

University of Strathclyde

Department of Naval Architecture, Ocean, and Marine Engineering

Forecasting and Time-Resolved Life Cycle Assessment for Maritime Decarbonization

by

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Signed:

Ioannis Chalaris

Date:

17 September 2026

This thesis is lovingly dedicated to my grandfather, Michalis, and to my beloved dog,

Giselle.

*Though neither of you is here to witness this moment, I like to believe that you are
watching over me. I hope that, in some small way, I have made you proud...*

Abstract

Maritime transport is central to global trade but remains heavily dependent on carbon-intensive fuels, creating significant environmental, regulatory, and strategic challenges for decarbonization. This thesis develops and applies a maritime life cycle assessment (LCA) framework integrating Well-to-Wake (WTW) emissions accounting, Holt–Winters forecasting, scenario analysis, regulatory interpretation, and operational activity data to evaluate alternative marine fuel pathways under future demand, regulatory, and operational uncertainty.

The framework is demonstrated through two case studies at different decision scales. The first assesses the Singapore–Rotterdam containership green corridor using a representative containership with a capacity of 8,000 twenty-foot equivalent units (TEU) and compares marine diesel oil (MDO), bio-methanol, and e-methanol under future demand and regulatory scenarios. Forecasting-oriented LCA links lifecycle emissions with projected transport demand, FuelEU Maritime requirements, and European Union Emissions Trading System (EU ETS) exposure. The results show that renewable e-methanol provides the strongest lifecycle performance among the assessed corridor pathways, although outcomes depend strongly on electricity source, production pathway, and infrastructure assumptions.

The second case study applies an Automatic Identification System (AIS)-based, time-resolved port-based life cycle assessment (Port-LCA) framework to seven container-vessel trajectories within a 20-nautical-mile (NM) boundary around the Port of Busan. MDO, natural-gas-derived methanol, e-methanol, natural-gas-derived ammonia, and e-ammonia

are compared by linking vessel movement, propulsion demand, fuel consumption, and WTW emissions. The analysis reveals vessel-level variability and short-duration emission peaks that may be obscured by aggregated inventories.

Overall, the thesis demonstrates that forecasting and time-resolved operational analysis can increase the decision relevance of maritime LCA. Fuel-production pathways are more influential than fuel labels alone, while future activity growth may offset improvements in emissions intensity. The framework is intended for comparative and strategic decision support rather than deterministic forecasting or official emissions inventories.

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Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
AIS	Automatic Identification System
AMR	Amsterdam Metropolitan Region
ANN	Artificial Neural Network
AP	Acidification Potential
ARIMA	Autoregressive Integrated Moving Average
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CEAS	Computerised Engine Application System
CI	Carbon Intensity
CIH	Carbon Intensity Indicator
CML	Centrum voor Milieukunde Leiden
COP	Conference of the Parties
DAC	Direct Air Capture
DNV	Det Norske Veritas
DWT	Deadweight Tonnage
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EP	Eutrophication Potential
ETS	Emissions Trading System
EU	European Union
EU ETS	European Union Emissions Trading System
FT	Fischer–Tropsch
GDP	Gross Domestic Product
GFI	Greenhouse Gas Fuel Intensity
GHG	Greenhouse Gas
GPS	Global Positioning System
GWP	Global Warming Potential
GWP20	Global Warming Potential over a 20-year Time Horizon
GWP100	Global Warming Potential over a 100-year Time Horizon
HFO	Heavy Fuel Oil

Abbreviation	Definition
HPSCR	High-Pressure Selective Catalytic Reduction
HSFO	High-Sulphur Fuel Oil
HVO	Hydrotreated Vegetable Oil
IAM	Integrated Assessment Model
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEAP	Long-range Energy Alternatives Planning System
LFO	Light Fuel Oil
LGIM	Liquid Gas Injection Methanol
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MAE	Mean Absolute Error
MAN	Maschinenfabrik Augsburg-Nürnberg
MASE	Mean Absolute Scaled Error
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MMSI	Maritime Mobile Service Identity
MSW	Municipal Solid Waste
NM	Nautical Mile
NO_x	Nitrogen Oxides
NZF	Net-Zero Framework
OPEX	Operating Expenditure
OPS	Onshore Power Supply

Abbreviation	Definition
PM	Particulate Matter
PM_{2.5}	Particulate Matter with an Aerodynamic Diameter of 2.5 µm or Less
POCP	Photochemical Ozone Creation Potential
Port-LCA	Port-based Life Cycle Assessment
PV	Photovoltaic
RFNBO	Renewable Fuel of Non-Biological Origin
RMSE	Root Mean Square Error
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
SGC	Specific Gas Consumption
SMAPE	Symmetric Mean Absolute Percentage Error
SMCR	Specified Maximum Continuous Rating
SO_x	Sulphur Oxides
SPOC	Specific Pilot Oil Consumption
SSP	Shared Socioeconomic Pathway
TEU	Twenty-foot Equivalent Unit
TTW	Tank-to-Wake
ULSFO	Ultra-Low-Sulphur Fuel Oil
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention on Climate Change
VLSFO	Very Low-Sulphur Fuel Oil
WTT	Well-to-Tank
WTW	Well-to-Wake

Nomenclature

Latin Symbols and Variables

Symbol	Description	Unit
A	Activity level or activity data	Context-dependent
C	Capacity or compliance balance	TEU, MJ, or context-dependent
CI	Carbon intensity	g CO ₂ -eq/MJ
D	Distance travelled	nautical miles or km
d	Distance between consecutive AIS positions	nautical miles or km
E	Emissions	kg or t CO ₂ -eq
E_i	Emission of greenhouse gas species i	kg or t
E_{TTW}	Tank-to-Wake emissions	kg or t CO ₂ -eq
E_{WTT}	Well-to-Tank emissions	kg or t CO ₂ -eq
E_{WTW}	Well-to-Wake emissions	kg or t CO ₂ -eq
EF	Emission factor	kg emission/kg fuel or g CO ₂ -eq/MJ
$EF_{i,f}$	Emission factor of species i for fuel pathway f	kg or t emission per unit of fuel
FC	Fuel consumption	kg or t
FC_t	Fuel consumption during time interval t	kg
GFI	Greenhouse gas fuel intensity	g CO ₂ -eq/MJ
GDP	Gross domestic product	constant currency units
I	Impact result	kg CO ₂ -eq or impact-category unit
IF_i	Impact factor for species i	dimensionless or kg CO ₂ -eq/kg emission
LHV	Lower heating value	MJ/kg
m	Fuel mass	kg or t

Symbol	Description	Unit
N	Number of vessels or observations	dimensionless
N_v	Capacity-equivalent number of vessels	vessels
P	Engine power	kW
P_{MCR}	Maximum continuous rating power	kW
P_t	Estimated propulsion power at time t	kW
r	Pearson correlation coefficient	dimensionless
$SFOC$	Specific fuel oil consumption	g/kWh
SGC	Specific gas consumption	g/kWh
$SPOC$	Specific pilot oil consumption	g/kWh
t	Time or residence time	s, min, or h
TEU	Container throughput or vessel capacity	TEU
V	Vessel speed	kn
V_{ref}	Reference or service speed	kn
x, y	Observed or model variables	Context-dependent
$\hat{y}$	Predicted value	Same unit as the response variable

Greek Symbols and Statistical Parameters

Symbol	Description	Unit
α	Level smoothing parameter in Holt–Winters forecasting	dimensionless
β	Trend smoothing parameter or regression coefficient	dimensionless or context-dependent
γ	Seasonal smoothing parameter	dimensionless
Δt	Time interval between consecutive AIS observations	s, min, or h
Δd	Distance travelled during a time interval	nautical miles or km
η	Efficiency	dimensionless or %
μ	Mean value	Same unit as the variable

Symbol	Description	Unit
σ	Standard deviation	Same unit as the variable
ε	Error or residual term	Same unit as the response variable
ρ	Density or correlation parameter, depending on context	kg/m ³ or dimensionless

Subscripts and Superscripts

Subscript or Superscript	Definition
<i>aux</i>	Auxiliary engine or auxiliary system
<i>bio</i>	Biomass-derived pathway
<i>e</i>	Electrofuel pathway
<i>f</i>	Fuel or fuel pathway
<i>i</i>	Greenhouse gas species, observation, or process index
<i>j</i>	Vessel, scenario, or secondary index
<i>ME</i>	Main engine
<i>MCR</i>	Maximum continuous rating condition
<i>NG</i>	Natural-gas-based production pathway
<i>obs</i>	Observed value
<i>pred</i>	Predicted value
<i>PV</i>	Solar photovoltaic pathway
<i>ref</i>	Reference value
<i>t</i>	Time step
<i>TTW</i>	Tank-to-Wake stage
<i>WTT</i>	Well-to-Tank stage
<i>WTW</i>	Well-to-Wake total

Chemical Symbols

Symbol	Definition
CH ₄	Methane
CO	Carbon monoxide
CO ₂	Carbon dioxide
CO ₂ -eq	Carbon dioxide equivalent
H ₂	Hydrogen
NH ₃	Ammonia
N ₂ O	Nitrous oxide
NO _x	Nitrogen oxides
O ₂	Oxygen
SO _x	Sulphur oxides

Units

Unit	Definition
°	Degree
°C	Degree Celsius
g	Gram
g CO ₂ -eq/MJ	Grams of carbon dioxide equivalent per megajoule
g/kWh	Grams per kilowatt-hour
h	Hour
kg	Kilogram
kg CO ₂ -eq	Kilograms of carbon dioxide equivalent
km	Kilometre
kn	Knot
kW	Kilowatt
kWh	Kilowatt-hour
m	Metre
m ³	Cubic metre
min	Minute
MJ	Megajoule
NM	Nautical mile
s	Second
t	Tonne
t CO ₂ -eq/year	Tonnes of carbon dioxide equivalent per year
TEU	Twenty-foot equivalent unit
%	Per cent

1 Introduction

This chapter establishes the context, motivation, and research direction of the thesis. It introduces the regulatory and environmental challenges associated with maritime decarbonization, the role of alternative marine fuel pathways and lifecycle assessment, and the need to account for both future demand and vessel-specific operational conditions. The chapter then identifies the research gap addressed by the thesis, clarifies the principal methodological contribution and the relationship between the two analytical scales, presents the research questions, and concludes by outlining the structure of the thesis.

1.1 Background and Regulatory Context

Maritime transport is a crucial element of the global economy, facilitating the movement of goods within international supply chains. The sector accounts for the majority of global trade by volume, with recent studies indicating that approximately 80–90% of world trade relies on maritime transport (Robalo-Cabrera et al., 2025). Shipping is considered an efficient mode of freight transport; however, its extensive scale contributes significantly to greenhouse gas (GHG) emissions, representing approximately 2.5–3% of global CO₂ or GHG emissions (Zhang et al., 2025). The decarbonization of shipping has emerged as a significant environmental, regulatory, and strategic priority.

The challenge is exacerbated by the anticipated increase in maritime activity. In the absence of further mitigation measures, shipping emissions are likely to rise alongside the growth of global trade and transport demand (Kanchiralla et al., 2026). This is especially pertinent to container shipping, which is intricately linked to long-distance trade routes,

significant ports, and global supply chains. Lu et al. (2023) emphasize that container shipping constitutes a significant portion of maritime emissions, with trade growth continuing to be a primary factor in the increase of emissions. Maritime decarbonization should not be viewed solely as a matter of fuel substitution; it also necessitates an examination of future demand, operational activities, infrastructure, and regulatory developments.

International regulation has become a pivotal factor in the maritime energy transition. The International Maritime Organization (IMO) updated its GHG strategy in 2023, establishing indicative targets for reducing total GHG emissions from international shipping by a minimum of 20% by 2030 and 70% by 2040, relative to 2008 levels, to achieve net-zero GHG emissions by approximately 2050 (IMO, 2021a; Kanchiralla et al., 2026). Recent regulatory developments emphasize greenhouse gas fuel intensity and Well-to-Wake (WTW) accounting, suggesting that future compliance will rely on both emissions produced onboard ships and the lifecycle performance of marine fuels (Zincir, 2026).

The direction of IMO regulation is increasingly moving from general emissions-reduction ambition toward fuel-intensity-based compliance. The emerging IMO Greenhouse Gas Fuel Intensity (GFI) framework links compliance to the annual GHG intensity of energy used by ships, expressed on a WTW basis, and introduces a comparison between attained and target fuel-intensity values (Zincir, 2026). This development is important because it connects fuel choice, lifecycle emissions, operational energy use, and compliance exposure within a single regulatory logic. Consequently, shipowners and operators will need assessment tools that can evaluate not only whether a fuel reduces onboard emissions, but

also whether its full lifecycle performance remains compatible with future fuel-intensity requirements.

Regional policies are transforming the methods by which shipping companies evaluate emissions and compliance risks. The integration of maritime transport into the European Union Emissions Trading System (EU ETS) has established carbon pricing for shipping. Concurrently, FuelEU Maritime mandates incremental reductions in the lifecycle GHG intensity of energy utilized on ships (Lloyd's Register, 2024). These measures establish new responsibilities for shipowners, operators, and charterers, encompassing emissions monitoring, allowance surrendering, reporting, verification, fuel-intensity assessment, and penalty management. Consequently, maritime decarbonization is increasingly associated with financial risk, operational planning, fuel procurement, and long-term investment decisions.

Table 1-1. Key regulatory drivers motivating lifecycle and future-oriented maritime emissions assessment.

Regulatory driver	Main relevance to this thesis	Assessment implication
IMO GHG Strategy	Establishes long-term decarbonization direction towards net-zero GHG emissions	Requires assessment of long-term emissions pathways
IMO GFI framework	Links compliance with GHG fuel intensity on a WTW basis	Requires lifecycle fuel-intensity assessment
FuelEU Maritime	Reduces lifecycle GHG intensity of energy used onboard ships	Requires WTW comparison of fuel pathways
EU ETS	Introduces carbon-pricing exposure for maritime emissions	Requires emissions and cost-exposure assessment
Port and local environmental regulation	Increases attention to emissions near ports and populated areas	Requires spatially and operationally informed emissions assessment

Source: Compiled by the author based on the IMO GHG Strategy, IMO lifecycle GHG guidance, FuelEU Maritime and EU ETS regulatory frameworks discussed in Section 1.1.

A variety of technical and operational measures are under consideration in response to these pressures. These encompass alternative marine fuels, energy-efficiency technologies, hull optimization, power management, slow steaming, voyage optimization, monitoring systems, shore power, wind assistance, and onboard carbon capture (DNV, 2025; Robalo-Cabrera et al., 2025). Nonetheless, the variety of vessel types, routes, operational profiles, and infrastructure conditions indicates that a singular solution cannot be presumed to decarbonize the entire sector. DNV (2025) highlights that the decarbonization of shipping necessitates a portfolio approach, wherein low-GHG fuels, energy-efficiency measures, onboard carbon capture, and digital optimization serve as complementary pathways.

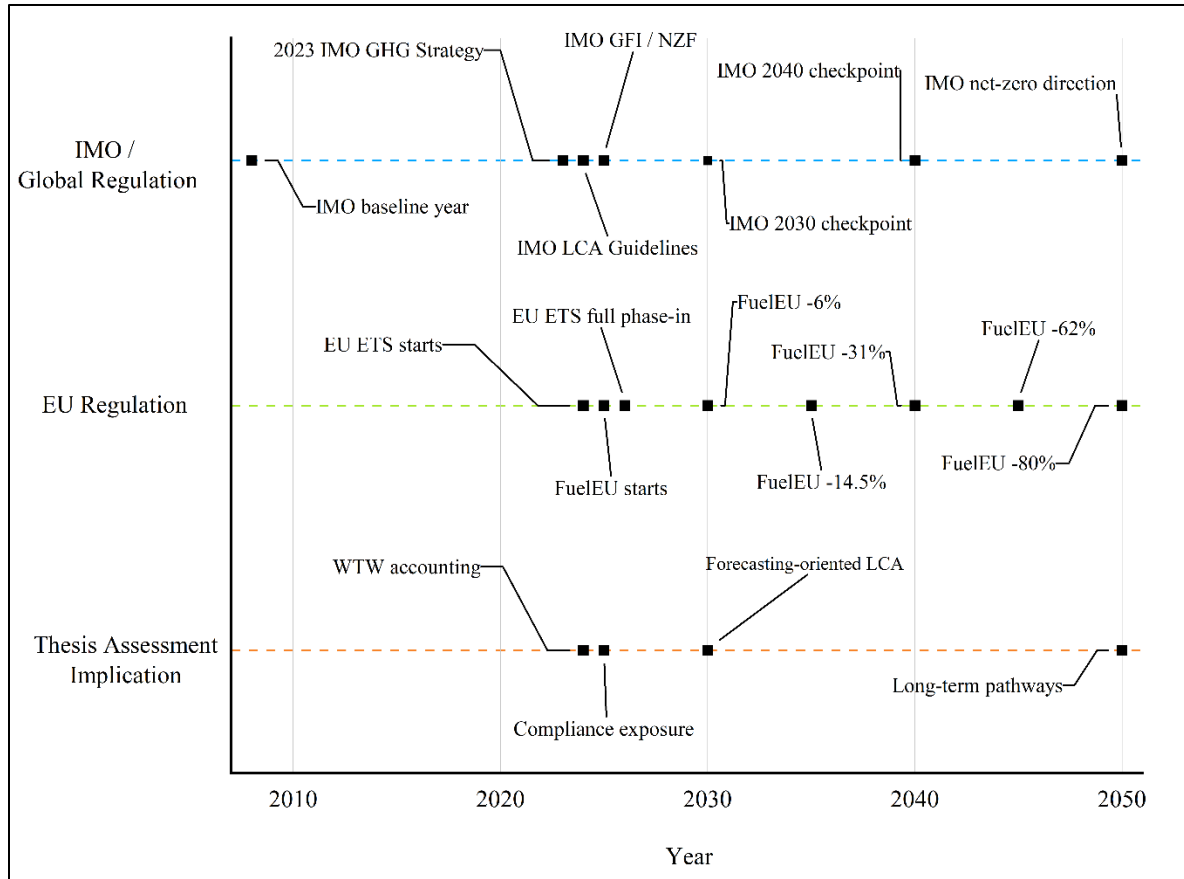


Figure 1-1. Key maritime decarbonization milestones and their implications for lifecycle-based emissions assessment. The timeline summarizes relevant IMO and EU regulatory developments from 2008 to 2050 and links them to the need for WTW accounting, compliance-exposure assessment, forecasting-oriented LCA, and long-term pathway evaluation.

