thus reducing lost shipments and optimizing resource allocation.

Also known as: Intelligent Container Monitoring; Automated Cargo Tracking

Source: (Efimova & Saini, 2023)



Travel time decreased from 2.4 to 2.3 hours (port to CFS) and from 4.8 to 3.7 hours (CFS to port). Carbon emissions reduced from 113.4 kg CO2/liter to 106.7 kg CO2/liter (port to CFS) and from 222.4 kg CO2/liter to 172.1 kg CO2/liter (CFS to port), leading to a 6% decrease in emissions for imports and a 23% decrease for exports. (Efimova & Saini, 2023)

KPIs and Impact:



Security of data, the privacy of information, and the reliance on technology that may fail or be manipulated.

Slow Steaming



A practice of operating maritime vessels at reduced speeds to decrease fuel consumption and emissions.

Also Known as: Eco-speed, Reduced Speed Sailing

Source: (Zincir, 2023)



Significant reductions in CO2, CH4, N2O, and Black Carbon emissions, improving ship Carbon Intensity Indicator (CII), aiming for CO2 reduction targets of 40% by 2030 and 50% by 2050 (Zincir, 2023).

KPIs and Impact:



Longer voyage durations may affect shipping schedules and delivery efficiency (Zincir, 2023).

6.1.6 Diagram for Connectivity and Automated Systems, Potential Impacts and Sustainability Impact Cards

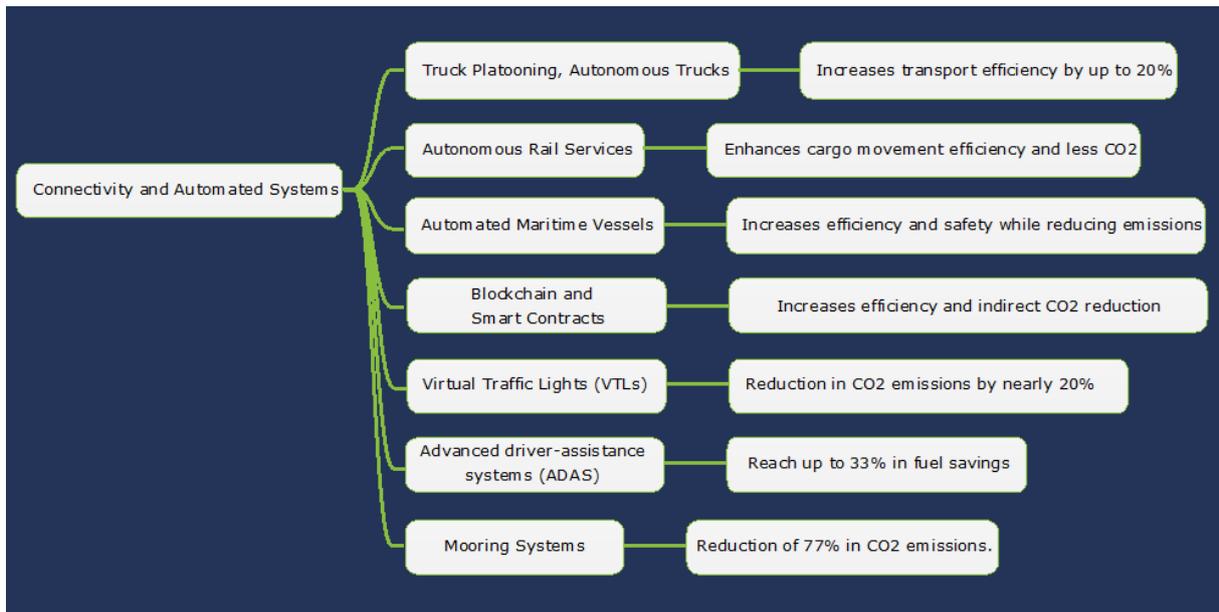


Figure 53: Diagram for Connectivity and Automated Systems Measure and Potential Impacts

Sustainability Impact Cards

The set of Sustainability Impact Cards consider a random set of technological options across transport modes. During the semi-structured interviews previously outlined in chapter 4 companies have not considered “Connectivity and Automated Systems” as options to be implemented until 2030.

Autonomous Road Trucks (ARTs)

The integration of ARTs into transportation networks to enhance efficiency and safety through automation.

Also Known as: Automated Vehicles (AVs), Self-Driving Trucks, Driverless Trucks

Source: (Greenblatt & Shaheen, 2015)

Up to 35% emission reduction via eco-driving and platooning (Massar et al., 2021).

5% ART presence could reduce emissions by 15-73%, mitigating stop-and-go waves, (Stern et al., 2019).