Adapted by the author from IMO (2023, 2024, 2025), Regulation (EU) 2023/1805, and European Commission guidance.

This regulatory and technical context necessitates the development of more integrated assessment methods. Conventional fuel comparisons offer valuable screening information; however, they are inadequate for assessing the performance of maritime decarbonization pathways in the context of future demand growth, changing regulations, lifecycle emissions boundaries, and actual operational conditions. This thesis is situated within this issue. It examines the integration of LCA with forecasting, scenario analysis, regulatory interpretation, and operational activity data to enhance the evaluation of maritime decarbonization pathways.

1.2 Alternative Marine Fuels

Alternative marine fuels play a crucial role in addressing the maritime decarbonization challenge, as future compliance will increasingly rely on the GHG intensity of energy utilized onboard vessels. However, transitioning from conventional fossil fuels involves more than merely substituting one fuel for another. It raises questions regarding lifecycle, regulation, infrastructure, and investment. Fuels including methanol, ammonia, hydrogen, biofuels, synthetic fuels, and transitional fossil-based alternatives can aid in decarbonization; however, their effectiveness is contingent upon the methods of production, supply, storage, onboard usage, and evaluation under forthcoming emissions regulations.

This underscores the necessity for alternative fuel assessment to extend beyond Tank-to-Wake (TTW) emissions exclusively. A fuel may seem advantageous when evaluating onboard emissions; however, its climate benefits may vary when accounting for upstream production, feedstock supply, electricity source, fuel transport, storage, and distribution. The WTW perspective is essential as it integrates Well-to-Tank (WTT) and TTW emissions, providing a comprehensive representation of the climate impact of a marine fuel pathway (IMO, 2024).

The primary concern is not merely identifying the optimal alternative fuel but rather determining the conditions under which a fuel pathway can facilitate decarbonization. The same fuel type can result in varying lifecycle emissions based on its production method, whether derived from fossil sources, bio-based processes, or renewable electricity-based routes. Consequently, fuel selection ought to be regarded as a pathway decision rather than

merely a fuel-type decision. This distinction is becoming increasingly significant as maritime regulation shifts towards compliance frameworks based on fuel intensity and lifecycle considerations.

This thesis adopts a lifecycle perspective. It employs LCA to analyze specific marine fuel pathways within established system boundaries and regulatory frameworks. This section aims to elucidate the necessity of evaluating fuel selection through a WTW and future-oriented framework, rather than to offer an exhaustive review of alternative marine fuels, which is detailed in Chapter 2. This establishes the basis for the subsequent case studies presented in the thesis: the Singapore–Rotterdam green corridor and the Port of Busan.

1.3 Dynamic Emissions Assessment

The regulatory transition outlined presents a significant methodological challenge for the shipping industry. Assessment of compliance with future maritime decarbonization requirements cannot rely solely on current fuel comparisons or fixed emissions factors. Shipowners, ports, fuel suppliers, and policymakers must comprehend the potential evolution of emissions and compliance exposure in light of tightening regulations, shifting transport demand, and the maturation of alternative fuel pathways.

This is significant as the environmental performance of a fuel pathway is variable. The outcome is contingent upon the fuel-production route, the carbon intensity of the energy utilized in fuel production, the efficiency of onboard conversion, vessel operating conditions, and the scale of future maritime activities. A fuel can decrease emissions intensity; however, total emissions may still rise if demand growth results in increased vessel activity, greater fuel consumption, or additional port calls. Thus, an effective

assessment framework should analyze both emissions intensity and absolute emissions over time.

A further limitation of static assessment is its tendency to oversimplify vessel operation. Emissions are influenced by factors such as speed, engine load, maneuvering, low-load operation, duration spent in port approaches, and the parameters defining the measurement boundaries of emissions. Operational factors are particularly significant in proximity to ports, as vessel emissions can affect local air quality. Additionally, port authorities require spatially explicit information to enhance emissions management and infrastructure planning. Automatic Identification System (AIS)-derived vessel activity data can effectively address this issue by correlating emissions estimates with observed vessel movement, rather than depending solely on average operational assumptions.

Forecasting and scenario analysis are essential elements of maritime decarbonization assessment. Forecasting enables the linkage of historical activity indicators, including trade, gross domestic product (GDP), cargo demand, and port throughput, to prospective emissions scenarios. Scenario analysis facilitates the transparent comparison of alternative assumptions regarding demand growth, fuel pathways, regulatory exposure, and operating conditions. This approach does not yield a definitive prediction of the future; instead, it offers a systematic method for examining how various potential futures may influence emissions and compliance results.

This thesis employs a dynamic perspective to address this issue. It combines LCA with forecasting, scenario analysis, and operational data derived from AIS to examine the potential evolution of maritime emissions and compliance exposure under future regulatory

and operational conditions. The objective is to compare fuels and to analyze the performance of alternative fuel pathways in the context of future demand growth, lifecycle boundaries, vessel activity, and regulatory pressure. The thesis directly addresses the necessity of investigating and preparing for the impacts of IMO, FuelEU Maritime, EU ETS, and broader environmental regulations on the shipping industry.

1.4 Research Gap and Thesis Response

The preceding sections indicate that the primary concern is not merely the availability of alternative marine fuels, but rather the shipping industry's capacity to evaluate their implications under forthcoming regulatory and operational conditions. Environmental regulations, including the IMO GHG strategy, FuelEU Maritime, and the EU ETS, are altering the framework for measuring, reporting, pricing, and reducing maritime emissions (Lloyd's Register, 2024). Simultaneously, the growing implementation of WTW assessment necessitates that fuel selections be analyzed not only in terms of onboard combustion but also throughout the entire lifecycle of fuel production, supply, and utilization (IMO, 2024).

The research gap identified in this thesis pertains to the necessity for a more cohesive approach to maritime emissions assessment. Numerous fuel comparisons serve to identify potential low-carbon alternatives; however, their utility may be constrained when regarded as static evaluations. They may not adequately reflect the variations in emissions outcomes resulting from future transport demand, regulatory targets, port activity, vessel operations, or uncertainty. This represents a significant limitation, as decisions regarding maritime decarbonization are inherently long-term in nature. Planning for fuel infrastructure, vessel

investment, bunkering systems, and compliance strategies is essential before a complete understanding of future regulatory impacts.

A gap persists between strategic fuel assessment and operational emissions assessment. Green-corridor planning necessitates a comprehensive analysis of fuel pathways, demand growth, lifecycle emissions, and regulatory exposure over an extended timeframe. Decarbonization of ports necessitates a comprehensive understanding of vessel operations, including activity levels, speed, engine load, duration within designated boundaries, and emissions in proximity to the port. These two decision scales are interrelated; however, they are frequently evaluated independently. A more effective assessment approach should thus connect lifecycle fuel performance with anticipated demand and operational activities.

This thesis addresses this gap by developing and applying an LCA framework that integrates forecasting and time-resolved operational analysis for maritime decarbonization. The framework integrates WTW emissions accounting, demand forecasting, scenario analysis, regulatory interpretation, and operational activity data. It aims to advance from a static comparison of fuel alternatives to an evaluation of the performance of alternative fuel pathways under prospective maritime conditions.

The thesis employs this framework via two case studies. The initial case study analyzes the Singapore–Rotterdam containership green corridor, emphasizing future demand, alternative fuel pathways, lifecycle emissions, and regulatory implications under FuelEU Maritime and the EU ETS. The second case study analyzes the Port of Busan, utilizing AIS-derived vessel activity to estimate time-resolved port-boundary emissions and to investigate the potential impact of future port activity on lifecycle emissions across various

fuel pathways. Together, these case studies enable the thesis to explore the maritime sector's assessment and preparation for the impacts of decarbonization regulations in greater depth.

The primary originality of this thesis resides in the integration and adaptation of established analytical techniques into a cohesive framework for assessing maritime decarbonization, rather than in the creation of the individual techniques themselves. LCA and WTW emissions accounting, Holt–Winters forecasting, scenario analysis, regression methods, and AIS-based vessel activity analysis represent established methodologies. The methodological contribution of this research lies in its structured integration within a maritime-specific framework that connects fuel-production pathways, future transport demand, regulatory exposure, and vessel-specific operational activity. This integration is executed at two complementary decision scales: a forecasting-oriented LCA approach for long-term evaluation of green corridors and an AIS-based, time-resolved Port-LCA approach for assessing operational emissions within a specified port boundary. The originality lies in the methodological framework, integration, and maritime application of these techniques to facilitate strategic and operational decarbonization decisions.

The integration of corridor-scale forecasting and port-boundary operational analysis within a unified doctoral framework is essential, as maritime decarbonization decisions are made at various interconnected spatial and temporal scales. The green-corridor perspective examines the strategic issue of the performance of alternative fuel pathways over time, considering the evolution of transport demand, regulation, and fleet requirements. The port-boundary perspective examines the operational performance of fuel pathways in

relation to vessel-specific activities, encompassing variations in speed, engine load, operating time, and movement within a designated area. The two scales are linked by a shared analytical framework that includes WTW lifecycle accounting, fuel-pathway comparison, activity-dependent emissions estimation, and scenario-based evaluation of future maritime demand. They are not regarded as identical analyzes or directly compared through a common numerical output; instead, they offer complementary evidence on the same decarbonization issue, connecting long-term strategic planning with operational emissions performance.

1.5 Research Questions

Building upon the research gap identified in Section 1.4, this thesis is guided by the following fundamental research question:

How can forecasting and time-resolved LCA enhance the evaluation of alternative marine fuel pathways for maritime decarbonization across green-corridor and port-boundary scales?

This fundamental question is addressed through the following supporting research questions:

RQ1: How can forecasting be integrated with LCA to evaluate the WTW emissions, regulatory exposure, and compliance-cost implications of alternative marine fuel pathways under future demand scenarios at the green-corridor scale?

RQ2: How can AIS-derived vessel activity data be integrated with LCA to quantify time-resolved WTW emissions from alternative marine fuel pathways within a defined port boundary?

RQ3: What methodological, practical, and policy insights emerge from applying forecasting and time-resolved LCA at green-corridor and port-boundary scales?

1.6 Thesis Structure

This thesis comprises eight chapters. Chapter 1 presents the regulatory and environmental framework surrounding maritime decarbonization, delineates the significance of alternative marine fuels and LCA, and elucidates the necessity for forecasting and time-resolved emissions evaluation. It delineates the primary research gap, articulates the research questions that emerge from this gap, and outlines the thesis structure.

Chapter 2 presents a comprehensive review of the relevant literature. It analyzes maritime decarbonization regulations, alternative marine fuels, LCA methodologies, WTW emissions accounting, green corridor development, port emission assessments, AIS-based emissions modeling, and relevant forecasting methods in shipping. This chapter lays the academic and technical groundwork for the research gap addressed in the thesis.

Chapter 3 outlines the primary research question, the research aims and objectives, as well as the comprehensive research design. The study progresses from the literature review and methodological development to two case-study applications, followed by an integrated discussion and conclusions.

Chapter 4 outlines the methodological framework employed in the thesis. The framework encompasses the definition of goals and scope, selection of lifecycle boundaries, representation of activities based on AIS, modeling of propulsion and fuel consumption, accounting for WTW emissions, forecasting, scenario analysis, and comparative interpretation. This establishes the methodological basis for the two case studies.

Chapter 5 utilizes the framework to analyze the green corridor between Singapore and Rotterdam for containerships. This case study analyzes the pathways of diesel, bio-methanol, and e-methanol in the context of future demand and regulatory scenarios. It assesses lifecycle emissions, alignment with FuelEU Maritime, exposure to the EU ETS, and the significance of forecasting-oriented LCA in the evaluation of long-term corridor decarbonization.

Chapter 6 utilizes the framework in the context of the Port of Busan. This case study develops an AIS-based Port-LCA application for specific container-vessel trajectories within a defined port boundary area. It assesses marine diesel oil (MDO), methanol, e-methanol, ammonia, and e-ammonia pathways and examines the influence of vessel activity, fuel pathway, operational variability, and future port demand on lifecycle emissions.

Chapter 7 presents a comprehensive analysis of the thesis findings. It analyzes the two case studies and examines the broader implications of transitioning from static fuel comparison to dynamic assessments of maritime decarbonization. The chapter analyzes the findings concerning fuel pathways, future demand, operational activities, uncertainty, policy implications, industry decision-making, and transferability.

Chapter 8 serves as the conclusion of the thesis. It summarizes the primary findings, elucidates the original contribution to knowledge, delineates the practical and policy implications, addresses the overall limitations of the research, and offers recommendations for future work. Together, the chapters demonstrate how forecasting-oriented and operationally informed lifecycle assessment can enhance the evaluation of maritime decarbonization pathways.

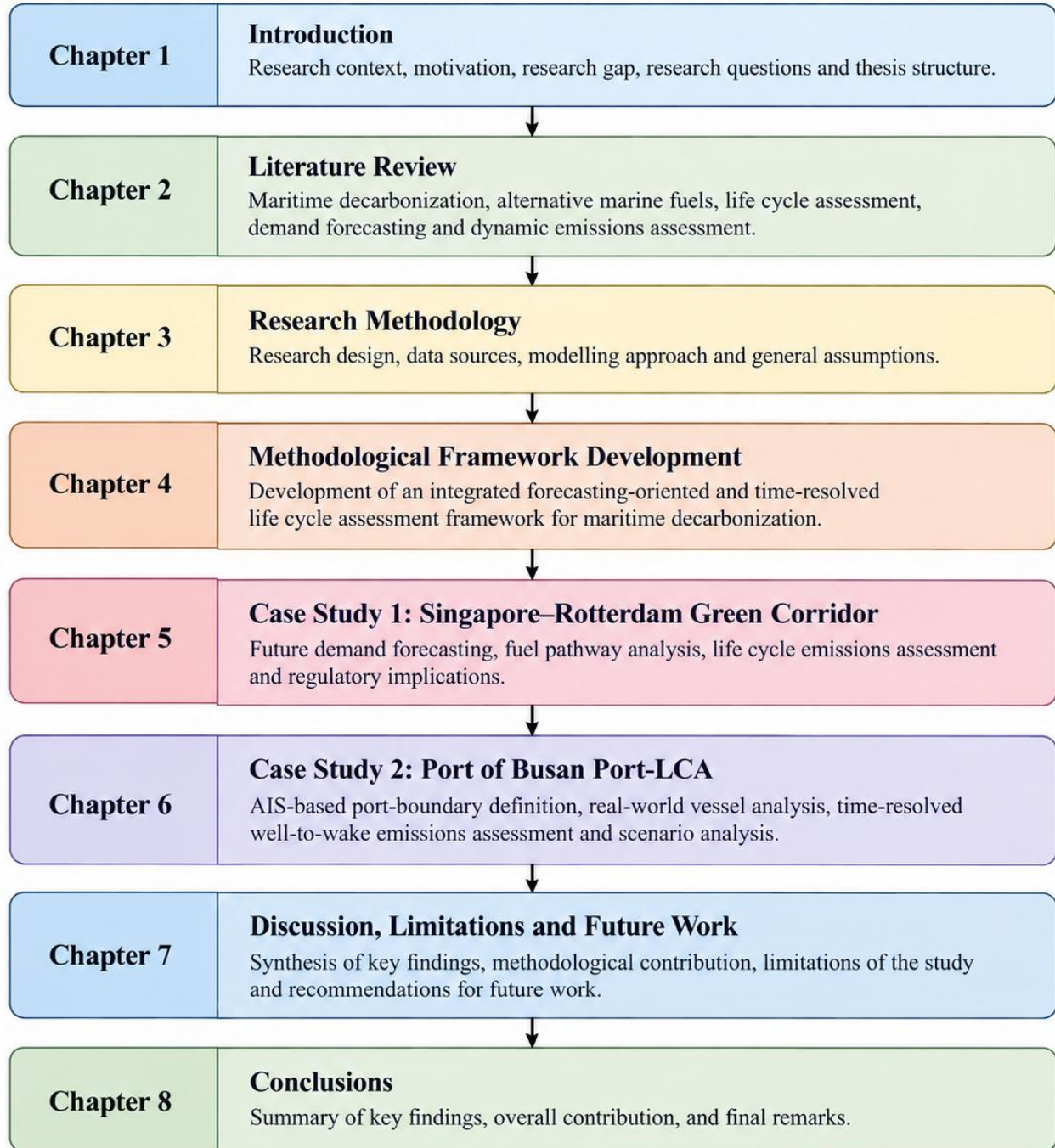


Figure 1-2. Graphical representation of the thesis structure.

1.7 Closing Remarks

The principal points established in this chapter can be summarised as follows:

- Maritime decarbonization requires assessment beyond static or TTW-only fuel comparisons, as the performance of alternative fuel pathways depends on lifecycle emissions, future activity, regulatory conditions, and vessel operation.
- The research gap addressed by this thesis lies in the limited integration of long-term strategic fuel assessment with time-resolved operational emissions assessment within maritime LCA. Green-corridor planning requires consideration of future demand and regulatory exposure, whereas port decarbonization requires greater resolution of vessel-specific operational activity.
- The principal originality of the thesis lies in the integration and maritime-specific adaptation of established LCA, WTW accounting, forecasting, scenario-analysis, regulatory, and AIS-based techniques within a unified assessment framework, rather than in the invention of the individual analytical techniques.
- The corridor and port-boundary analyses represent complementary rather than competing analytical scales. Corridor-scale forecasting supports long-term fuel, fleet, infrastructure, and regulatory planning, while port-boundary analysis captures vessel-specific and time-resolved operational emissions. They are connected through a common WTW fuel-pathway, activity-dependent emissions, and future-demand assessment logic and are not intended for direct numerical comparison. This complementarity is also reflected later in the thesis discussion.

- Accordingly, the thesis investigates how forecasting-oriented and time-resolved LCA can improve the evaluation of alternative marine fuel pathways at both strategic and operational decision scales, as formalized through the fundamental and supporting research questions presented in this chapter.

2 Literature Review of Life Cycle Assessment for Maritime Decarbonization

This chapter provides a critical review of the literature supporting the advancement of improved LCA methodologies for maritime decarbonization. This review encompasses 71 selected references, comprising peer-reviewed journal articles and international standards, addressing both general LCA theory and maritime-specific applications. The literature reviewed was chosen to illustrate the progression of LCA from its conceptual and standardized origins to more sophisticated applications and integrations, including alternative marine fuels, ship systems, uncertainty analysis, life cycle costing, prospective modeling, near real-time data, and artificial intelligence. The publication distribution indicates that the review is predominantly grounded in recent literature, with 71.83% of the reviewed papers published between 2020 and 2026. This underscores the contemporary relevance of the topic and the growing research interest in maritime LCA and decarbonization assessment.

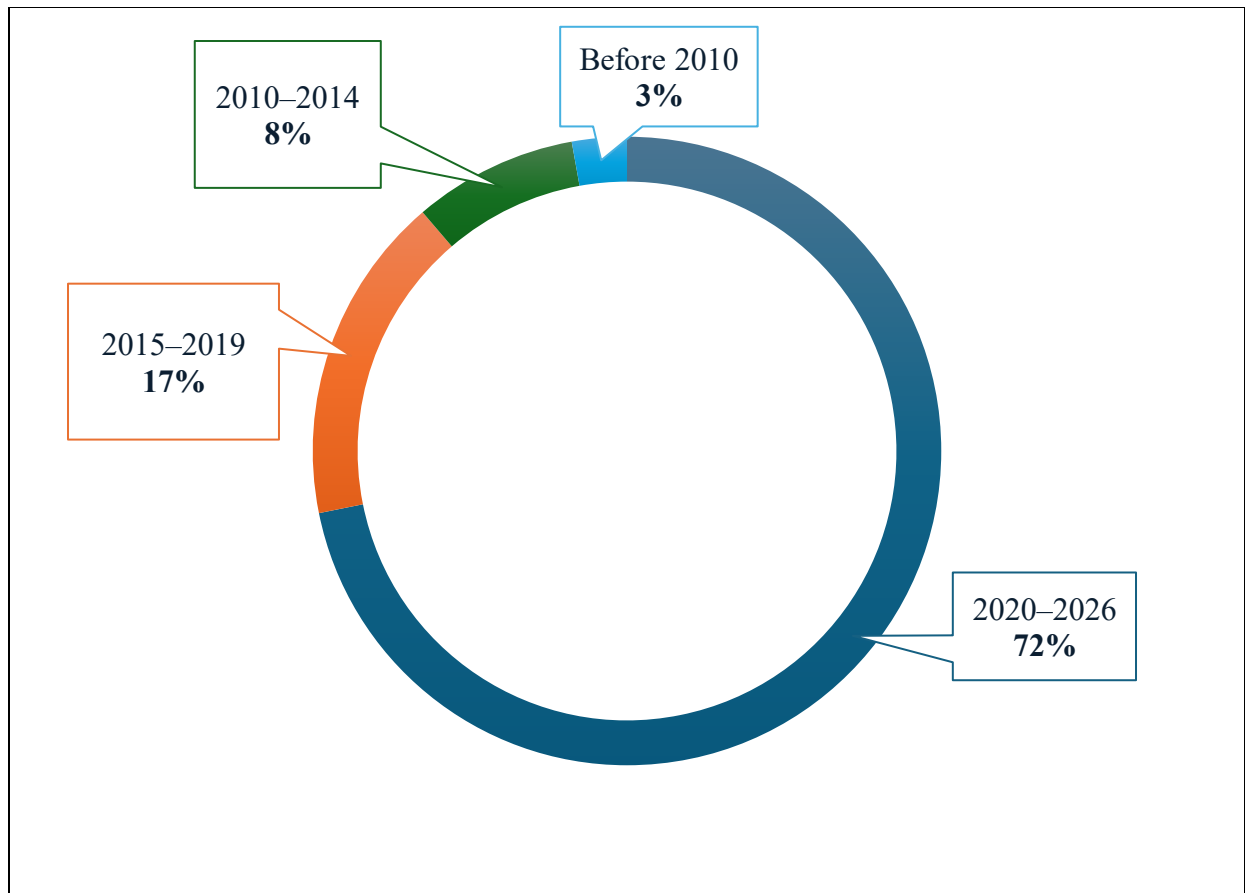


Figure 2-1. Distribution of reviewed literature by publication period.

This chapter is organized to construct a coherent critical argument instead of presenting the literature as a series of isolated studies. The review initiates with the conceptual foundations of LCA, encompassing its standardized procedures, historical development, system boundaries, functional units, and critical modeling choices. The reliability of maritime LCA is significantly influenced by the definitions and applications of these methodological elements. The review transitions from general LCA theory to its applications in the maritime sector, focusing on ship systems, propulsion technologies, retrofitting options, operational emissions, vessel activity modeling, and port-related applications. This outlines the contributions of LCA to maritime environmental

assessment, while also highlighting limitations related to case-specific assumptions, simplified operational profiles, and inconsistent boundaries. The chapter subsequently examines marine fuel pathways, encompassing conventional fuels, liquefied natural gas (LNG), biofuels, hydrogen, ammonia, methanol, e-fuels, and green corridor applications. It emphasizes that fuel performance assessment must extend beyond onboard emissions because upstream production, energy sources, infrastructure, scalability, and future fuel availability significantly influence overall carbon performance. Finally, the review analyzes the extensions of LCA through complementary methodologies, such as life cycle costing, multi-criteria decision support, uncertainty and sensitivity analysis, prospective and forecast-based modeling, and time-resolved or data-driven assessment. This chapter outlines the primary methodological and scope limitations of current maritime studies and highlights the necessity for improved LCA models that can connect life cycle fuel performance with vessel activity, future fuel and energy pathways, regulatory changes, and effective decarbonization decision-making.

2.1 Literature Search and Screening Methodology

The literature review was performed as a structured critical review instead of a formal systematic review. The objective was to delineate the current methodological advancements in maritime LCA, identify shortcomings in existing methodologies, and furnish the foundational evidence for the methodological advancements and case study selection conducted in this thesis. No single bibliographic database was utilized as the sole source. Relevant literature was identified through iterative topic-based scholarly searches, reference tracing, and examination of publications concerning maritime decarbonization, alternative marine fuels, forecasting-oriented assessment, vessel operational analysis, and related developments in LCA methodology.

The literature search encompassed publications from 2006 to 2026. Earlier sources from this period were retained for their foundational methodological contributions, particularly the ISO standards governing LCA. However, greater emphasis was placed on recent research that reflects advancements in maritime decarbonization, alternative marine fuels, prospective assessment, uncertainty analysis, and data-driven emissions modeling. The final critical review corpus included 71 sources from 28 journals and other reputable publications. Among these, 52 sources were published between 2020 and 2026, accounting for 73.24% of the literature reviewed.

Literature identification was directed by combinations of keywords related to the main themes of the thesis. Included terms pertain to maritime life cycle assessment, shipping, WTW emissions, alternative marine fuels, bio-methanol, e-methanol, ammonia, e-ammonia, automatic identification systems, vessel activity, port emissions, forecasting,

transport demand, green corridors, FuelEU Maritime, EU emissions trading system, uncertainty, and sensitivity analysis. Boolean operators, including AND and OR, were employed to integrate related concepts and adjust the scope of searches as necessary. Representative search logic encompassed combinations such as ("maritime" OR "shipping") AND ("life cycle assessment" OR "LCA"), ("alternative fuels" OR "decarbonization" OR "emissions") AND ("forecasting" OR "scenario analysis" OR "future demand"), and ("AIS" OR "port" OR "operational analysis") AND ("emissions" OR "life cycle assessment"). These combinations functioned as adaptable search structures instead of a singular fixed search string.

The screening process was carried out in a progressive manner. Publications were evaluated based on their title, abstract, and relevance to the research scope. Subsequently, potentially relevant studies were analyzed in depth to evaluate their methodological contributions and relevance to the thesis. Studies were included if they focused on maritime decarbonization, lifecycle or emissions assessment, alternative marine fuels, prospective or forecast-based assessment, operational vessel analysis, AIS-derived activity, uncertainty, sensitivity, or other methodological advancements applicable to the proposed framework. Eligible materials included peer-reviewed research and review articles, international standards, and authoritative technical or regulatory publications. A limited number of non-maritime studies were retained for their methodological approaches applicable to maritime LCA, including prospective, dynamic, real-time, artificial-intelligence-assisted, or uncertainty-based assessments.

Publications were excluded if they were duplicates or unrelated to the research scope, lacked a significant connection to lifecycle or emissions assessment, provided inadequate methodological detail for critical evaluation, or did not present a transferable methodological contribution. The review prioritized methodological relevance, transparency, and applicability over conducting a comprehensive systematic search of all publications related to shipping emissions.

The literature identification, screening, eligibility, and selection procedure is summarized in Figure 2-2.

Following this process, 71 sources were retained for detailed critical appraisal. Each source was assessed according to its research objective, methodological framework, principal findings, contribution, novelty, limitations, publication source, and publication year. The complete critical-review matrix is provided in Appendix APPENDIX C ensuring traceability between the reviewed evidence.

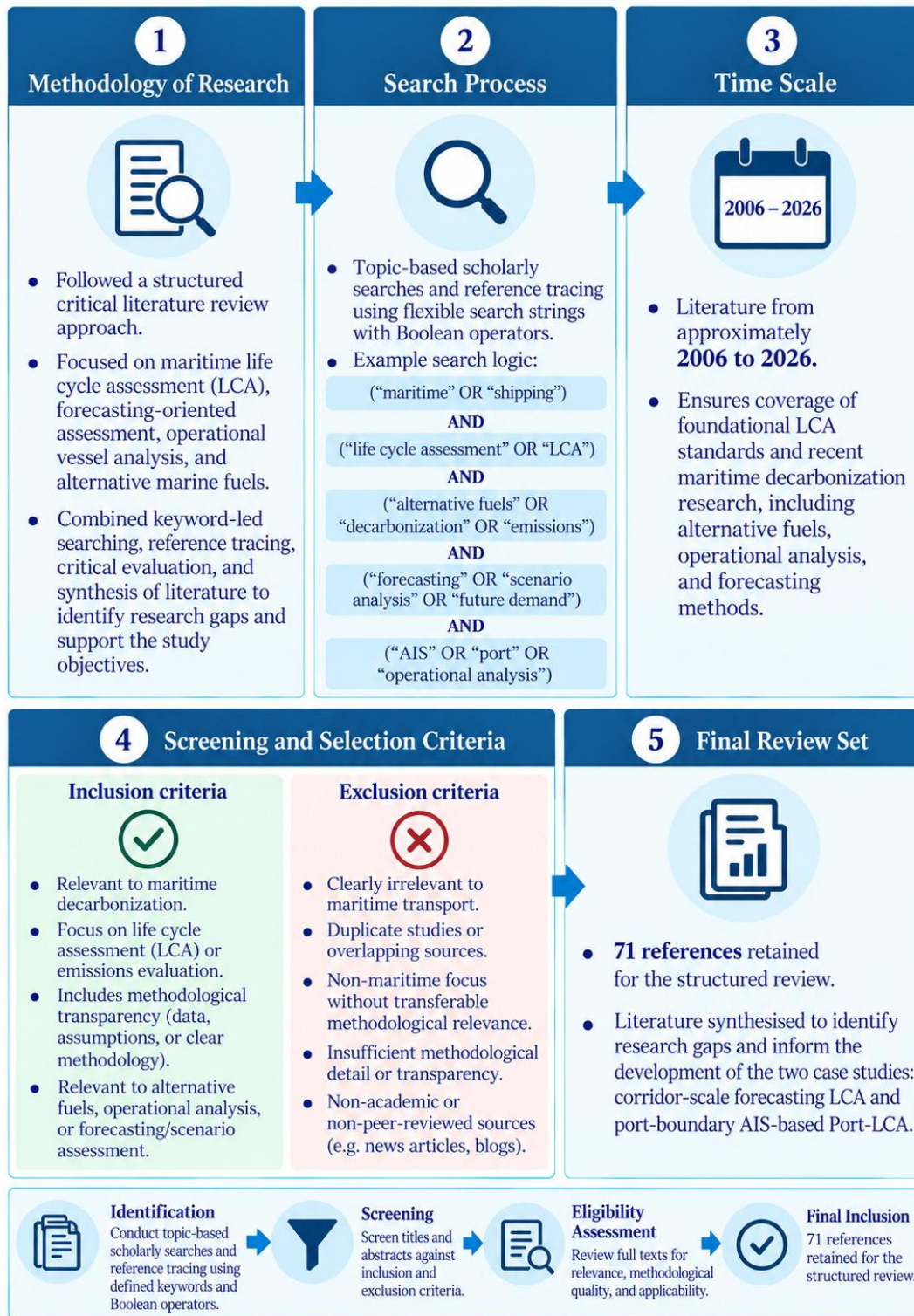


Figure 2-2. Structured critical literature review methodology, including search logic, time scale, screening criteria, and final literature selection.

2.2 Conceptual Foundations and Methodological Evolution

LCA is a structured approach for assessing the environmental characteristics and potential effects linked to a product, process, system, or service over its entire life cycle. The primary advantage is its capacity to evaluate environmental impacts across interconnected life cycle stages, rather than concentrating solely on a single phase of production or operation. The life cycle perspective is crucial as environmental enhancements in one phase may result in heightened burdens in another, thereby posing the risk of burden shifting.

The advancement of LCA has been motivated by the necessity for enhanced environmental decision-making processes. Previous environmental assessments primarily concentrated on direct emissions, energy consumption, or specific pollutants. In contrast, LCA offers a comprehensive framework for analyzing various environmental impacts throughout the entire system. LCA is particularly pertinent for sectors experiencing technological transitions, as new solutions may lower operational emissions while simultaneously increasing upstream impacts related to fuel production, electricity generation, material extraction, infrastructure needs, or end-of-life processes (Guinée et al., 2011; Hauschild et al., 2017).

In recent years, LCA has advanced beyond traditional static applications, as conventional LCA is constrained in its capacity to account for temporal variation, future technological change, operational variability, and decision-making uncertainty. Several methodological advancements have been implemented to overcome these limitations. Dynamic LCA enhances temporal representation by accounting for the timing of emissions; however, it may not adequately reflect future fuel demand, regulatory changes, or variations in vessel-

specific operations (Levasseur et al., 2010). Prospective LCA facilitates the evaluation of emerging technologies within future contextual frameworks. Nonetheless, the outcomes are significantly influenced by scenario assumptions, projections of technology maturity, and the uncertainties inherent in future energy systems (Sacchi et al., 2022). Hybrid LCA enhances system completeness by integrating process-based inventories with input-output methodologies; however, it may depend on aggregated economic data that are less appropriate for specific maritime applications (Miah et al., 2017). Integrated, data-driven, and time-resolved LCA approaches enhance decision support and operational accuracy by connecting environmental assessments with economic, digital, or activity-based data. Nonetheless, these methods are constrained by issues related to data availability, validation requirements, temporal resolution, and the difficulty of linking operational data with comprehensive life cycle inventories (Vyrkou et al., 2025). These limitations are crucial for maritime decarbonization, as fuel pathways, vessel operations, energy systems, infrastructure, and regulations are evolving concurrently. Existing LCA developments offer significant methodological foundations; however, they do not adequately fulfill the requirement for a maritime-specific LCA model that can connect life cycle fuel performance with time-resolved vessel activity and future carbon-performance forecasting. This gap underscores the need for the current thesis, which advances improved LCA methodologies utilizing time-resolved and forecast-based simulations for alternative marine fuels. The methodological characteristics and limitations of these LCA developments are examined in the subsequent sections of this chapter.

2.2.1 Definition, Principles, and System Boundaries of LCA

According to the International Organization for Standardization (ISO), LCA is defined as the systematic assessment of the inputs, outputs, and possible environmental effects of a product system over its entire life cycle. This definition emphasizes three critical components of the method: quantifying material and energy flows, assessing environmental impacts, and considering the complete life cycle of the system being analyzed. The product life cycle comprises sequential and interconnected stages, starting with the acquisition or generation of raw materials from natural resources and concluding with final disposal (ISO, 2006a).