4% total CO2 emission reduction with full autonomy (Conlon & Lin, 2019).

KPIs and Impact:

+

-

Possible emission increase by 41.24% due to induced travel (Massar et al., 2021).

Net energy and CO2 impact could be negative over the full lifecycle (Annema, 2020).

CO2 savings vary by road type and penetration rate, from an 18% reduction to a 4% increase (Bandeira et al., 2021).

Autonomous Rail Services (ARS)

Adoption of fully automated, IIoT-integrated rail systems for enhanced efficiency and sustainability in rail transport.

Also Known as: Driverless Trains, Decentralized Autonomous Train Control (D-ATC), Driverless Train Operation (DTO)

Source: (Singh et al., 2021)

Reduced energy consumption and emissions through IIoT-enabled technologies. Enhanced operational efficiency and capacity utilization. Improved safety and reliability with automated control systems (Singh et al., 2021).

Environmental benefits from modal shift from road to rail (Gan et al., 2020).

KPIs and Impact:

High-speed rail could increase regional CO2 emissions (Gan et al., 2020).

Automated Maritime Vessels (AMVs)

Ships integrated with advanced automation technology for efficient operation and navigation.

Also Known as: Autonomous Ships, Unmanned Surface Vessels, Self-Piloting Cargo Ships

Source: (Issa, M., Ilincă, A., & Martini, F., 2022)

Enhances fuel efficiency, reducing emissions in line with IMO targets (Issa et al., 2022).

Improves safety by reducing human-error-related incidents (Dumitrache et al., 2020).

KPIs and Impact:

Technological failures leading to new types of maritime incidents.

Potential job displacement within the maritime sector due to automation.

High initial investment and maintenance costs for implementing automation technologies.

7 Conclusions

To identify the new modes and, hence, the main technologies aligned with low emissions and energy transportation modes to greening freight transport we developed network-based methods and network community detection algorithms to analyse the vast scientific literature on green logistics and transport decarbonisation technologies comprising the following transport modes: road, rail, maritime and cross-modal. One of the novel features of the research pursued is that it addressed an already identified gap in the literature regarding the integration of bibliographic coupling and semantic analysis into a single network graph to offer a novel perspective in network science and document analysis, going beyond the traditional literature review. This represents a step further in the analysis of big sets of documentation with varied scientific contributions to the research goals, and potentially replicable by other EU-funded projects. Two methodological scientific articles have already been developed, one

article was recently published in the Knowledge-Based System Journal (Elsevier Journal Impact Factor: 8.8) and another one was submitted to another Journal (under review).

The integrated methodology included, besides the knowledge discovery in databases and the network-based approach mentioned, a survey and semi-structured interviews, aiming to foster a new dialogue across worldwide companies across ADMIRAL pilots, to understand possible pathways for sustainable transport transitions towards Net Zero. Through this way we responded to the task 2.2 goal set in the Grant Agreement, through identifying current transport modes and the new modes arising at the macro and micro levels, considering the set of managerial experiences and through the support of a comprehensive review of technologies across the various transport modes applications: Alternative fuels, Energy Efficiency, Digitalization and Monitoring and Connectivity and Automated Systems. One conference paper proposal on “Sustainability Transition in Transport & Logistics for the Net Zero Emissions: Insights from Stakeholders” was accepted to the 21st International Conference on Transport Science (ICTS 2024). Considering the complexity of the logistics and transport socio-technical system, more information will be gathered during the execution of WP2 regarding other sustainability dimensions, namely through the planned Workshops/Webinars in task 2.1.

The semi-structured interviews conducted seem to point that Worldwide shipping companies attach a higher role on reduction of carbon emissions and energy efficiency improvements to current/future developments in digitalization and monitoring technologies across shipping and inland transport (in comparison to all other technology categories) and to alternative fuels (LNG, e-Methanol, biofuels).

New digital tools applied to inland transport can account for the problem of empty vehicles and devise sharing schemes (supported by new business models) for a more efficient use of cargo vehicles. Gaps in current planning tools may represent an additional opportunity for future development within the ADMIRAL marketplace. On the other hand, enhanced digital tools and communities may help to strengthen relationships and build trust among its members, fostering a culture of collective responsibility towards sustainability.

Road freight transport is the dominant mode across pilots in inland transportation logistics. However, options in the category of “Connectivity and automated systems” were never selected/mentioned by the companies/stakeholders. One common quote mentioned is that these would require significant investments in infrastructures that are not likely to happen until 2030 and beyond.