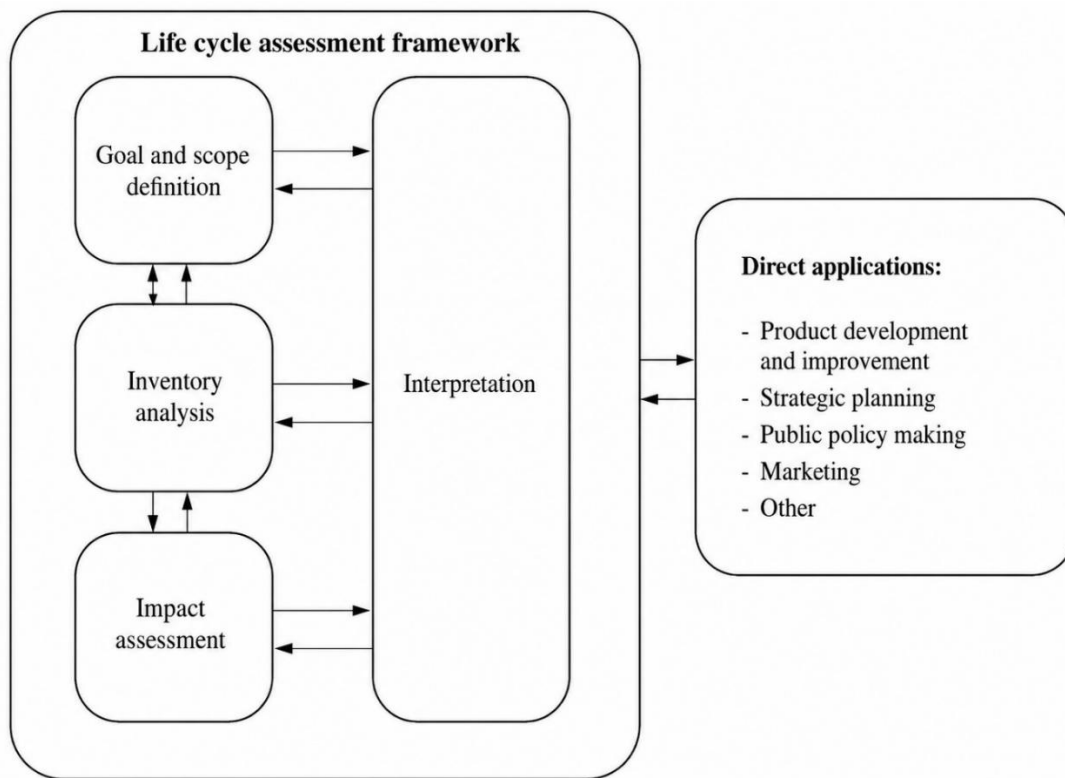


Figure 2-3. Life cycle assessment framework (ISO, 2006b)

The ISO framework delineates four primary phases of LCA: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. The goal and scope phase delineates the study's purpose, intended application, target audience, functional unit, system boundaries, assumptions, limitations, and data requirements. The life cycle inventory phase measures the pertinent inputs and outputs of the product system. The life cycle impact assessment phase assesses the potential environmental significance of inventory flows, whereas the interpretation phase analyzes the results in relation to the defined goals and scope to formulate conclusions and recommendations (ISO, 2006b).

The life cycle perspective is a fundamental principle of LCA. This indicates that environmental impacts are evaluated throughout the entire system rather than at a singular point of use. ISO 14040 highlights that this viewpoint aids in recognizing and preventing the transfer of potential environmental burdens across life cycle stages or specific processes (ISO, 2006a). This is especially significant when evaluating low-carbon or alternative technologies, as decreases in direct emissions may be counterbalanced by heightened upstream impacts from production, processing, transportation, or infrastructure.

A key principle is the application of a functional unit. LCA serves as a relative assessment method, indicating that all inputs, outputs, and impact results are associated with a specified function of the system (ISO, 2006a, 2006b). The functional unit facilitates the comparison of various systems based on identical services or performance metrics. This principle is particularly significant in maritime studies due to the substantial variations in fuel pathways, vessel technologies, and operational profiles. In the absence of a clearly

defined functional unit and consistent system boundary, comparisons among fuels or technologies may yield misleading results.

The definition of system boundaries is a critical methodological step in the LCA. ISO 14044 delineates the system boundary as the criteria that determine the inclusion of specific unit processes within the product system (ISO, 2006b). Boundaries in a study may be delineated as cradle-to-grave, cradle-to-gate, well-to-tank, tank-to-wake, or well-to-wake, depending on the study's objective. The well-to-wake boundary is critical in maritime fuel assessment as it encompasses both upstream fuel production and onboard fuel consumption. The expanded boundary is essential to ensure that alternative fuels are assessed not only on their operational emissions but also on emissions resulting from production, transport, and energy inputs.

The ISO standards emphasize the significance of transparency, consistency, sensitivity analysis, and critical review (ISO, 2006a). ISO 14044 indicates that comparisons between LCA studies are valid only when the assumptions and contexts of each study are consistent (ISO, 2006b). However, the application of LCA remains non-prescriptive. The outcome of an LCA study is significantly influenced by the methodological decisions of the practitioner. The reliability and comparability of LCA results hinge on both the standardized methodology and the transparency and consistency of the underlying assumptions. This represents a significant aspect of maritime LCA, as studies frequently vary in terms of system boundaries, fuel pathway assumptions, emission factors, operational profiles, and impact assessment methodologies.

2.2.2 Historical Development of Life Cycle Assessment

The origins of LCA can be identified in early research conducted during the 1960s and 1970s, which focused on the energy and material demands of consumer products. The initial studies primarily focused on resource utilization, energy consumption, and comparative environmental performance. It became evident that numerous environmental impacts extend beyond the use phase of a product, occurring also during production, transportation, and disposal. This acknowledgment facilitated the advancement of a more comprehensive life cycle perspective, which subsequently became formalized as LCA (Guinée et al., 2011).

In the 1980s and 1990s, LCA evolved from a limited focus on energy and resource accounting to a more comprehensive environmental assessment methodology. The growing interest in product and technology comparison has led to the establishment of methodological principles, databases, impact assessment methods, and reporting guidelines. The formalization of LCA within the ISO 14040 series enhanced its credibility and established a standardized framework for practitioners (ISO, 2006a, 2006b).

The scope of LCA has progressively broadened since its standardization. Previous applications frequently focused on a limited set of environmental indicators, including cumulative energy demand and solid waste generation. Recent applications have expanded LCA to encompass a wider range of impact categories, such as climate change, acidification, eutrophication, toxicity, biodiversity, and resource depletion. Concurrently, LCA has become increasingly associated with economic and social dimensions, resulting

in the development of broader concepts such as life cycle sustainability assessment (Hauschild et al., 2017).

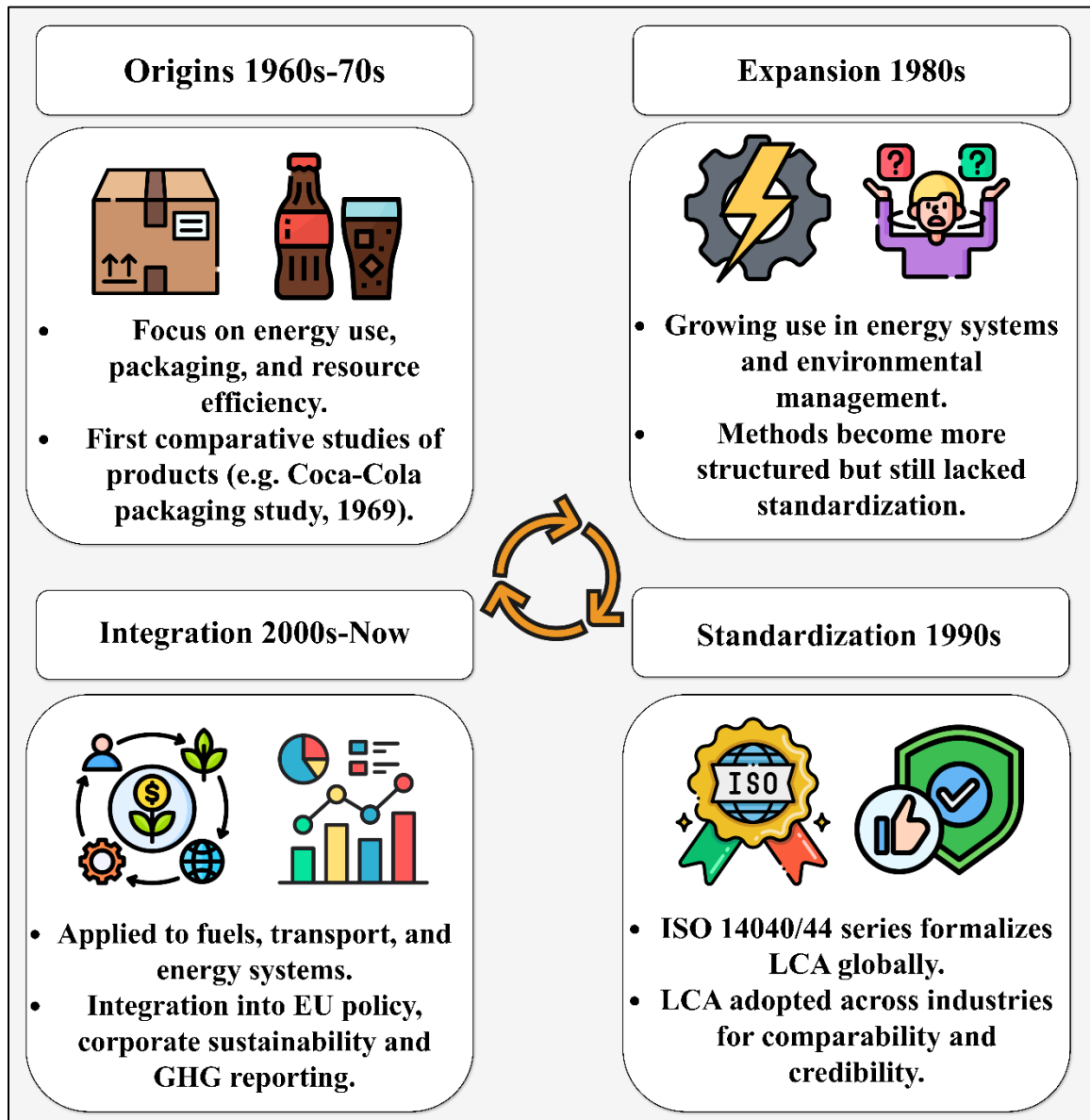


Figure 2-4. Historical evolution of LCA from early resource-efficiency studies to standardized and policy-integrated application.

Guinée et al. (2011) characterize this development as a shift from LCA as an environmental evaluation tool to life cycle sustainability analysis, positioning LCA within a broader transdisciplinary framework for tackling sustainability issues. This evolution indicates an

increasing necessity to assess environmental impacts alongside economic, social, technological, and policy implications of product systems and emerging technologies.

Recent reviews indicate that LCA has progressed in various directions, including dynamic LCA, hybrid LCA, social LCA, life cycle costing, and integration with digital and data-driven methodologies (M. Liu et al., 2024; Vyrkou et al., 2025). Traditional LCA encounters several limitations, including issues with functional unit definition, system boundary selection, impact assessment methods, data quality, temporal and spatial representation, and the evaluation of technologies with low technical readiness (van der Giesen et al., 2020).

The historical evolution is significant for the current thesis as maritime decarbonization is a dynamic issue. The environmental performance of alternative marine fuels is contingent upon future production pathways, the availability of renewable energy, vessel operations, infrastructure development, and regulatory changes. The evolution of LCA from static environmental accounting to dynamic, prospective, and integrated assessment establishes a methodological basis for advancing LCA methodologies within the maritime sector.

2.2.3 LCA Modelling Approaches and Methodological Choices

Various LCA modeling approaches have been established to address distinct research inquiries. Attributional LCA is employed to characterize the environmental burdens linked to a product system under specific conditions, whereas consequential LCA seeks to assess the environmental impacts resulting from alterations in demand, policy, or technology (Earles & Halog, 2011). Consequential LCA encompasses a comprehensive analysis of system responses, incorporating affected technologies, market dynamics, rebound effects,

and economic modeling. The distinction is significant as attributional and consequential approaches can yield divergent conclusions, especially in the evaluation of emerging technologies, alternative fuels, or co-product systems.

The selection of the LCA methodology significantly influences the interpretation of findings. Studies comparing attributional and consequential LCA for biofuel systems indicate that methodological choices concerning allocation, substitution, and market displacement can significantly alter the estimated environmental performance of the same fuel pathway (Moretti et al., 2022). This is especially pertinent for marine biofuels and alternative fuels, as the origin of feedstock, co-products, indirect land-use change, and displaced products can significantly affect the overall life cycle outcomes.

Data quality represents a significant methodological concern. LCA relies on foreground data that characterize the specific system under investigation, as well as background data that pertain to upstream processes, including energy supply, material production, and transportation. Data quality may exhibit considerable variability across different studies. Bicalho et al. (Bicalho et al., 2017) contend that traditional approaches to data quality in LCA frequently emphasize industry-average datasets, potentially overlooking organizational challenges associated with primary data collection, verification, access, and control. This limitation is significant in applied sectors like shipping, where vessel-specific operational data and fuel pathway information can greatly affect the assessment outcome.

Cellura et al. (2018) illustrate that LCA offers a more comprehensive estimation of greenhouse gas emissions compared to traditional inventory-based methods, since it considers both upstream and downstream processes, in addition to non-CO₂ GHGs. This is

crucial for maritime decarbonization, since fuel evaluation must encompass not just direct onboard emissions but also those linked to fuel production, distribution, and energy supply.

The temporal representation constitutes a significant limitation of traditional LCA. Conventional LCA typically consolidates emissions throughout the life cycle, neglecting the timing of these emissions. Levasseur et al. (2010) highlight the absence of temporal information as a significant limitation and suggest dynamic LCA as a method to enhance the temporal consistency of impact assessment. Dynamic LCA represents the life cycle inventory as a function of time, utilizing time-dependent characterization factors to assess impacts across designated time horizons.

Emerging methodologies, such as prospective and ex-ante LCA, have been developed to evaluate future technologies. These approaches are crucial when the technology being examined has not attained commercial maturity or is anticipated to function under future background conditions. Van der Giesen et al. (2020) characterize ex-ante LCA as the environmental evaluation of a novel technology before its commercial deployment, aimed at informing research and development choices. Prospective and ex-LCAs encounter distinct challenges, such as modeling future foreground systems, modeling future background systems, defining suitable functional units, and managing significant levels of uncertainty.

The methodological evolution of LCA indicates a transition from static, retrospective assessments to more dynamic, prospective, and data-driven methodologies. This evolution is crucial for maritime decarbonization. Alternative marine fuels require evaluation beyond current emission factors and simplified operational assumptions. Their environmental

performance is contingent upon future energy systems, production pathways, vessel-specific operations, regulatory conditions, and inherent uncertainties. The methodological choices outlined in this section establish the basis for the subsequent critical review of maritime LCA applications.

2.3 Introduction to Maritime LCA

The implementation of LCA in the maritime sector has gained significance as the shipping industry shifts from traditional emission-control methods to more comprehensive decarbonization strategies. In contrast to operational indicators that mainly concentrate on onboard emissions or energy efficiency, LCA facilitates the evaluation of environmental impacts throughout the entire life cycle of the ship and fuel. This is especially pertinent for maritime systems, where environmental impacts stem from fuel combustion as well as vessel construction, propulsion technology, retrofitting, maintenance, fuel supply chains, port operations, and end-of-life processes. This subsection introduces the primary applications of LCA in maritime transport, starting with evaluations of ship life cycle, propulsion, and retrofitting. It then explores operational emissions, vessel activity modeling, and applications related to ports. This review delineates the role of LCA in maritime environmental assessment and highlights limitations associated with case-specific assumptions, simplified operational profiles, and inconsistent system boundaries.

2.3.1 Applications of Life Cycle Assessment in Maritime Transport

The implementation of LCA in maritime transport has increased notably as the industry transitions from traditional emission-control methods, like Energy Efficiency Design Index (EEDI), Energy Efficiency Operational Indicator (EEOI), Energy Efficiency Existing Ship

Index (EEXI), and Carbon Intensity Indicator (CII), to more comprehensive decarbonization strategies. The significance of LCA in maritime transport is attributed to the intricate nature of ships as enduring assets and the variety of systems engaged in their operation. The environmental performance of a vessel is determined by fuel consumption during operation, as well as factors such as propulsion system design, auxiliary machinery, material production, maintenance strategies, retrofitting decisions, fuel supply chains, and dismantling practices. LCA offers a comprehensive framework for assessing whether a proposed maritime technology effectively mitigates environmental impacts or simply redistributes burdens across different life cycle stages. This is especially pertinent for decarbonization technologies, including battery propulsion, solar-assisted systems, LNG retrofits, scrubbers, onboard carbon capture, and alternative fuel systems, where operational advantages may coincide with further upstream or infrastructure-related effects (B. Jeong et al., 2018; Ling-Chin & Roskilly, 2016; Oh et al., 2024).

The application of LCA in maritime transport presents methodological challenges, despite its advantages. Maritime systems exhibit significant case specificity, leading to variability in LCA results based on factors such as vessel type, route, operating profile, engine load, fuel pathway, electricity mix, functional unit, and system boundary. The comparability and generalizability of maritime LCA studies are frequently constrained. The significance of this is heightened when LCA informs policy or investment decisions, as outcomes from a single vessel, route, or operational profile may not be applicable to different contexts. This section examines the primary applications of LCA in maritime transport, emphasizing ship life cycle and propulsion system evaluation, operational emissions, and vessel activity modeling, as well as applications related to short-sea, ferry, port, and harbor operations.

2.3.2 Ship Life Cycle, Propulsion Systems, and Retrofitting Assessment

A significant focus of maritime life cycle assessment research is the evaluation of ship life cycle stages, propulsion systems, and retrofitting options. Blanco-Davis and Zhou (2016) argued that LCA serves as a supplementary tool to current shipping energy-efficiency regulations, demonstrating that LCA offers more comprehensive environmental insights than regulatory metrics by themselves. EEDI and EEOI primarily address CO₂ emissions related to transport work, whereas LCA encompasses nitrogen oxides (NO_x), sulphur oxides (SO_x), material utilization, energy consumption, and hazardous emissions throughout various phases of a vessel's life cycle. This underscores the capability of LCA to aid in the evaluation of both new and existing vessels, especially when regulatory indicators offer an incomplete depiction of environmental performance.

Retrofitting has been analyzed through the lens of LCA. Blanco-Davis and Zhou (2014) utilized LCA to evaluate various ballast water treatment system alternatives, illustrating that LCA can assist shipowners and fleet managers in making informed retrofit decisions by integrating environmental assessments with cost-benefit analyses. Retrofitting is significant because it is frequently advocated as an effective means of enhancing the environmental performance of existing fleets. Retrofit technologies may necessitate supplementary equipment, increased energy demand, maintenance obligations, and additional material inputs. LCA assists in assessing whether the environmental benefits realized during operation surpass the impacts incurred during manufacturing, installation, and end-of-life phases.