Companies/stakeholders at the micro (pilot) levels seems to attach a varying role for alternative fuels in shipping, electrification of the road fleet, eco-driving, and digital tools (optimisation tools across modes such as route optimisation, cargo load optimisation), shifting cargo from road to rail and intermodal transport, reflecting the different contexts. Most companies (except two cases) considered that the quantification of CO₂ emissions (direct and indirect emissions, including scope 3 emissions) along the entire supply chain is of key importance, responding that more knowledge and information is required to enable its calculation in the future. In the context of transport and logistics, the accurate calculation of CO₂ emissions is essential for developing strategies to reduce the environmental impact of transportation activities. Various modes of transport, including road, rail, sea, and air, contribute to the overall carbon footprint of the supply chain. Data availability and data integration represent common challenges to overcome.

The wide range of low energy and low energy technologies reviewed showed that each option has positive and less positive advantages that need to be accounted for the respective transport mode and supply chains. The literature suggests a strategic shift towards fuels with a lower carbon footprint, such as LNG and advanced biofuels, and an eventual transition to zero-carbon fuels like hydrogen and green ammonia. Each alternative fuel presents its own set of challenges, such as economic cost, technological readiness, and infrastructure requirements. The move towards renewable options is not only a response to environmental concerns but also a strategic shift to future-proof the industry against the volatility of fossil fuel markets and the tightening of global emissions regulations, which leads to more sustainable modes. For example, the maritime industry must consider the EU Emissions Trading Scheme (ETS) and IMO's emission reduction goals when adopting a mixed approach for new fuel technologies.

Digital platforms, along with smart technology in the context of container logistics represents a paradigm shift toward heightened efficiency and sustainability. Synergies to be explored have been found to be important amongst some companies interviewed. The integration of advanced tracking and tracing capabilities not only improves visibility and transparency throughout the supply chain but also significantly reduces the risk of lost or misplaced shipments.

The diagram of technologies across different transport modes developed aims to constitute a solutions domain - reference of transport modes/evolving technologies and related performance indicators. These comprise the relevant inputs for the impact assessment framework of solutions to be developed in WP 6 – “*Assessment of Solutions and Impact Assessment, task 6.1 Impact assessment framework, KPIs definition and prioritization*”. The sustainability impact cards outlined reveal further impacts/KPIs following the evidence found. The full list of KPIs covering the various impact categories, considering the evidence in the reviewed literature in chapters 3 and 5, is also presented in the Annex (8.3) to the present Deliverable as an important reference basis for task 6.1, as planned.

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8 Annex

8.1 WP2 Working Meetings

Regular Working Meetings online (via Teams) were organized by the LNEC WP2 Leader (WPL). Invitations were sent to all partners that filled the VTT form for WP2 activities. The attendance is shown following the Teams report for each working meeting (attendance.xls).

- 18.05.2023 Task 2.1 22 people
- 1.06.2023 Task 2.1 25 people
- 15.06.2023 Task 2.1 22 people
- 22.06.2023 Task 2.1 24 people
- 06.07.2023 Task 2.1 18 people
- 27.07.2023 Task 2.1 20 people
- 31.08.2023 Task 2.1 & Task 2.2 27 people
- 14.09.2023 Task 2.1 & Task 2.2 22 people
- 28.09.2023 Task 2.1 & Task 2.2 22 people

- 04.10.2023 (ADMIRAL Consortium Meeting, UL, Slovenia) - Presentation of WP2 (WPL)

- 9.11.2023 Idem 18 people
- 30.11.2023 Idem 20 people
- 14.12.2023 Idem 20 people
- 18.01.2024 Idem 20 people
- 01.02.2024 Task 2.1 & Task 2.2 & Kick-off task 2.3 22 people
- 22.02.2024 Idem 20 people
- 14.03.2024 (ADMIRAL Consortium Meeting, LNEC, Lisbon) – Presentation of draft D2.2 (WPL)
50 people (49 signed)

8.2 Semi-structured Interviews Guide

ADMIRAL WP2 • Task 2.2 Different transport modes and their sustainability now and in the future

Semi-structured interview model to adapt to each company/Pilot case

Semi-structured interviews are a qualitative research method that will allow us to explore the topic addressed in our survey in depth with the interviewee company, while following a flexible and adaptable guide of open-ended questions that relate to the research objectives of task 2.2. As such, other follow-up questions can be posed to each company and order can be slightly adapted in each part (transitioning from “now” to the “future”).

Instructions to be adapted

Thanks from us.

(APS) or (UPM) as promoter of the contact with (Company name) initiates the initial presentation of the ADMIRAL team.

(LNEC) Thank you for agreeing to participate in the interview. As part of the EU-funded ADMIRAL that seeks to develop and pilot AI-driven solutions for managing logistics supply chains, including related missions to reduce transport and logistics emissions and increase transparency, resilience of logistics supply chains, and stakeholder cooperation...we are now gathering views of large companies on the role of low carbon and energy efficient freight transport and logistics technology options (now and in the future) to enable carbon neutrality by 2050 as envisaged by the EU’s Green Deal, and achieve sustainability goals.

1 - Presentation of company (setting the scene)

- The company is asked to introduce itself (e.g., vision, main activities, market, interest in the multimodal corridor Sines-Madrid, etc.).

2 - How Sustainability is being addressed in your company & What are the main barriers/challenges that follow from experience (e.g. in sustainability reporting)?

- How sustainability issues (environmental, social, governance) are being addressed by your company? (in the interview we can start by mentioning for example, if sustainability is considered in the company vision or strategy and, if so, how? and if annual sustainability reporting is made?)
- Is your company aware of the European Corporate Sustainability Reporting Directive that entered in force in January 2023 that requires soon companies to report emissions along the whole supply chain, that is direct (scope 1) and indirect (scope 2 and 3) emissions.
- Do you foresee any barriers/challenges in implementing the European Corporate Sustainability Reporting Directive that entered in force in January 2023? OR Would you be interested in knowing the implications of this Directive for your business?
- More specifically... What barriers/challenges exist from your experience, for example regarding data sharing in logistics? and regarding estimation of CO2 emissions?

3 - (NOW) Role of Technology solutions to reduce carbon emissions/improve energy efficiency

- HOW important is transport technology to reduce CO₂ emissions/improve energy efficiency in comparison to other soft/non-technology measures? (examples are alternative fuels, electric vehicles, digital platforms to collaborate with other companies, etc.)
- WHAT type of measures/solutions have you company implemented recently to reduce carbon emissions and/or improve energy efficiency? [Screen outline from survey via Teams] & Which impacts of sustainability are to be tackled?

4 - (FUTURE) Solutions to address sustainability goals (such as the reduction of CO₂ emissions along the whole supply chain)

- WHAT type of measures/solutions would you like to implement until 2030 to address sustainability goals such as to reduce CO₂ emissions along supply chains and transport?
- HOW important is collaborative and digital logistics for your company? (e.g., innovative platforms for linking sellers and buyers of various logistic services as envisaged in ADMIRAL)
- From your experience, which measures [Screen list from survey] are likely to have a higher impact to decarbonize transport and supply chains from your perspective until 2030? Any effects of the cited measure(s) are foreseen on the social and governance dimensions?

5- (Linking with ADMIRAL ongoing and future activities)

If the company is not yet in the ADMIRAL Stakeholder Collaborative Forum, then the company is invited to join the ADMIRAL Stakeholder Forum to link with our project activities here:

<https://www.surveymonkey.com/r/ADMIRALProject>

- a) Invitation to the Workshop in the next ADMIRAL consortium meeting 14-15 March?
- b) Is your company interested in learning more about ADMIRAL subjects? [Screen list from survey e.g. Regulations affecting sustainability reporting such as the European Corporate Sustainability Reporting Directive, quantification of CO₂ emissions direct and indirect including scope 3, etc.]