Jang et al. (2020) developed a Parametric Trend Life Cycle Assessment approach for marine SOx scrubber systems, analyzing wet open-loop, wet closed-loop, and hybrid scrubbers across numerous ocean-going Ro-Ro vessels. The findings indicated that closed-loop scrubbers exhibited superior performance regarding global warming potential and acidification potential, whereas open-loop systems demonstrated better outcomes in terms of eutrophication potential. This study's significant contribution lies in its expansion beyond a single-vessel case study, facilitating the identification of general trends across various ship parameters. This is especially significant as traditional maritime LCA studies tend to be overly case-specific, limiting their applicability for fleet-level decision-making.

The evaluation of propulsion systems has emerged as a key application of maritime LCA. Ling-Chin and Roskilly (2016) conducted a comparison of conventional, retrofit, and new-build marine power systems utilizing component-level life cycle assessment models. The findings indicate that advanced marine power systems can decrease operational fuel consumption and emissions; however, they may exacerbate impacts in other life cycle stages due to the increased resources required for manufacturing, dismantling, and end-of-life treatment. This highlights a critical aspect of maritime LCA: technologies that seem advantageous during operation may result in environmental trade-offs at other stages of the life cycle.

Battery-electric propulsion has garnered significant interest in maritime life cycle assessment. Jeong et al. (2020) evaluated the environmental advantages throughout the life cycle of fully battery-powered vessels in comparison to marine diesel propulsion. Their findings demonstrated significant decreases in global warming potential (GWP),

acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP) with the use of battery propulsion. The study emphasized that the environmental benefits of battery-powered ships are significantly influenced by the electricity generation mix. This finding is significant as battery-electric vessels can achieve zero emissions during operation; however, their lifecycle impacts are contingent upon electricity production, battery manufacturing, and the decarbonization of future energy systems.

End-of-life and scrapping of ships have also been examined in maritime LCA. Ko and Gantner (2016) evaluated the environmental impacts and local added value throughout the phases of ship production, usage, and end-of-life. The study demonstrated that economic advantages and environmental impacts are disproportionately allocated throughout the ship life cycle, with shipowners primarily reaping benefits during the use phase, whereas shipbuilders and dismantlers may encounter greater environmental burdens in relation to local added value. This underscores the wider sustainability implications of ship life cycles, especially concerning dismantling regions where worker health, environmental management, and material recovery practices are significant issues.

Recent studies have applied LCA to emerging decarbonization technologies, including onboard carbon capture. Oh et al. (2024) assessed the WTW GHG emissions of shipping incorporating onboard carbon capture in accordance with the FuelEU Maritime regulation. The findings indicate that onboard carbon capture can significantly decrease TTW emissions and may enable certain fossil-fueled vessels to meet FuelEU Maritime GHG intensity standards until 2044. They noted that long-term compliance necessitates

additional measures, such as capture from auxiliary systems and reductions in upstream fuel emissions. This illustrates that LCA is applicable for comparing technologies and evaluating their regulatory significance within prospective policy frameworks.

LCA studies on ship life cycle, propulsion systems, and retrofitting illustrate the importance of considering factors beyond operational emissions alone. Environmental performance is contingent upon the interplay of ship design, technology selection, fuel utilization, manufacturing impacts, maintenance, and end-of-life processes. Many of these studies are case-specific and frequently rely on assumed operating profiles, chosen impact categories, and restricted system boundaries. This necessitates the development of more generalizable, operationally detailed, and data-driven life cycle assessment approaches in maritime transport.

2.3.3 Operational Emissions and Vessel Activity Modelling

Operational emissions are the primary contributors to numerous life cycle impacts of ships, especially for vessels powered by conventional fossil fuels. Accurately representing vessel operation in LCA is complex due to the variability of ship emissions, which are influenced by factors such as vessel type, engine configuration, speed, load, voyage distance, cargo capacity, route, port waiting time, and weather or sea conditions. LCA studies that utilize realistic operational profiles yield more significant insights compared to those based on generic assumptions.

Seithe et al. (2020) conducted a comprehensive well-to-propeller LCA of maritime transport, examining various vessel types, engine configurations, fuel supply chains, and operational profiles. The study encompassed container ships, tankers, Ro-Pax vessels, and

cruise ships, comparing the pathways of heavy fuel oil (HFO) and LNG. The results indicate that environmental performance is significantly affected by vessel type, methane slip, cargo-capacity penalties, and the configuration of the fuel supply chain. Furthermore, the advantages of LNG are not universally applicable and are contingent upon engine technology and upstream supply-chain assumptions. This confirms that maritime LCA must accurately reflect operational and technical conditions instead of considering ships as generic fuel-consuming entities.

Operational modeling specifically for routes has been utilized in tanker transport. Tripathi et al. (2024) evaluated WTW GHG emissions and life cycle costs for SUEZMAX tankers utilizing high-sulphur fuel oil (HSFO), very-low-sulphur fuel oil (VLSFO), and LNG on the Saudi Arabia–Japan and Saudi Arabia–Netherlands routes. Their findings indicated that LNG decreased life cycle GHG emissions by approximately 11–12% relative to conventional fuels, with the cost of carbon abatement fluctuating considerably based on factors such as methane slip, LNG pricing, and anchoring duration. This indicates that route-specific operations and operational uncertainties significantly influence LCA and cost outcomes.

The studies indicate that vessel operation should not be regarded as a fixed or secondary parameter in maritime LCA. Ships operate under varying speeds, engine loads, port conditions, waiting times, maneuvering patterns, and voyage requirements. This is particularly pertinent for port emissions and green corridor applications, as operational behavior can vary considerably among vessel classes and route segments. The literature increasingly indicates the necessity for operationally resolved LCA methods that integrate

real vessel activity data, including AIS-based speed and location profiles, instead of depending solely on average assumptions.

2.3.4 Short-Sea, Ferry, and Port Applications

Short-sea shipping, ferries, harbor vessels, and port-related operations have garnered increasing interest in maritime LCA due to their potential for electrification, hybrid systems, solar-assisted propulsion, and operational optimization. These applications are significant as short routes, and port operations typically entail repetitive voyage patterns, frequent maneuvering, berthing, and proximity to densely populated coastal regions. Consequently, enhancements in these sectors can yield benefits for both climate and local air quality.

Wang et al. (2019) evaluated the environmental and economic impacts of implementing solar panel arrays on a short-route ferry in the Marmara Sea. The results of the LCA and life cycle cost assessment (LCCA) indicated that the implementation of onboard solar panels has the potential to decrease fuel consumption and yield economic savings throughout the vessel's operational lifespan, with an estimated payback period of approximately three years. The research indicates that renewable energy technologies provide tangible advantages in short-route applications. The contribution of solar power is limited by factors such as available deck area, weather conditions, solar efficiency, vessel energy demand, and route characteristics.

Battery-powered ferries have been analyzed using an integrated environmental and economic evaluation. Guven and Kayalica (2023) conducted a comparative analysis of various lithium-ion battery chemistries and MDO for a passenger ferry operating in

Istanbul. Their findings demonstrated that lithium iron phosphate batteries exhibited advantageous environmental performance compared to other battery alternatives, whereas economic viability was contingent upon carbon credit scenarios and assumptions regarding the energy mix. This study highlights the significance of analyzing distinct battery chemistries instead of considering battery propulsion as a homogeneous alternative. Nonetheless, it indicates that battery systems may transfer environmental impacts to electricity generation and battery production.

Bordbar et al. (2025) expanded LCA to small craft by analyzing electric versus petrol-powered rigid inflatable boats for recreational and harbor-master uses. The cradle-to-grave assessment indicated that electric RIBs decreased global warming potential by 34% for recreational use and 52% for harbor-master use, although they exhibited greater impacts during the production phase and in various non-GWP categories. This finding is significant as it demonstrates that electrification yields the greatest environmental benefits under conditions of high utilization and when the electricity supply is cleaner. This underscores the necessity of assessing various impact categories instead of solely concentrating on GHG emissions.

Collectively, short-sea, ferry, port, and harbor applications demonstrate that LCA can yield valuable insights for smaller vessels and operationally constrained maritime systems. The studies underscore the potential of batteries, solar systems, and electrification while also identifying persistent limitations. Numerous assessments continue to rely on case-specific pathways, regional electricity compositions, presumed usage intensity, and chosen technology configurations. Furthermore, port and harbor operations are frequently depicted

using simplified assumptions instead of detailed operational data. This establishes a significant methodological gap for time-resolved or near-real-time LCA approaches that can account for operational variability within port boundaries, encompassing the phases of approach, anchoring, maneuvering, berthing, and departure.

2.4 Lifecycle Impacts of Maritime Fuels, Green Corridors, and Port-LCA

The LCA of maritime fuels is essential for decarbonization, as the environmental performance of a fuel cannot be assessed solely based on its onboard emissions. Alternative fuels have the potential to decrease TTW emissions; however, their overall carbon performance is contingent upon various factors, including upstream production pathways, feedstock availability, sources of electricity, fuel transportation, storage requirements, onboard conversion efficiency, infrastructure readiness, and future scalability. This section reviews the lifecycle impacts of conventional fuels, LNG, biofuels, hydrogen, ammonia, methanol, and e-fuels, and subsequently examines their relevance to green corridors and port-based applications. Green corridors offer a critical context for evaluating future fuel deployment on a route-specific basis. This section analyzes fuels, corridors, and port-boundary applications collectively, highlighting the limitations of static fuel comparisons and illustrating the necessity for more operationally detailed and context-specific maritime lifecycle assessment approaches.

2.4.1 Life Cycle Assessment of Marine Fuel Pathways

The LCA of marine fuel pathways is a critical research focus for maritime decarbonization, as the environmental performance of a fuel extends beyond its onboard combustion emissions. Alternative marine fuels have the potential to decrease TTW emissions;

however, their overall climate benefits are significantly influenced by factors such as feedstock origin, fuel production technology, electricity source, transportation distance, storage requirements, engine type, pilot fuel usage, and onboard conversion efficiency. Consequently, WTW assessment is crucial for the consistent comparison of conventional fuels, LNG, biofuels, hydrogen, ammonia, methanol, and e-fuels.

Existing marine fuel LCA studies indicate that no single fuel pathway is universally superior across all conditions. Fuel performance is significantly influenced by the assumptions regarding production pathways, background energy systems, vessel type, operational profile, and impact categories. Fuels characterized by low or zero carbon emissions during onboard use can still result in considerable upstream emissions if they are produced using fossil-based electricity or carbon-intensive feedstocks. Fuels like LNG can decrease certain air pollutants; however, they are still affected by methane slip and emissions from the upstream gas supply chain (Seithe et al., 2020; Tripathi et al., 2024). This underscores the necessity of assessing marine fuels from a comprehensive life cycle viewpoint instead of relying on simplified operational emission factors.

The literature has transitioned from single-fuel comparisons to more comprehensive comparative assessments and future-oriented evaluations. Recent studies evaluate various fuel pathways based on environmental, economic, and regulatory criteria, encompassing fossil fuels, LNG, biofuels, hydrogen, ammonia, methanol, e-fuels, and onboard carbon capture configurations (Kanchiralla et al., 2022; Law et al., 2021; Zincir & Arslanoglu, 2024). The studies offer valuable insights into fuel selection, but they also highlight significant limitations, such as inconsistent system boundaries, uncertain fuel production

data, limited operational resolution, and inadequate representation of future energy-system changes. This subchapter provides a critical review of conventional and alternative marine fuel pathways and potential green corridor applications.

2.4.2 Conventional Marine Fuels, LNG, and Transitional Fuel Pathways

Conventional fossil fuels, including HFO, MDO, marine gas oil (MGO), VLSFO, and ultra-low-sulphur fuel oil (ULSFO), serve as critical reference pathways in maritime LCA, as they establish the baseline for evaluating alternative fuels. Bilgili (2021) conducted a comparative analysis of the life cycle environmental performance of marine fuels, considering the IMO 2020 Sulphur Cap, specifically examining HFO, light fuel oil (LFO), VLSFO, and ULSFO. The research indicated that while low-sulphur fuels decrease SO_x emissions during use, their overall life cycle effects may exceed expectations because of increased refining and upstream processing demands. This indicates that regulation primarily targeting operational sulphur emissions may neglect broader life cycle trade-offs.

LNG has garnered significant attention as a transitional marine fuel due to its ability to decrease SO_x, NO_x, and particulate matter emissions compared to traditional oil-based fuels. LCA studies indicate that climate performance is significantly influenced by methane slip, engine technology, and upstream supply-chain emissions. El-Houjeiri et al. (2019) conducted a comparative analysis of the life cycle GHG emissions associated with HFO, MGO, and LNG derived from Saudi crude oil and natural gas across various global regions. The findings indicated that the reduced carbon content and enhanced engine efficiency of LNG may be partially counterbalanced by methane emissions throughout the supply chain, particularly when evaluated with shorter time-horizon climate metrics.

A similar conclusion is found in broader LNG-focused maritime LCA studies. The study by Jang et al. (2021) on LNG and fossil marine fuels indicates that LNG could offer climate advantages under certain supply-chain and engine conditions; however, its overall efficacy remains uncertain. Seithe et al. (2020) demonstrated that the performance of LNG is influenced by vessel type, operational profile, engine configuration, methane slip, and cargo capacity effects. Their assessment of the well-to-propeller transition from HFO to LNG indicates that this shift is affected by factors including fuel combustion, liquefaction processes, upstream natural gas supply, and diminished cargo capacity resulting from LNG storage needs.

Ha et al. (2023) emphasized the significance of regional supply chains through an evaluation of fossil marine fuels in South Korea, a nation dependent on energy imports. Their research demonstrated that international fuel transportation and import routes can substantially influence WTW emissions. This is particularly pertinent for nations reliant on imported LNG, methanol, or alternative fuels, as upstream transportation and supply-chain configuration may affect the overall WTW outcome.

Maydison et al. (2024) assessed LNG dual-fuel retrofitting using LCA and demonstrated that substituting a portion of marine diesel oil with LNG can decrease global warming potential at certain replacement ratios. The findings are significantly influenced by vessel type, operating profile, LNG assumptions, engine load, and the emission factors employed, highlighting the necessity for case-specific uncertainty assessment.

Overall, the literature suggests that LNG and low-sulphur conventional fuels may provide transitional benefits, especially for air pollutant reduction and regulatory compliance.

However, their climate performance is limited by upstream emissions, methane slip, fuel processing, and operational assumptions. Therefore, while LNG may act as a transitional fuel in specific cases, it cannot be treated as a long-term decarbonization solution without careful life cycle and uncertainty assessment.

2.4.3 Biofuels and Biomass-Based Pathways

Biofuels are often considered viable alternatives for maritime decarbonization due to their compatibility with existing engines and fuel infrastructure, requiring minimal modifications. This is especially appealing for deep-sea shipping, where complete electrification is frequently limited by energy density, voyage duration, and storage needs. Biofuel sustainability is significantly influenced by factors such as feedstock type, production pathway, land-use impacts, co-product treatment, supply availability, and conversion efficiency.

Brynnolf et al. (2014) conducted a comparative analysis of LNG, liquefied biogas, methanol, and bio-methanol as marine fuels through LCA. Their research indicated that fossil-based LNG and methanol can enhance certain environmental metrics; however, they do not inherently provide significant climate advantages when compared to HFO. Conversely, liquefied biogas and bio-methanol demonstrated greater potential for reducing climate impact. This preliminary comparative study highlighted that the environmental advantages of alternative marine fuels are significantly influenced by the fuel's classification as either fossil-based or renewable, rather than solely by its combustion characteristics onboard.

Biofuels have also been assessed in non-maritime and cross-sector contexts that are relevant for maritime fuel pathway evaluation. For example, studies on rapeseed biodiesel

and waste-derived Fischer–Tropsch fuels indicate that biofuel outcomes are significantly influenced by feedstock origin, substitution assumptions, carbon accounting, and production pathway design (Herrmann et al., 2013; U. Lee et al., 2023a). The findings hold significance for maritime applications, as drop-in biofuels may demonstrate advantages under one allocation or substitution method while appearing less advantageous under another. Methodological transparency is essential in the utilization of biofuels within shipping decarbonization strategies.

Ouedraogo et al. (2021a) conducted a comparison of gasification and landfilling for municipal solid waste through LCA, revealing significant differences in greenhouse gas emissions, air pollution, human health impacts, and environmental burdens associated with these waste treatment pathways. This reinforces the broader argument that pathways for waste-derived fuel or feedstock require careful evaluation, as their sustainability is contingent upon the alternative waste-management system and the chosen life cycle boundaries.

Watanabe et al. (2022) conducted a prospective LCA to evaluate drop-in biofuels for deep-sea shipping, utilizing Norwegian forest residues. Their findings indicated climate mitigation potentials ranging from 65% to 85% when utilizing 20-year global warming potential (GWP20) and from 78% to 87% with 100-year global warming potential (GWP100) in comparison to fossil alternatives. The research indicated that forthcoming technological advancements and modifications to background systems could potentially decrease the climate impacts of biofuels by as much as 54% by the year 2050. This is significant as it illustrates that the life cycle performance of biofuels is dynamic, influenced

by evolving energy systems, conversion technologies, transport systems, and climate metrics.

The evaluation of biofuels should encompass wider sustainability and selection criteria. Sevim and Zincir (2025) employed the Analytic Hierarchy Process to determine the optimal sustainable biofuels for maritime transportation, considering safety, WTW emissions, compatibility, and indirect land-use change. Their findings demonstrated that Fischer–Tropsch (FT) diesel and third-generation hydrotreated vegetable oil (HVO) exhibited favorable safety, compatibility, and emissions characteristics. This study is significant as it transcends the focus on GHG emissions, demonstrating that the selection of biofuels must integrate technical, environmental, operational, and sustainability criteria concurrently.