8.3 List of KPIs found in the literature review

KPI	Measurement	Category	Units	Applicable Mode
Novel business models	Qualitative, Quantitative	Business	-	Road, Rail, Maritime
SMEs using the solutions/marketplace	Quantitative	Business	Count	Road, Rail, Maritime
Customer satisfaction	Quantitative	Business	Scale (1-5)	Road, Rail, Maritime
Connected logistics services	Quantitative	Business	Count	Road, Rail, Maritime
Modal shift efficiency improvement	Quantitative	Crossmodal	Percentage	Crossmodal
Intermodal connectivity efficiency	Quantitative	Crossmodal	Index	Crossmodal
Crossmodal freight transfer efficiency	Quantitative	Crossmodal	Hours/transfer	Crossmodal
Integrated multimodal transport system efficiency	Quantitative	Crossmodal	Index	Crossmodal
Reduction in energy cost	Quantitative	Economic	\$/km	Road, Rail, Maritime
Reduction in fuel cost per trip	Quantitative	Economic	\$/trip	Road, Rail, Maritime
Reduction in resources cost	Quantitative	Economic	\$	Road, Rail, Maritime
Percentage decrease in fuel consumption	Quantitative	Energy	%	Road, Rail, Maritime
Increase in miles per gallon (MPG)	Quantitative	Energy	mpg	Road, Rail, Maritime
Decrease in liters of fuel per 100 kilometers	Quantitative	Energy	l/100 km	Road, Rail, Maritime
Well-to-wheels energy consumption	Quantitative	Energy	MJ/km	Road
Tank-to-wheels energy consumption	Quantitative	Energy	MJ/km	Road
Energy efficiency in rail transport	Quantitative	Energy	MJ/tonne-km	Rail
Average locomotive fuel efficiency	Quantitative	Energy	gallons/mile	Rail
Reduction in emissions (GHG, NOx, SO2, CO2)	Quantitative	Energy Environmental	kg/km	Road, Rail, Maritime
Reduction in particulate matter (PM)	Quantitative	Energy Environmental	g/km	Road, Rail, Maritime
Reduction in air pollution	Quantitative	Energy Environmental	kg/km	Road, Rail, Maritime
Reduction in energy used	Quantitative	Energy Environmental	kWh/km	Road, Rail, Maritime
Noise Limit	Quantitative	Energy Environmental	dB	Road, Rail
Energy efficiency ratio	Quantitative	Energy Environmental	%	Road, Rail, Maritime
Climate Policy Integration	Qualitative	Energy Environmental	-	Road, Rail, Maritime
Reduction in CO2 emissions per ton-mile	Quantitative	Energy Environmental	g/ton-mile	Road, Rail, Maritime
Reduction in SO2 emissions per ton-kilometer	Quantitative	Energy Environmental	g/ton-km	Maritime
Reduction in VOC emissions per mile	Quantitative	Energy Environmental	g/mile	Road
Reduction in PM10 emissions per trip	Quantitative	Energy Environmental	g/trip	Road
Reduction in CO2 emissions due to implementation of EEDI	Quantitative	Energy Environmental	kg/km	Maritime
Reduction in CO2 emissions due to implementation of EEXI	Quantitative	Energy Environmental	kg/km	Maritime
Reduction in CO2 emissions per unit of transportation work (EEOI)	Quantitative	Energy Environmental	kg/capacity n	Maritime
Annual reduction factor in operational carbon intensity (CII)	Quantitative	Energy Environmental	Percentage	Maritime
Adoption of electric vehicles (EVs)	Quantitative	Energy Environmental	Count	Road, Rail
Usage of hybrid vehicles	Quantitative	Energy Environmental	Count	Road, Rail
Utilization of biofuels	Quantitative	Energy Environmental	%	Road, Rail, Maritime
Integration of regenerative braking systems	Quantitative	Energy Environmental	%	Road, Rail
Adoption of hydrogen fuel cells	Quantitative	Energy Environmental	Count	Road, Rail