Recent broad comparative LCA studies have also highlighted the potential of marine bio-oil and biomass-derived fuels. Zincir and Arslanoglu (2024) conducted a comparative analysis of various alternative marine fuels, revealing that marine bio-oil exhibited superior performance across multiple environmental criteria, attributed to its CO₂ and methane consumption during production and low emissions during combustion. Nevertheless, these results are contingent upon assumptions regarding feedstock availability, conversion efficiencies, production scale, and the chosen impact assessment method.

Manikandan et al. (2025) conducted a review of biofuel innovations for marine propulsion, demonstrating that advanced biofuels, including HVO, biodiesel, and algae-based fuels, can mitigate black carbon emissions under certain operational conditions. The study

identifies ongoing challenges concerning scalability, storage, feedstock availability, cost, and overall life cycle sustainability.

Despite their potential, biofuels face important limitations. Their scalability is uncertain, particularly for deep-sea shipping, where fuel demand is great and sustainable biomass resources are limited. Biofuel pathways may also compete with food production, land use, biodiversity, and other sectors that require biomass for decarbonization (i.e., aviation, automobile industry). Moreover, some biofuels reduce climate change impacts but may increase other environmental burdens, such as eutrophication, acidification, or land-use-related impacts. Therefore, biofuels should be assessed through multi-impact, transparent, and future-oriented LCA frameworks rather than being treated as automatically carbon-neutral solutions.

2.4.4 Hydrogen, Ammonia, Methanol, and E-Fuels

Hydrogen, ammonia, methanol, and e-fuels are prominent candidates for the long-term decarbonization of the shipping sector. The potential of these fuels to reduce or eliminate onboard carbon emissions is significantly influenced by their production methods, impacting their WTW performance. Specifically, the availability of renewable electricity, efficiency of electrolysis, hydrogen production method, carbon source for methanol, ammonia synthesis route, and onboard conversion technology significantly impact the overall environmental outcome.

Hydrogen has been evaluated as a direct fuel and as an intermediary for the production of ammonia, methanol, and other e-fuels. Jang et al. (2022) utilized Parametric Trend LCA to evaluate hydrogen fuel cell applications in shipping, demonstrating that the environmental

performance of hydrogen is significantly influenced by the production pathway and the type of fuel cell used. Renewable electrolysis presents significant decarbonization potential, whereas fossil-based hydrogen pathways may lead to substantial life cycle impacts. This aligns with comprehensive evaluations of alternative fuels, indicating that hydrogen qualifies as a low-carbon marine fuel solely when generated from low-carbon or renewable energy sources.

Ammonia is regarded as appealing due to its lack of carbon content and its potential to eliminate carbon emissions during onboard utilization. Nevertheless, LCA studies indicate that the climate performance of ammonia is significantly influenced by the upstream production of hydrogen and potential nitrous oxide emissions during combustion. Chalaris et al. (2022) utilized Parametric Trend LCA to assess ammonia as a marine fuel, revealing that WTT emissions are the primary contributors to ammonia's carbon footprint. Similarly, Tomos et al. (2024) emphasized the uncertainty regarding nitrous oxide emissions from ammonia combustion, indicating that N_2O possesses a significant global warming potential, which may diminish some of ammonia's anticipated climate advantages. Consequently, ammonia should not be considered solely as a carbon-free molecule; a comprehensive evaluation of its entire production and combustion chain is necessary. Levikhin and Boryaev (2025) conducted a review of low-carbon ammonia as a marine fuel, emphasizing its potential for decarbonizing shipping, attributed to its carbon-free molecular structure and established industrial production practices. They emphasized that the adoption of ammonia is limited by factors such as toxicity, safety management, storage requirements, cost, engine development, and the carbon intensity associated with ammonia production.

Methanol and e-methanol have garnered considerable attention due to their ease of storage, established handling protocols, and compatibility with dual-fuel engines. Nonetheless, the life cycle performance of methanol is contingent upon its production source, which may include fossil natural gas, biomass, renewable hydrogen, or captured CO₂. E-methanol has the potential to significantly reduce GHG emissions when generated from renewable electricity and sustainable carbon sources. However, its effectiveness may decline if fossil carbon sources or carbon-intensive electricity are utilized (Law et al., 2021; Tomos et al., 2024). This underscores a significant challenge for electro-fuels: their environmental performance is determined not by the fuel itself, but by the energy and carbon sources utilized in their production.

Lindstad et al. (2021) investigated the potential of e-fuels in mitigating greenhouse gas emissions in maritime contexts, demonstrating that e-hydrogen, e-ammonia, e-diesel, e-LNG, and e-methanol can facilitate decarbonization contingent upon the availability of adequate renewable electricity. Their study emphasizes that the evaluation of e-fuel adoption should consider energy demand, cost, and fuel flexibility, rather than focusing solely on GHG reduction potential.

Kanchiralla et al. (2022) conducted a comparison of future fossil-free shipping fuel and propulsion alternatives through LCA and life cycle costing methodologies. Their findings indicate that e-methanol, hydrogen, ammonia, battery-electric systems, fuel cells, and onboard carbon capture can effectively lower GHG emissions when powered by low-carbon electricity. Nonetheless, the study revealed that abatement costs are still elevated and that environmental trade-offs may arise in the categories of toxicity and ecotoxicity.

This indicates that the evaluation of future fuels should encompass not only greenhouse gas reduction but also a wider range of environmental factors and economic viability.

Prospective assessments are particularly important for e-fuels. Perčić et al. (2025) analyzed cost-effective strategies for achieving FuelEU Maritime targets, concluding that e-ammonia, FT diesel, and e-methanol are viable options for meeting the 2050 target, whereas e-LNG and ship-based carbon capture have lower effectiveness under the evaluated conditions. Their results are contingent upon future background systems, production locations, electrolyser assumptions, technology maturity, and cost projections. These studies indicate that the long-term performance of e-fuels should be evaluated using prospective LCA rather than relying on current static assumptions.

Extensive comparative studies illustrate the complexity involved in fuel selection. Law et al. (2021) conducted a comparison of 22 alternative fuel pathways regarding lifecycle energy demand and cost. Their findings indicate that battery-electric propulsion demonstrates high efficiency, but it is impractical for long-distance shipping. In contrast, hydrogen and ammonia are associated with significant energy and cost challenges. The studies offer extensive fuel coverage; however, their outcomes are contingent upon assumptions regarding technology readiness, energy sources, fuel availability, operational conditions, and impact assessment methodologies.

Overall, hydrogen, ammonia, methanol, and e-fuels offer significant decarbonization potential, but only under specific production and operational conditions. Their benefits are strongly linked to renewable electricity, low-carbon hydrogen, sustainable carbon sources, efficient onboard conversion, and future infrastructure development. Therefore, their

assessment requires prospective and uncertainty-aware frameworks capable of capturing both upstream production variability and downstream operational performance.

2.4.5 Green Corridors and Long-Distance Shipping Applications

Green corridors serve as strategic frameworks for enhancing maritime decarbonization by centralizing infrastructure, fuel supply, regulation, and stakeholder coordination along designated routes. From an LCA perspective, green corridors are significant as they offer a specific geographical and operational framework for a more realistic evaluation of alternative fuel pathways. Long-distance routes, exemplified by the Singapore–Rotterdam corridor, are particularly significant due to their high fuel demand, intricate bunkering requirements, adherence to international regulations, and considerable uncertainty regarding future fuel availability.

Chalaris et al. (2025) established an econometrically enhanced LCA framework for the Singapore–Rotterdam containership green corridor. This framework integrates LCA with Holt–Winters forecasting, GDP, population, twenty-foot equivalent unit (TEU) demand, regression analysis, FuelEU Maritime, and EU ETS penalty calculations. The research indicated that e-methanol generated from solar electricity exhibited the lowest WTW emissions among the evaluated fuel pathways and most closely aligned with FuelEU targets through 2045. This study contributes by connecting life cycle fuel performance to demand forecasting and regulatory cost assessment within a specific corridor context.

Comprehensive pathway analyses for zero-carbon shipping yield valuable insights applicable to corridor-based implementations. Peng et al. (2026) evaluated 172 configurations of container ship energy systems through LCA, cost analysis, regulatory

penalty modelling, and multi-criteria decision analysis. Their findings indicated that e-hydrogen configurations and wind-assisted systems exhibit strong performance under specific assumptions. These studies are pertinent to green corridors as they indicate that fuel selection must be assessed in conjunction with onboard energy systems, auxiliary technologies, regulatory penalties, and the preferences of decision-makers.

Green corridor LCA studies, therefore, represent an important shift from generic fuel comparison towards route-specific and policy-relevant assessment. The existing literature is constrained in multiple areas. Numerous studies concentrate on specific fuels, representative vessels, or simplified operational assumptions; however, uncertainties persist regarding fuel availability, infrastructure readiness, renewable electricity supply, port-side emissions, and future demand growth. This necessitates the development of improved LCA models capable of integrating WTW fuel assessments, vessel activity data, forecasting methodologies, regulatory scenarios, and decision-support indicators. This requirement is fundamental to the methodological approach of the current thesis.

2.5 The Demand for Enhanced LCA Modelling

Existing maritime LCA studies offer valuable insights into ship systems, fuel pathways, and decarbonization technologies; however, their applicability for long-term decision-making is constrained by methodological and modeling limitations. Numerous studies depend on static inventories, fixed emission factors, deterministic assumptions, limited sensitivity testing, and simplified operational profiles. These limitations pose challenges in maritime decarbonization, as fuel pathways, energy systems, regulations, costs, vessel activity, and infrastructure are anticipated to undergo significant changes over time. This section examines the demand for improved LCA modelling through the integration of complementary methods, including life cycle costing, multi-criteria decision support, uncertainty and sensitivity analysis, prospective and forecast-based modelling, and time-resolved or data-driven assessment. The objective is to demonstrate that future maritime LCA frameworks need to progress beyond static comparisons and enhance their ability to account for operational variability, future scenarios, uncertainty, and decision-support needs.

2.5.1 Integration of LCA with Complementary Assessment Methodologies

LCA offers a systematic approach for assessing environmental impacts throughout the life cycle; however, its effectiveness in decision-making is enhanced when combined with additional assessment methods. This is especially significant in maritime decarbonization, as fuel and technology selection must consider factors beyond environmental performance alone. Alternative marine fuels and propulsion systems encompass considerations of economic feasibility, regulatory compliance, technological readiness, infrastructure

requirements, operational uncertainty, and long-term scenario changes. Recent LCA studies increasingly integrate environmental assessment with LCCA, multi-criteria decision-making, uncertainty analysis, prospective modelling, real-time data, digital twins, and artificial intelligence methods.

This methodological integration illustrates the growing complexity inherent in sustainability decision-making. In the maritime sector, the optimal fuel or technology varies based on priorities such as GHG reduction, cost-effectiveness, technical compatibility, safety, scalability, fuel availability, and regulatory compliance. LCA is increasingly utilized not only as an environmental accounting tool but also within broader decision-support frameworks. This thesis seeks to enhance maritime LCA by utilizing time-resolved and forecast-based simulations to evaluate the performance of alternative marine fuels.

2.5.2 Integration of LCA and Life Cycle Cost Assessment

The integration of LCA and LCCA is increasingly crucial, as environmental performance alone does not suffice for effective fuel or technology selection. Shipowners, operators, policymakers, and port authorities must consider investment costs, fuel prices, operational costs, payback periods, carbon pricing, regulatory penalties, and infrastructure requirements. LCA–LCCA integration offers a comprehensive decision-making framework by merging environmental and economic performance throughout the system life cycle.

Furthermore, Jeong et al. (2018) established a framework that integrates LCA and LCCA to facilitate the selection of optimal marine propulsion systems. Their framework was

utilized for a short-route hybrid ferry and an offshore tug vessel, demonstrating that environmental and economic outcomes are significantly influenced by vessel type, operational profile, propulsion configuration, and cost assumptions. The research illustrates the significance of integrating LCA and LCCA into ship design and technology selection, while also emphasizing the case-specific characteristics of these evaluations.

Battery-electric and hybrid systems have been evaluated using integrated environmental and economic methodologies. Guven and Kayalica (2023) utilized LCA and LCCA to evaluate lithium-ion batteries for a passenger ferry. Their findings indicate that battery systems can mitigate environmental impacts relative to MDO, but their viability is contingent upon the electricity mix, battery type, and assumptions regarding carbon credits.

In summary, LCA–LCCA studies demonstrate that maritime decarbonization pathways must be evaluated through both environmental and economic lenses. However, many existing studies remain dependent on fixed cost assumptions, limited vessel cases, and uncertain future fuel prices. This creates a need for more dynamic environmental–economic assessment frameworks that can incorporate future regulatory scenarios, operational variation, and uncertainty in fuel production and market conditions.

2.5.3 LCA-Based Decision-Support and Multi-Criteria Assessment

The results of LCA can be intricate, as various fuels or technologies may exhibit strong performance in one impact category while demonstrating weak performance in another. Consequently, LCA is progressively integrated with decision-support and multi-criteria assessment methodologies. These methods facilitate the ranking of alternatives by simultaneously evaluating multiple environmental, economic, technical, and operational

criteria. This is especially pertinent in maritime decarbonization, where fuel selection necessitates balancing emissions, safety, compatibility, cost, scalability, fuel availability, and regulatory compliance.

Jeong et al. (K. Jeong et al., 2019) utilized LCA to integrate environmental, human health, and economic indicators for a comparative analysis of concrete and steel sump systems, illustrating the capacity of life cycle methods to facilitate sustainability-focused decision-making. This study demonstrates the importance of integrating environmental and cost-related indicators in the selection process of competing technological or material alternatives, despite being outside the maritime sector.

Recent methodological advancements have suggested a more formal integration of LCA with decision-support techniques. Miah et al. (2017) established a hybrid framework that integrates environmental LCA and life cycle costing. This framework encompasses multi-criteria decision analysis, multi-objective linear programming, eco-efficiency, hybrid LCA, and environmental life cycle costing. This work, while not specific to maritime contexts, is pertinent as it illustrates the integration of LCA into systematic decision-making processes that require a balance between environmental and economic priorities.

Decision-support methodologies have been directly utilized in the selection of marine fuels. Sevim and Zincir (2025) employed the Analytic Hierarchy Process to determine the most suitable sustainable biofuels for maritime transportation. The assessment encompassed criteria including safety, WTW emissions, compatibility, and indirect land-use change. The results indicated that Fischer–Tropsch diesel and third-generation HVO were among the most suitable biofuel options. This study demonstrates that the most

environmentally favorable fuel may not be the most practical or safest choice, highlighting the need to integrate LCA-related indicators with technical and operational criteria.

Advanced decision-support methods have been employed for zero-carbon shipping pathways. Peng et al. (2026) evaluated 172 configurations of container ship energy systems through the integration of LCA, cost analysis, regulatory penalty modelling, and multi-criteria decision analysis employing SMAA-2 and Choquet integral methodologies. Their research illustrates that fuel and propulsion choices are affected by the interplay of criteria and the uncertainty of preferences. These approaches are significant as maritime stakeholders may emphasize various objectives, including cost, compliance, emissions reduction, or technology readiness.

LCA has been integrated with various environmental accounting methodologies beyond the maritime sector. Liu et al. (2019) integrated LCA with energy analysis to evaluate the co-benefits of waste and by-product reutilization in an industrial park. This study, while not specific to shipping, demonstrates the potential for extending LCA through complementary methods to encompass wider environmental and resource-related aspects. This is pertinent to maritime decarbonization as future decision-support tools may require the integration of environmental, economic, resource, and operational indicators.

LCA-based decision-support methods effectively convert complex environmental results into more accessible information for policymakers and industry stakeholders. Nonetheless, these methods introduce additional uncertainties, especially concerning criteria selection, weighting, stakeholder preferences, and data availability. Consequently, decision-support frameworks must maintain transparency and should not supplant comprehensive LCA

interpretation. They should enhance LCA by aiding stakeholders in comprehending trade-offs and identifying robust options across multiple criteria.

2.5.4 Uncertainty and Sensitivity Analysis in LCA

Uncertainty and sensitivity analysis are critical in LCA as outcomes are influenced by data quality, methodological assumptions, system boundaries, emission factors, technology performance, and future scenario conditions. In maritime fuel assessment, uncertainty plays a critical role due to the involvement of immature technologies in alternative fuel pathways, uncertain fuel production efficiencies, diverse electricity mixes, pilot fuel ratios, engine load variations, infrastructure assumptions, and projected cost trajectories. LCA results may seem more definitive in the absence of uncertainty analysis.

Studies on prospective fuels indicate that uncertainty significantly influences the ranking of alternative fuels. Ingwersen et al. (2025) evaluated cost-effective strategies for meeting FuelEU Maritime targets, revealing that outcomes are significantly influenced by future technology assumptions, production sites, electrolyser selections, background systems, and cost forecasts. Lee et al. (2024) demonstrated that fuel costs, carbon pricing, and assumptions regarding future energy systems significantly affect the viability of alternative marine fuels. The studies underscore the necessity of scenario-based sensitivity testing in the assessment of long-term maritime decarbonization pathways.

Studies on LNG also highlight the significance of uncertainty analysis. Taghavifar and Perera (2023) integrated sensitivity and risk analysis within a framework of LCA and Life Cycle Costing for LNG-retrofitted vessels. The findings indicated that fuel quality, Wobbe

Index, engine load, fuel price, and payback period significantly affect both environmental and economic outcomes.

Uncertainty analysis has recently emerged as a critical component of LCA for green corridors. Wang et al. (2025) evaluated renewable liquefied hydrogen, ammonia, and methanol for the Singapore–Rotterdam green shipping corridor by utilizing multi-source renewable energy data, AIS-derived vessel activity, Monte Carlo simulation, and sensitivity analysis. The findings indicated that solar-based fuels attained merely 71–81% of the emission reductions realized by wind-based fuels, whereas pilot fuel ratios in dual-fuel engines could diminish emission benefits by as much as 12.5%. This indicates that fuel decisions at the corridor level should consider both upstream renewable electricity conditions and downstream vessel operations.

The literature indicates that uncertainty analysis is essential in maritime life cycle assessment. Evaluating emerging fuels, future technologies, and long-distance shipping pathways is essential. Yet, numerous current studies continue to employ deterministic assumptions or exhibit restricted sensitivity testing. There is a necessity for uncertainty-aware LCA frameworks that integrate production-stage variability, operational uncertainty, future scenarios, and regulatory conditions in a transparent and decision-relevant manner.

2.5.5 Prospective, Forecast-Based, and Scenario-Driven LCA

Prospective, forecast-based, and scenario-driven LCA approaches have emerged in response to the limitations of conventional static LCA. Traditional LCA frequently relies on contemporary background systems and static inventory data, posing challenges when evaluating technologies intended to function within future energy systems, regulations, and

supply chains. This is especially pertinent for maritime decarbonization, as alternative fuels are anticipated to evolve concurrently with the expansion of renewable electricity, alterations in fuel production pathways, and the introduction of new regulatory frameworks.

Prospective LCA has been developed to evaluate technologies under future conditions. Van der Giesen et al. (2020) posited that ex-ante life cycle assessment is essential for evaluating emerging technologies before their large-scale commercial deployment. Major challenges were identified, including the modelling of future foreground systems, the modelling of future background systems, addressing scale-up uncertainty, and engaging stakeholders in the assessment process. The challenges are pertinent to alternative marine fuels, many of which remain unproduced or underutilized at scale.

A primary challenge in prospective LCA is preventing a temporal mismatch between foreground and background systems. Emerging technologies can be conceptualized at a future maturity level, whereas the underlying database may continue to reflect current energy systems, industrial processes, and supply chains. Future background systems can be modeled using scenarios derived from Integrated Assessment Model (IAM) and Shared Socioeconomic Pathway (SSP) frameworks to address this issue (Sacchi et al., 2022). This enables LCA databases to more accurately represent future electricity mixes, fuel production pathways, industrial processes, and decarbonization trajectories.

The integration of LCA with energy and integrated assessment models has become an important way to represent future background systems. Chen et al. (2021) integrated the Long-range Energy Alternatives Planning System (LEAP) with LCA to evaluate

prospective city-level energy demand, carbon reduction, and environmental co-benefits within various policy scenarios. Tokimatsu et al.(2020) connected life cycle impact assessment with integrated assessment modelling to assess long-term environmental impacts in future global scenarios. These methodologies enable LCA databases and inventories to incorporate anticipated changes in electricity generation, transportation, fuel production, industrial processes, and climate policy trajectories.

Scenario-driven LCA has been utilized beyond the maritime sector, offering valuable methodological insights. Müller et al. (2024) integrated prospective LCA with assessment model scenarios to analyze clinker production within future decarbonization pathways. The study demonstrates the integration of sectoral transition scenarios into life cycle inventories to assess future environmental impacts, moving beyond static present-day assumptions. Spreafico (2025) proposed a patent-based prospective LCA approach for eco-design, illustrating that prospective LCA can facilitate the identification and evaluation of future design solutions, rather than solely assessing existing products.

Prospective and scenario-driven LCA offer a robust methodological framework for assessing future maritime fuel pathways. Existing studies predominantly emphasize future background systems or fuel production pathways, with insufficient focus on operational forecasting, vessel demand growth, route-specific activity, and regulatory cost implications. This facilitates the development of forecast-based maritime LCA approaches that integrate macroeconomic trends, trade demand, vessel activity, fuel pathways, and future emission trajectories.

2.5.6 Real-Time, Digital Twin, AIS-Based, and Artificial Intelligence (AI)-Enhanced LCA

Recent advancements in LCA increasingly emphasize real-time data, digital twins, AIS-based vessel operations, and artificial intelligence. These methodologies mitigate a fundamental constraint of traditional LCA: its dependence on static or average inventory data. This is especially pertinent in marine shipping, as vessel speed, engine load, route, anchoring, maneuvering, berthing, and weather conditions can fluctuate significantly over time.

Real-time monitoring has been suggested as a method to enhance the life cycle inventory quality. Da Costa et al. (2024) examined real-time data monitoring and its capacity to enhance dynamic life cycle inventories, demonstrating that sensors, IoT technology, and real-time monitoring may elevate LCA data quality and provide more adaptive environmental assessments. Nonetheless, they emphasized that the practical execution and ecological costs of monitoring devices must be taken into account.

Hagen et al. (2020) presented the concept of Live-LCA within learning factories, integrating physical production systems, sensors, computational models, and environmental assessments to deliver real-time feedback on the impacts of product life cycles. This study offers a significant methodological foundation for the application of real-time LCA in operational systems, where environmental performance varies with process conditions, despite not being specific to maritime contexts.

Live-LCA approaches have shown the capability of integrating near-real-time data with environmental assessments. Park et al. (2022) created a Live-LCA model for an electric

propulsion vessel utilizing solar photovoltaic technology. Their methodology employed simulation-based operational data to evaluate the environmental performance of solar-electric propulsion across various regional and climatic contexts. This study is significant as it illustrates the incorporation of dynamic operational and environmental conditions into maritime life cycle assessment, moving beyond reliance on static assumptions.

Digital twin methodologies advance this area further. Kim (2025) created a real-time lifecycle analysis model that incorporates digital twin technology and optimal load control for electric and hybrid propulsion vessels. The research demonstrated that real-time LCA facilitates ongoing monitoring of lifecycle GHG performance and supports operational decision-making. The author emphasized the necessity for additional validation through the use of actual operational data, sampling intervals, and data communication systems.

Artificial intelligence and machine learning are increasingly integrated with LCA. Wan et al. (2024) developed an artificial neural network (ANN)-LCA framework to forecast meteorological impacts on the environmental sustainability of large-scale solar plants. Similarly, Yu et al. (2024) combined LCA with machine learning to predict the environmental impacts of smallholder wheat production under future climate scenarios. Although these studies are not specific to maritime contexts, they illustrate how machine learning can enhance prediction, scenario analysis, and environmental decision-making in systems affected by complex and uncertain variables. Mehdi et al. (2024) integrated LCA with a neural network model to evaluate energy consumption and environmental emissions in sugar beet production, illustrating the role of artificial intelligence in enhancing predictive environmental assessment. The study, while not specific to maritime contexts,

is methodologically significant as it demonstrates how machine learning can enhance LCA by transitioning from static evaluations to predictive modeling in variable system conditions.

Recent reviews elucidate the differences between dynamic and real-time LCA. Vyrkou et al. (2025) found that dynamic LCA has seen growing application in sectors including buildings, waste management, agriculture, and utilities, whereas real-time LCA is infrequently used and has not been widely adopted in industrial practice. This differentiation is significant for maritime applications, as port and vessel operations generate continuous data streams that could enable real-time environmental evaluation.

AIS-based methodologies hold significant importance for maritime LCA. Jang et al. (2024) conducted a comparison between predictive modeling and LCA simulation regarding ship operational CO₂ emissions, revealing that predictive model outcomes were approximately 83% higher than those from LCA simulations. This discrepancy arose because simplified LCA simulations failed to adequately account for engine characteristics, external forces, and operational conditions. Similarly, Wang et al. (2025) incorporated AIS-derived vessel activity into green corridor LCA, utilizing operational data to analyze TTW uncertainty. These investigations demonstrate that AIS and operational data enhance the precision of maritime LCA by accurately reflecting vessel movement, speed variations, and routing behavior.

In essence, real-time, AIS-based, digital twin, and AI-enhanced LCA methodologies signify a significant advancement in the field. They provide the capability to transition marine LCA from a static, assumption-driven evaluation to a dynamic, operationally

resolved, and decision-support-focused modeling approach. Still, current applications are constrained, disjointed, and frequently centered on particular technology or case studies. This underscores the necessity for the advancement of time-resolved marine LCA frameworks, especially for port-boundary emissions and operational phases, including approach, anchoring, maneuvering, berthing, and departure.

2.6 Synthesis of Research Gaps and Proposed Methodology

The literature examined demonstrates that LCA is progressively acknowledged as a crucial instrument for assessing maritime decarbonization alternatives, especially since it encompasses effects beyond direct emissions from vessels. Nonetheless, the evidence indicates that marine LCA is methodologically fragmented, with variations in system boundaries, functional units, databases, impact categories, operational assumptions, and uncertainty management among studies. As a result, data from various research studies are sometimes challenging to compare, therefore constraining their use for strategic decision-making.

This limitation is especially important for this thesis because the decarbonization of shipping is not a static problem. Alternative marine fuels should be assessed not only based on their present WTW performance but also on the potential evolution of their carbon intensity within future energy systems, fuel production pathways, regulations, and operational conditions. Therefore, the primary deficiency lies not merely in the absence of fuel comparison studies, but in the lack of advanced LCA methods that can connect lifecycle emissions with both actual vessel activity and predictive future scenarios.

2.6.1 Limitations of Existing Maritime LCA Studies

Current maritime LCA studies offer significant insights into ship systems, alternative fuels, propulsion technologies, and operational emissions. Nonetheless, notable limitations persist. Jacquet et al. (2024) demonstrate that comprehensive maritime LCA studies are challenging to compare due to substantial methodological discrepancies, especially concerning functional units, system boundaries, databases, impact categories, temporal and spatial dimensions, as well as uncertainty and sensitivity analyses. This underscores the ongoing absence of methodological uniformity and sector-specific standardization in maritime LCA.

Roux et al. (2024) identify a comparable issue in their review of maritime fuel LCA studies, noting that despite the assessment of numerous alternative fuels, the literature continues to exhibit a lack of transparency regarding methodological choices and assumptions. A small proportion of studies provide comprehensive life cycle inventories or incorporate quantitative uncertainty analysis. This represents a significant vulnerability, as alternative marine fuels, particularly hydrogen, ammonia, methanol, e-fuels, and biofuels, are characterized by considerable uncertainty regarding production pathways, electricity sources, fuel supply chains, and onboard utilization.

A further limitation is that numerous maritime LCA studies are static and specific to individual cases. They frequently depend on representative vessels, average operating profiles, fixed emission factors, and contemporary background systems. While these assumptions facilitate preliminary comparisons, they inadequately represent actual shipping operations, where emissions fluctuate due to the industry's dynamic

characteristics. Consequently, existing LCA methodologies may fail to account for the operational variability that significantly impacts vessel emissions.

These limitations reduce the ability of existing LCA studies to support robust maritime decarbonization decisions. For this thesis, the key issue is that current methods are often unable to connect three essential dimensions: lifecycle fuel performance, real vessel activity, and future decarbonization pathways. This creates the need for enhanced LCA models that are more operationally detailed, future-oriented, and decision-relevant.

2.6.2 Comparative Synthesis and Fuel-Pathway Selection

The reviewed literature indicates that maritime LCA has evolved from traditional comparative evaluations to prospective, uncertainty-aware, forecast-oriented, and operationally informed methodologies. Table 2-1 presents a summary of key studies that are significant to the methodological approach and fuel-pathway selection utilized in this thesis. The table serves to complement the comprehensive 71-source critical-review matrix found in Appendix APPENDIX C, rather than duplicating it.

Table 2-1. Comparative synthesis of selected studies informing the methodological approach and fuel-pathway selection of this thesis.

Source	Approach	Primary distinction	Main methodological limitation	Fuels / pathways assessed
Brynolf et al. (2014)	Comparative maritime LCA	Comparison of fossil- and biomass-derived fuel pathways across the lifecycle.	Static and pathway-specific; sensitive to production and supply-chain assumptions.	LNG, liquefied biogas, methanol, bio-methanol
Law et al. (2021)	Comparative multi-fuel lifecycle assessment	Broad comparison based on lifecycle energy, emissions and cost.	Relies substantially on literature and modelling assumptions, with limited operational resolution.	HFO, LNG, hydrogen, ammonia, methanol, biofuels, electricity and other alternatives
Kanchiralla et al. (2022)	Prospective LCA and LCC	Future-oriented environmental and economic assessment of fossil-free shipping options.	Dependent on assumptions regarding future technologies, energy systems and costs.	E-methanol, hydrogen, ammonia, batteries, fuel cells, onboard carbon capture; MGO reference
Watanabe et al. (2022)	Prospective LCA	Incorporates future background systems, scenarios and uncertainty.	Scenario- and pathway-dependent.	Drop-in biofuels
Taghavifar and Perera (2023)	Uncertainty-aware LCA and LCCA	Integrates WTT/TTW assessment with sensitivity and Monte Carlo analysis.	Case-specific and dependent on operational and economic assumptions.	Diesel, LNG
Tomos et al. (2024); Zincir and Arslanoglu (2024)	Comparative WTW LCA	Broad lifecycle comparison of conventional and alternative marine fuels.	Mainly representative/static assessments with limited temporal resolution.	Conventional fuels, hydrogen, ammonia, methanol, biofuels and e-fuels

Wang et al. (2025)	AIS-supported, uncertainty-integrated LCA	Combines renewable-fuel uncertainty with AIS-derived vessel activity.	Corridor-specific and sensitive to pathway and operational assumptions.	Renewable hydrogen, ammonia and methanol
Chalaris et al. (2025)	Forecast-oriented LCA	Integrates lifecycle assessment with future demand, forecasting and regulatory analysis.	Uses a representative annual vessel profile rather than time-resolved AIS trajectories.	MDO, bio-methanol, e-methanol

The comparison further substantiates the fuel selection implemented in the two case studies. Methanol and ammonia are frequently identified in the literature as significant candidate fuels for maritime decarbonization, while conventional marine fuels are typically maintained as reference pathways. The literature indicates that lifecycle performance is significantly influenced by the production pathway, feedstock, and energy source, rather than solely by the type of fuel. This approach favors a pathway-oriented comparison instead of considering methanol or ammonia as uniform alternatives.

Thus, the Singapore–Rotterdam case study evaluates MDO, bio-methanol, and e-methanol, which correspond to conventional fossil, bio-derived, and renewable synthetic pathways, respectively. The case study of the Port of Busan broadens the comparison to include MDO, natural-gas-derived methanol, e-methanol, natural-gas-derived ammonia, and e-ammonia, facilitating an analysis of both fuel types and upstream production pathways under consistent vessel operating conditions. The selection of fuels is thus informed by literature and is representative, rather than comprehensive.

The methodological limitations outlined in Table 2-1 indicate that a comparison of fuels alone is inadequate. Fixed assumptions, unpredictable future scenarios, and inadequate representation of vessel-specific temporal variability limit current research. These limitations necessitate the exploration of forecast-based and time-resolved maritime life cycle assessment approaches, which are addressed in the subsequent subsection.

2.6.3 The Need for Time-Resolved and Forecast-Based Maritime LCA

The primary methodological requirement is time- or operationally resolved LCA. Shipping emissions are variable due to the non-static operational conditions of vessels. Emissions vary continuously throughout different phases of a voyage and associated port activities, such as approach, anchoring, maneuvering, berthing, and departure. A conventional static LCA model is insufficient to accurately depict the emissions profile of vessels within port boundaries or along designated routes.

Real-time maritime LCA can overcome this limitation by utilizing vessel activity data to estimate emissions with greater temporal and operational precision. This is especially pertinent for port applications, as emissions are concentrated in proximity to coastal populations and operational phases can differ markedly among vessel types. The development of a Port-LCA methodology is essential to enhance conventional LCA for time-resolved evaluation of vessel emissions within port boundaries.

A second methodological requirement is forecast-based LCA. Current fuel selections will function within the context of future energy, regulatory, and market conditions. The carbon performance of alternative fuels is contingent upon future availability of renewable electricity, advancements in fuel production technology, infrastructure development,

policy mandates, and shipping demand. Consequently, current LCA results are inadequate for guiding long-term fuel selection and maritime decarbonization strategies.

Forecast-based LCA addresses this gap by connecting lifecycle emission factors with prospective scenarios of fuel production, trade activity, vessel demand, and regulatory requirements. The primary objective of this thesis is to compare alternative marine fuels and to develop LCA methods that can evaluate their carbon performance using time-resolved and forecast-based simulations.

2.6.4 Research Gaps and Thesis Response

The critical review demonstrates that existing maritime LCA research has substantially advanced the assessment of marine fuels, propulsion technologies, and ship environmental performance. However, several methodological limitations continue to restrict its ability to support maritime decarbonization decisions under changing future and operational conditions. Based on the literature reviewed in this chapter, five principal research gaps are identified:

- Static and limited temporal representation of conventional LCA, restricting its ability to capture changes in fuel pathways, maritime activity, and emissions over time.
- Limited integration of prospective and forecast-based analysis, particularly in relation to evolving transport demand, alternative fuel pathways, energy systems, and regulatory conditions.
- Insufficient integration of time-resolved vessel activity and operational variability within lifecycle emissions assessment, particularly with respect to variations in vessel speed, engine load, operating duration, and movement.

- Methodological inconsistency and limited transparency across maritime LCA studies, particularly regarding system boundaries, functional units, databases, emission factors, and modelling assumptions.
- Limited treatment of uncertainty and sensitivity, despite substantial uncertainty associated with alternative-fuel production pathways, energy sources, supply chains, future maritime activity, and onboard fuel use.

Collectively, these gaps indicate that the principal limitation is not the absence of maritime fuel LCA studies, but the limited integration of lifecycle fuel assessment with both future maritime activity and detailed operational conditions. Static fuel comparisons remain valuable for environmental screening; however, maritime decarbonization decisions require an understanding of how lifecycle performance may evolve as demand, regulation, fuel-production pathways, and vessel operations change. The methodological response of this thesis is therefore to integrate established LCA with forecasting, scenario analysis, regulatory interpretation, and time-resolved vessel activity within a common maritime assessment framework.

2.6.5 Case-Study Selection and Link to the Research Gaps

The identified research gaps also directly inform the selection of the two case-study applications used in this thesis. The Singapore–Rotterdam containership green corridor is selected to address the strategic and prospective dimensions of maritime decarbonization. The case study provides a context in which lifecycle fuel performance can be examined together with future container demand, fleet requirements, alternative fuel-production pathways, and evolving regulatory requirements. It therefore addresses particularly the

limitations associated with static LCA and the limited integration of forecast-based and scenario-driven assessment. The case study uses a representative 8,000 TEU containership and evaluates alternative fuel pathways through a common WTW basis while extending the assessment to future activity and regulatory scenarios. This strategic and forecast-oriented role of the Singapore–Rotterdam application is consistent with the methodological structure subsequently applied in Chapter 5.