Utilization of natural gas vehicles (NGVs)	Quantitative	Energy Environmental	%	Road, Rail
Increase in percentage of renewable energy usage	Quantitative	Energy Environmental	%	Road, Rail, Maritime
Implementation of carbon capture technology	Quantitative	Energy Environmental	Count	Road, Rail, Maritime
Reduction in air conditioning energy consumption	Quantitative	Energy Environmental	kWh/km	Road, Rail
Introduction of lightweight vehicle materials	Quantitative	Energy Environmental	%	Road, Rail, Maritime
Implementation of eco-driving training programs	Quantitative	Energy Environmental	%	Road, Rail
Adoption of aerodynamic vehicle designs	Quantitative	Energy Environmental	%	Road, Rail
Reduction in vehicle idling time	Quantitative	Energy Environmental	%	Road, Rail
Utilization of energy-efficient tires	Quantitative	Energy Environmental	%	Road, Rail
Implementation of low rolling resistance tires	Quantitative	Energy Environmental	%	Road, Rail
Increase in percentage of electric miles traveled	Quantitative	Energy Environmental	%	Road, Rail
Increase in the use of renewable energy sources for transportation	Quantitative	Energy Environmental	%	Road, Rail
Adoption of energy-efficient lighting systems in transportation facilities	Quantitative	Energy Environmental	%	Road, Rail
Introduction of energy-efficient HVAC systems in transportation hubs	Quantitative	Energy Environmental	%	Road, Rail
Utilization of passive solar design principles in transportation infrastructure	Quantitative	Energy Environmental	%	Road, Rail
Implementation of green building standards for transportation facilities	Quantitative	Energy Environmental	%	Road, Rail
Reduction in energy consumption during vehicle manufacturing processes	Quantitative	Energy Environmental	kWh/vehicle	Road, Rail
Increase in the use of recycled materials in vehicle production	Quantitative	Energy Environmental	%	Road, Rail
Adoption of closed-loop manufacturing systems for vehicle components	Quantitative	Energy Environmental	%	Road, Rail
Implementation of eco-friendly disposal methods for end-of-life vehicles	Quantitative	Energy Environmental	Count	Road, Rail
Utilization of carbon capture and storage (CCS) technology in transportation	Quantitative	Energy Environmental	Count	Road, Rail
Introduction of bio-based lubricants for vehicle maintenance	Quantitative	Energy Environmental	%	Road, Rail
Increase in energy recovery from transportation-related processes	Quantitative	Energy Environmental	%	Road, Rail
Adoption of efficient cargo handling systems at ports and terminals	Quantitative	Energy Environmental	Count	Maritime
Implementation of green procurement policies for transportation equipment	Quantitative	Energy Environmental	%	Road, Rail
Reduction in overall energy intensity of transportation systems	Quantitative	Energy Environmental	%	Road, Rail
Increase in energy productivity of transportation operations	Quantitative	Energy Environmental	%	Road, Rail
Utilization of energy-efficient traffic management systems	Quantitative	Energy Environmental	%	Road, Rail
Implementation of smart grid technology for electric transportation	Quantitative	Energy Environmental	Count	Road, Rail
Reduction in energy losses during electricity transmission for transportation	Quantitative	Energy Environmental	%	Road, Rail
Adoption of vehicle-to-grid (V2G) technology for energy storage	Quantitative	Energy Environmental	Count	Road, Rail

Introduction of demand response programs for transportation energy	Quantitative	Energy Environmental	%	Road, Rail
Increase in the use of energy-efficient heating systems for transportation	Quantitative	Energy Environmental	%	Road, Rail
Implementation of energy-efficient propulsion systems for ships	Quantitative	Energy Environmental	%	Maritime
Utilization of hybrid energy systems for remote transportation facilities	Quantitative	Energy Environmental	%	Road, Rail, Maritime
Adoption of energy-efficient practices for railway track maintenance	Quantitative	Energy Environmental	%	Rail
Implementation of regenerative braking systems for trains	Quantitative	Energy Environmental	%	Rail
Reduction in energy consumption during railway electrification	Quantitative	Energy Environmental	kWh/km	Rail
Increase in the use of energy-efficient signaling systems for railways	Quantitative	Energy Environmental	%	Rail
Utilization of energy-efficient lighting systems for transportation corridors	Quantitative	Energy Environmental	%	Road, Rail
Implementation of low-energy road construction techniques	Quantitative	Energy Environmental	%	Road
Adoption of energy-efficient tunnel ventilation systems	Quantitative	Energy Environmental	%	Road, Rail
Introduction of energy-efficient heating systems for transportation tunnels	Quantitative	Energy Environmental	%	Road, Rail
Increase in the use of energy-efficient cooling systems for transportation tunnels	Quantitative	Energy Environmental	%	Road, Rail
Utilization of energy-efficient conveyor systems for freight handling	Quantitative	Energy Environmental	%	Road, Rail
Increase in the use of energy-efficient lighting systems for transportation hubs	Quantitative	Energy Environmental	%	Road, Rail
Utilization of energy-efficient propulsion systems for marine vessels	Quantitative	Energy Environmental	%	Maritime
Implementation of waste heat recovery systems for transportation corridors	Quantitative	Energy Environmental	%	Road, Rail
Adoption of energy-efficient refrigeration systems for transportation hubs	Quantitative	Energy Environmental	%	Road, Rail
Introduction of energy-efficient loading and unloading procedures	Quantitative	Energy Environmental	%	Road, Rail
Increase in the use of energy-efficient packaging materials for transportation	Quantitative	Energy Environmental	%	Road, Rail
Utilization of energy-efficient vehicle maintenance practices	Quantitative	Energy Environmental	%	Road, Rail
Implementation of energy-efficient route planning algorithms	Quantitative	Energy Environmental	%	Road, Rail
Adoption of energy-efficient vehicle tracking systems	Quantitative	Energy Environmental	%	Road, Rail
Introduction of energy-efficient warehousing and storage practices	Quantitative	Energy Environmental	%	Road, Rail
Increase in the use of energy-efficient cold chain logistics for temperature-sensitive goods	Quantitative	Energy Environmental	%	Road, Rail
Utilization of energy-efficient intermodal transportation systems	Quantitative	Energy Environmental	%	Road, Rail
Implementation of energy-efficient freight forwarding practices	Quantitative	Energy Environmental	%	Road, Rail
Adoption of energy-efficient reverse logistics processes	Quantitative	Energy Environmental	%	Road, Rail
Introduction of energy-efficient vehicle sharing programs	Quantitative	Energy Environmental	%	Road, Rail
Well-to-wheels GHG emissions	Quantitative	Environmental	kgCO2e/km	Road
Tank-to-wheels GHG emissions	Quantitative	Environmental	kgCO2e/km	Road
GHG emissions per tonne-km	Quantitative	Environmental	kgCO2e/tonne-km	Road, Rail
Rail network electrification rate	Quantitative	Environmental	Percentage	Rail
Reduction in noise pollution level (dB)	Quantitative	Environmental	dB	Road, Rail
Reduction in water usage per vehicle	Quantitative	Environmental	l/vehicle	Road, Rail
Adoption of rainwater harvesting systems	Quantitative	Environmental	%	Road, Rail
Usage of sustainable materials in vehicle manufacturing	Quantitative	Environmental	%	Road, Rail
Reduction in packaging waste per shipment	Quantitative	Environmental	kg/shipment	Road, Rail
Introduction of recyclable packaging materials	Quantitative	Environmental	%	Road, Rail
Increase in percentage of recycled vehicle components	Quantitative	Environmental	%	Road, Rail
Implementation of eco-friendly cleaning products	Quantitative	Environmental	%	Road, Rail
Reduction in paper usage through digitalization	Quantitative	Environmental	%	Road, Rail
Introduction of vehicle recycling programs	Quantitative	Environmental	Count	Road, Rail
Decrease in land use for transportation facilities	Quantitative	Environmental	m ²	Road, Rail
Adoption of sustainable land use practices	Quantitative	Environmental	%	Road, Rail
Enhancement in water quality preservation efforts	Quantitative	Environmental	%	Road, Rail
Reduction in deforestation associated with transportation activities	Quantitative	Environmental	%	Road, Rail
Implementation of wildlife conservation measures	Quantitative	Environmental	Count	Road, Rail
Reduction in habitat fragmentation due to transportation infrastructure	Quantitative	Environmental	%	Road, Rail
Reduction in water usage per vehicle	Quantitative	Environmental	liters/vehicle	Road, Rail
Modal split	Quantitative	Operational	%	Road, Rail, Maritime
Empty vehicle km	Quantitative	Operational	km	Road, Rail, Maritime
Unit cost of delivery	Quantitative	Operational	\$/delivery	Road, Rail, Maritime
Load factor	Quantitative	Operational	%	Road, Rail, Maritime
Loss and damage (e.g., parcels)	Qualitative, Quantitative	Operational	Count	Road, Rail, Maritime
Overall supply chain optimization	Quantitative	Operational	%	Road, Rail, Maritime
Increase in energy efficiency of transportation hubs	Quantitative	Operational	%	Road, Rail
Reduction in turnaround time at transportation hubs	Quantitative	Operational	minutes	Road, Rail
Implementation of route optimization algorithms	Quantitative	Operational	-	Road, Rail
Increase in vehicle tracking accuracy	Quantitative	Operational	%	Road, Rail
Reduction in time spent in traffic congestion	Quantitative	Operational	minutes	Road, Rail
Adoption of alternative transport routes	Quantitative	Operational	Count	Road, Rail
Utilization of multi-modal transportation systems	Quantitative	Operational	-	Road, Rail

Enhancement in last-mile delivery efficiency	Quantitative	Operational	%	Road, Rail
Reduction in delivery lead times	Quantitative	Operational	minutes	Road, Rail
Implementation of just-in-time delivery systems	Quantitative	Operational	-	Road, Rail
Increase in vehicle loading efficiency	Quantitative	Operational	%	Road, Rail
Utilization of vehicle platooning technology	Quantitative	Operational	-	Road, Rail
Reduction in delivery vehicle dwell time	Quantitative	Operational	minutes	Road, Rail
Improvement in on-time delivery performance	Quantitative	Operational	%	Road, Rail
Implementation of dynamic routing algorithms	Quantitative	Operational	-	Road, Rail
Adoption of blockchain technology in supply chain	Quantitative	Operational	-	Road, Rail
Utilization of warehouse automation systems	Quantitative	Operational	-	Road, Rail
Reduction in inventory holding costs	Quantitative	Operational	%	Road, Rail
Improvement in order accuracy	Quantitative	Operational	%	Road, Rail
Increase in inventory turnover rate	Quantitative	Operational	%	Road, Rail
Number of new production jobs created	Quantitative, forecasting	Societal	Jobs/year	Road, Rail, Maritime
Number of new assembly jobs created	Quantitative, forecasting	Societal	Jobs/year	Road, Rail, Maritime
Number of jobs lost due to lower manning requirements	Quantitative, forecasting	Societal	Jobs/year	Road, Rail, Maritime
Number of accidents or incidents	Quantitative	Societal	Count	Road, Rail, Maritime
Accessibility	Qualitative	Societal	Scale (1-5)	Road, Rail, Maritime
Reduction in transportation-related accidents	Quantitative	Societal	Count	Road, Rail
Improvement in driver safety training programs	Quantitative	Societal	%	Road, Rail
Reduction in transportation-related fatalities	Quantitative	Societal	Count	Road, Rail
Enhancement in transportation infrastructure accessibility	Quantitative	Societal	-	Road, Rail
Increase in transportation infrastructure resilience	Quantitative	Societal	%	Road, Rail
Implementation of transportation equity measures	Quantitative	Societal	-	Road, Rail
Reduction in transportation-related social inequities	Quantitative	Societal	-	Road, Rail
Reduction in transportation-related health issues	Quantitative	Societal	%	Road, Rail
Adoption of fair pricing policies for transportation	Quantitative	Societal	-	Road, Rail
Implementation of transportation data privacy measures	Quantitative	Societal	-	Road, Rail
Improvement in transportation system reliability	Quantitative	Societal	%	Road, Rail
Increase in transportation system transparency	Quantitative	Societal	%	Road, Rail
Reduction in transportation-related noise pollution	Quantitative	Societal	dB	Road, Rail
Implementation of community engagement programs	Quantitative	Societal	Count	Road, Rail
Enhancement in transportation disaster preparedness	Quantitative	Societal	%	Road, Rail
Increase in transportation-related economic opportunities	Quantitative	Societal	%	Road, Rail
Reduction in transportation-related carbon footprint	Quantitative	Societal	kg/km	Road, Rail
Implementation of transportation-related cultural preservation prog	Quantitative	Societal	Count	Road, Rail
Enhancement in transportation-related emergency response capabili	Quantitative	Societal	%	Road, Rail
Increase in transportation-related educational initiatives	Quantitative	Societal	%	Road, Rail
Document digitalization	Quantitative	Technological	GB/year	Road, Rail, Maritime
Technology Readiness Level (TRL)	Qualitative	Technological	Scale (1-9)	Road, Rail, Maritime
Introduction of electric vehicle charging stations	Quantitative	Technological	Count	Road
Implementation of predictive maintenance systems	Quantitative	Technological	%	Road, Rail, Maritime
Development of autonomous vehicle technology	Qualitative	Technological	-	Road, Rail
Increase in vehicle telematics utilization	Quantitative	Technological	%	Road, Rail, Maritime
Enhancement in vehicle-to-vehicle communication	Quantitative	Technological	%	Road, Rail
Expansion of vehicle electrification infrastructure	Quantitative	Technological	Count	Road, Rail
Adoption of alternative propulsion technologies	Qualitative	Technological	-	Road, Rail
Internet of Things (IoT) devices deployed	Quantitative	Technological	Count	Road, Rail, Maritime
Implementation of blockchain technology	Qualitative	Technological	-	Road, Rail, Maritime
Utilization of artificial intelligence (AI) algorithms	Quantitative	Technological	%	Road, Rail, Maritime
Integration of machine learning systems	Quantitative	Technological	%	Road, Rail, Maritime
Adoption of augmented reality (AR) applications	Quantitative	Technological	Count	Road, Rail, Maritime
Implementation of virtual reality (VR) training programs	Quantitative	Technological	Count	Road, Rail, Maritime
Utilization of digital twin technology	Quantitative	Technological	Count	Road, Rail, Maritime
Deployment of smart sensors	Quantitative	Technological	Count	Road, Rail, Maritime
Increase in cybersecurity measures	Quantitative	Technological	%	Road, Rail, Maritime
Implementation of cloud computing solutions	Quantitative	Technological	%	Road, Rail, Maritime
Development of mobile applications	Quantitative	Technological	Count	Road, Rail, Maritime
Utilization of big data analytics	Quantitative	Technological	%	Road, Rail, Maritime
Adoption of geospatial technology	Quantitative	Technological	%	Road, Rail, Maritime
Integration of autonomous navigation systems	Quantitative	Technological	%	Road, Rail, Maritime
Deployment of predictive maintenance software	Quantitative	Technological	Count	Road, Rail, Maritime
Utilization of 3D printing technology	Quantitative	Technological	Count	Road, Rail, Maritime
Implementation of supply chain management software	Quantitative	Technological	%	Road, Rail, Maritime
Adoption of electronic logging devices (ELDs)	Quantitative	Technological	Count	Road, Rail
Integration of vehicle tracking systems	Quantitative	Technological	Count	Road, Rail, Maritime
Implementation of automated ticketing systems	Quantitative	Technological	Count	Rail, Maritime
Utilization of digital freight brokerage platforms	Quantitative	Technological	Count	Road, Rail, Maritime
Deployment of electronic proof of delivery systems	Quantitative	Technological	Count	Road, Rail, Maritime
Integration of electronic payment systems	Quantitative	Technological	Count	Road, Rail, Maritime