The Port of Busan case study is selected to address the operational and time-resolved dimensions of the identified research gaps. In contrast to the representative operational profile used at the corridor scale, the Busan application employs AIS-derived trajectories from seven anonymized container vessels to represent vessel-specific movement and operational variability. The framework converts these activity records into time-resolved estimates of distance, speed, propulsion demand, fuel consumption, and WTW emissions within a defined port boundary. Busan therefore provides an appropriate context for examining the limitations of static and aggregated vessel assumptions and for demonstrating how operational data can be incorporated into lifecycle emissions assessment. The case study also combines the resulting vessel-level emission intensities with future port-activity scenarios, allowing the operational and prospective dimensions of the framework to be linked.

The use of containerships in both case studies establishes a common maritime application context while allowing the framework to be examined at two complementary spatial and temporal scales. Chapter 5 uses a representative containership to investigate long-term corridor-level fuel, demand, and regulatory scenarios, whereas Chapter 6 uses individual

container-vessel trajectories to investigate vessel-specific operational variability within a port boundary. The two applications are not intended to produce directly comparable numerical results, as their functional units, system boundaries, and analytical purposes differ. Instead, they examine complementary dimensions of the same maritime decarbonization problem: the strategic implications of future fuel and activity pathways and the operational implications of vessel-specific activity.

The remaining research gaps concerning methodological transparency and uncertainty are addressed across both applications through the explicit definition of system boundaries, functional units, fuel pathways, modelling assumptions, scenario conditions, and sensitivity or robustness assessments. These elements are incorporated into the generalized methodology developed in Chapter 4 and adapted according to the analytical purpose and data availability of each case study.

Accordingly, the contribution of this thesis is not the invention of LCA, forecasting, or AIS-based analysis as individual techniques. Rather, it is their structured integration and maritime-specific adaptation into a framework capable of evaluating alternative marine fuel pathways across complementary strategic and operational decision scales. The Singapore–Rotterdam and Busan case studies therefore function as complementary demonstrations of how the research gaps identified through the literature review can be addressed through forecasting-oriented and time-resolved maritime LCA.

2.7 Closing Remarks

The principal findings arising from the literature review can be summarised as follows:

- The structured critical review of 71 sources published between 2006 and 2026 demonstrates the rapid development of maritime LCA, with 52 sources (73.24%) published from 2020 onwards. The literature has expanded from conventional static fuel comparisons towards prospective, uncertainty-aware, data-driven, and operationally informed approaches.
- Maritime fuel assessment requires a WTW lifecycle perspective, as environmental performance depends not only on onboard emissions but also on fuel-production pathways, feedstocks, electricity sources, supply chains, and operational assumptions. Consequently, alternative fuels cannot be evaluated reliably from the fuel type alone.
- The comparative literature supports the pathway-oriented fuel selection adopted in this thesis. MDO provides a conventional reference, while methanol, bio-methanol, e-methanol, ammonia, and e-ammonia enable comparison of conventional, bio-derived, fossil-derived alternative, and renewable synthetic pathways. The selected fuels are therefore representative of key pathways identified in the literature rather than an exhaustive set of maritime fuel options.
- Five principal methodological limitations emerge from the review: the predominantly static representation of conventional LCA, limited integration of prospective and forecasting methods, insufficient incorporation of time-resolved vessel activity, methodological inconsistency and limited transparency between studies, and incomplete treatment of uncertainty and sensitivity. Existing assessments consequently remain

limited in their ability to connect lifecycle fuel performance, future maritime activity, and actual vessel operations.

- These gaps establish the basis for the methodological approach developed in the thesis: an integrated forecasting-oriented and time-resolved maritime LCA framework. The Singapore–Rotterdam case study addresses the strategic, future-oriented dimension through demand forecasting, lifecycle fuel pathways, and regulatory assessment, while the Port of Busan case study addresses the operational dimension through AIS-derived, time-resolved vessel activity. These applications are complementary rather than directly numerically comparable and collectively provide the basis for addressing the research questions developed in the following chapters.

3 Research Aim and Objectives

This chapter articulates the research gap identified in the preceding chapters into the research question, aim, objectives, and implementation approach of the thesis. It delineates the primary research question and positions the study within a unified maritime LCA framework, executed through two complementary applications: a forecast-oriented green-corridor assessment and an AIS-based, time-resolved port-boundary assessment. The chapter delineates the research objectives, the criteria employed to evaluate the enhancement of conventional maritime LCA, and the primary tasks through which the research is executed.

3.1 Fundamental question

The shift to low- and zero-carbon transportation necessitates dependable approaches for evaluating the lifetime efficacy of alternative marine fuels. LCA offers a methodical framework for assessing emissions during fuel production, distribution, and utilization aboard vessels. Conventional LCA systems are frequently constrained by static operating assumptions, oversimplified activity profiles, and inadequate incorporation of future demand and fuel-transition scenarios. These constraints diminish their capacity to facilitate decision-making in a sector characterized by quickly altering operating conditions, fuel supply, regulations, and technological maturity.

As introduced in Section 1.5, this thesis is guided by the following fundamental research question, which is restated here to establish its direct alignment with the research aim and objectives:

How can forecasting and time-resolved life cycle assessment enhance the evaluation of alternative marine fuel pathways for maritime decarbonization across green-corridor and port-boundary scales?

3.2 Aim and Objectives

This thesis aims to develop and apply an integrated maritime LCA framework that combines forecasting and time-resolved operational analysis to assess alternative marine fuel pathways across green-corridor and port-boundary scales. Specifically, the thesis develops a single overarching maritime LCA framework that is implemented through two complementary applications rather than two independent methodologies. The two applications share a common methodological basis comprising WTW lifecycle accounting, explicit goal and scope definition, fuel-pathway comparison, scenario-based interpretation, and decision-support objectives. They differ, however, in their spatial and temporal scales and in the activity data used. The Singapore–Rotterdam application employs a representative containership operating profile and forecasting to support long-term green-corridor assessment, whereas the Port of Busan application employs AIS-derived vessel activity to support time-resolved port-boundary assessment. The two applications therefore examine complementary strategic and operational dimensions of maritime decarbonization and are not intended to produce directly comparable absolute numerical results.

To attain this aim, the following objectives must be fulfilled:

Objective 1: To develop an integrated methodological framework combining LCA, forecasting, scenario analysis, regulatory interpretation, and AIS-derived operational data, providing the methodological basis for addressing the fundamental research question.

Objective 2: To apply the forecasting component of the framework to the Singapore–Rotterdam containership green corridor and evaluate selected alternative marine fuel pathways under future demand and regulatory scenarios, considering WTW emissions, FuelEU Maritime performance, EU ETS exposure, and associated compliance-cost implications (*addressing RQ1*).

Objective 3: To develop and apply an AIS-based, time-resolved Port-LCA framework to the Port of Busan, enabling the evaluation of selected alternative marine fuel pathways, vessel operational variability, port-boundary WTW emissions, and future port-activity scenarios (*addressing RQ2*).

Objective 4: To synthesize the findings from the green-corridor and port-boundary applications and identify their broader methodological, practical, regulatory, and policy implications for maritime decarbonization decision-making (*addressing RQ3*).

The four objectives collectively address the fundamental research question by establishing the overarching framework, analyzing its forecast-oriented and time-resolved applications, and synthesizing the resulting methodological and decision-support insights.

Enhancement of conventional maritime LCA is assessed according to the following criteria:

- **Future-oriented capability:** representation of future maritime activity and changing conditions through forecasting and scenario analysis.
- **Operational resolution:** representation of vessel-specific and time-resolved operational variability.

- **Lifecycle completeness:** differentiation of WTT, TTW, and WTW emissions across fuel pathways.
- **Decision-support relevance:** interpretation of results in relation to regulatory, operational, and strategic maritime decisions.
- **Methodological transparency and robustness:** explicit assumptions, consistent comparisons, forecast-error assessment, sensitivity analysis, and acknowledgement of validation constraints.

3.3 Approaches

To accomplish the aforementioned study aims and goals, specific activities were executed as delineated in the accompanying diagram and elaborated on below.

Task 1.1: Critical Review of Maritime Life Cycle Assessment Approaches

This task entails a critical review of current maritime LCA studies, focusing on the methodological limitations that hinder their applicability to future-oriented and operationally detailed evaluations. Attention is focused on static operating assumptions, simplified vessel activity profiles, inconsistent system boundaries, limited treatment of regulatory developments, and restricted integration of forecasting and time-resolved operational data.

Task 1.2: Definition of the Methodological Framework

This task delineates the essential methodological components necessary for the integrated framework, encompassing system boundaries, functional units, fuel pathways, environmental indicators, regulatory parameters, data requirements, and scenario

assumptions. Establishing these elements ensures consistency between the two case-study applications while enabling each methodology to address the specific characteristics of the green-corridor and port-boundary assessment scales.

Task 1.3: Integration of Forecasting and Time-Resolved Operational Analysis

This task incorporates forecasting, scenario analysis, regulatory assessment, and operational analysis derived from AIS within the comprehensive framework of LCA. The forecasting component facilitates the assessment of future fuel demand and regulatory exposure, while the time-resolved component records fluctuations in vessel activity and emissions within port boundaries. Their integration allows the framework to assess various marine fuel pathways across complementary temporal and spatial dimensions.

Task 2.1: Development of Future Transport Demand Scenarios

This task involves the development of future transport-demand scenarios for the Singapore–Rotterdam green corridor through econometric analysis and forecasting. Historical data on container transport and socioeconomic factors are analyzed to identify appropriate explanatory relationships, which are then utilized to forecast future corridor activity under central, lower, and higher demand scenarios. These projections serve as the operational foundation for assessing the future performance of the chosen marine fuel pathways.

Task 2.2: Evaluation of Regulatory and Compliance Costs

This task assesses the chosen alternative marine fuel pathways within the established transport-demand scenarios. The assessment measures WTW GHG emissions and evaluates performance in relation to FuelEU Maritime and the EU ETS. The regulatory exposure and related compliance-cost implications are analyzed to facilitate the comparison of fuel pathways considering evolving maritime decarbonization requirements.

Task 3.1: Development of Time-Resolved Vessel Operational Profiles

This task analyzes AIS-derived vessel activity data to create time-resolved operational profiles within the specified Busan port boundary. Vessel movements are categorized based on their operational phases, with speed, distance, duration, engine load, and fuel consumption characteristics determined at the necessary temporal resolution. These operational profiles serve as the foundational activity data for the emissions calculations in the Port-LCA.

Task 3.2: Port-Boundary Emissions and Scenario Evaluation

This study quantifies the time-resolved WTW emissions of selected alternative marine fuel pathways within the Busan port boundary. The assessment analyzes differences among vessels, operational phases, and activity conditions, thereby illustrating the impact of operational variability on emissions at the port level. Future port activity scenarios are analyzed to evaluate the impact of variations in vessel traffic and fuel adoption on the environmental performance of the port system.

3.4 Closing Remarks

The principal elements established in this chapter can be summarized as follows:

- The thesis is guided by the fundamental research question of how forecasting and time-resolved LCA can enhance the evaluation of alternative marine fuel pathways across green-corridor and port-boundary scales.
- A single overarching maritime LCA framework is developed and implemented through two complementary applications. The Singapore–Rotterdam application addresses long-term strategic assessment through forecasting, while the Port of Busan application addresses operational assessment through AIS-derived, time-resolved vessel activity.
- The four research objectives provide a structured response to the research question: Objective 1 establishes the common methodological framework, Objective 2 addresses the forecast-oriented green-corridor assessment and RQ1, Objective 3 addresses the time-resolved port-boundary assessment and RQ2, and Objective 4 integrates the resulting methodological, practical, regulatory, and policy insights associated with RQ3.
- Enhancement of conventional maritime LCA is evaluated through future-oriented capability, operational resolution, lifecycle completeness, decision-support relevance, and methodological transparency and robustness.

- The research tasks translate these objectives into the analytical activities required for the development and application of the framework. The detailed methodological procedures are presented in Chapter 4.

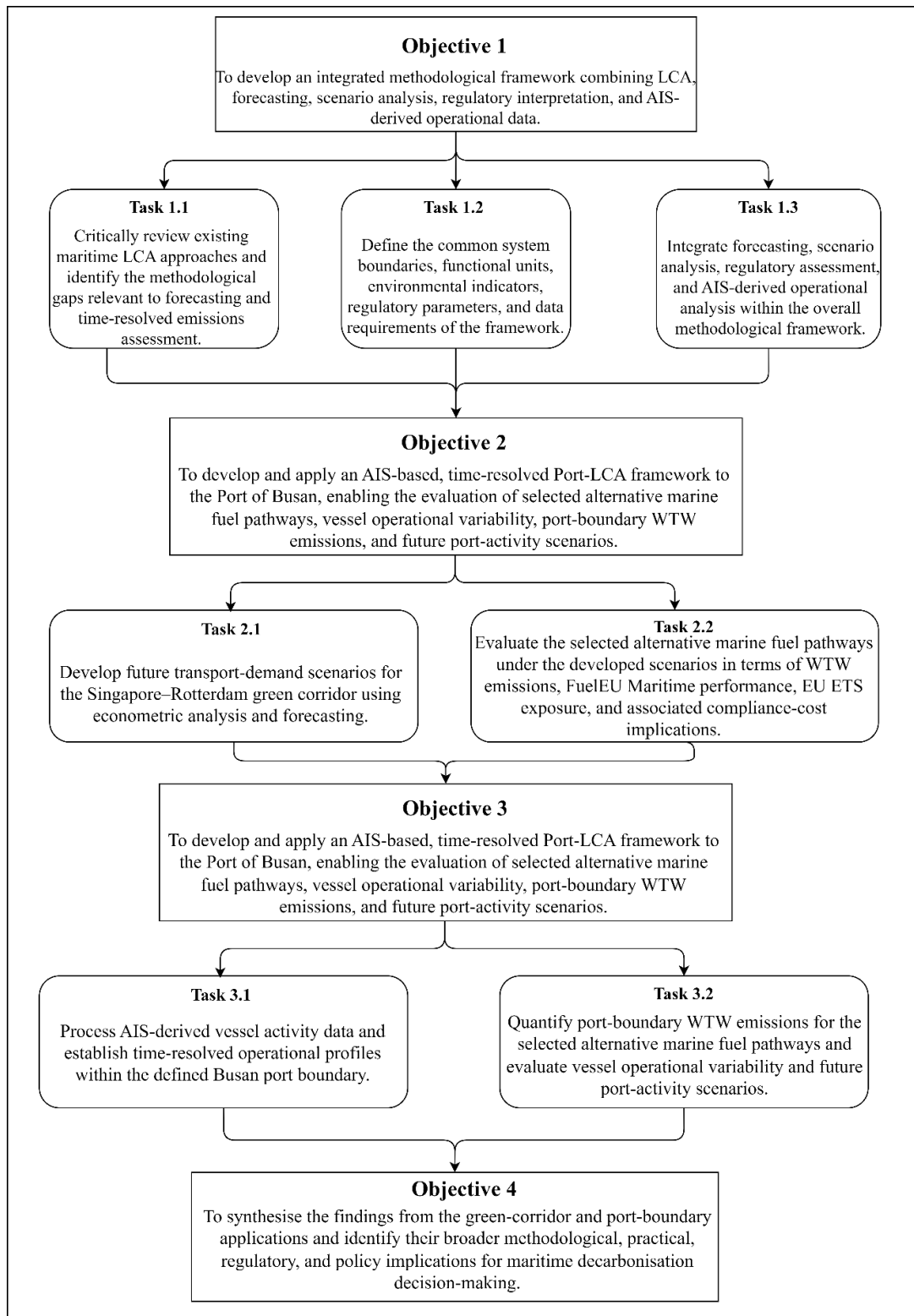


Figure 3-1. Outline flowchart for the research

4 Methodology

The methodology presented in this chapter establishes a generalized framework for evaluating maritime emissions using a time-resolved and forecast-based LCA approach. The framework is designed for applicability across various maritime contexts, including port areas, shipping routes, green corridors, and broader operational zones. It consists of six sequential methodological steps: defining goals, scope, and system boundaries; reconstructing trajectories and profiling activities based on AIS; modeling propulsion power and fuel consumption; developing a time-resolved lifecycle emissions inventory; projecting activities and emissions based on forecasts; and producing outputs for comparison and decision support. This structure facilitates the assessment of vessel activity, fuel consumption, lifecycle emissions, and future emissions trajectories in an integrated and transparent manner. The proposed methodological framework's general structure is illustrated in Figure 4-1, with a detailed analysis of each stage provided in the subsequent sections of this chapter.

To clarify the methodological positioning of the proposed framework, Table 4-1 compares its relationship with attributional, consequential, and prospective/ex-ante LCA approaches identified in the literature review.

Table 4-1. Positioning of the proposed framework in relation to established LCA approaches.

LCA approach	Main purpose	Position in this thesis	Consequences for system boundaries, data and interpretation	Relevant literature
Attributional LCA	Quantifies environmental burdens associated with a defined product or system under specified conditions.	Primary lifecycle-accounting basis of the framework.	Uses explicitly defined WTT and TTW boundaries, selected fuel-production pathways and case-specific functional units. Results represent the environmental performance of the assessed pathways under the stated assumptions.	Moretti et al. (2022); ISO (2006a, 2006b)
Consequential LCA	Examines the wider environmental consequences arising from changes in demand, policy or technology.	Not adopted as the primary approach.	Marginal suppliers, market displacement, rebound effects and wider economic-system responses are not modelled. Results should therefore not be interpreted as the full system-wide consequences of large-scale fuel adoption or policy intervention.	Earles & Halog (2011)
Prospective/ex-ante LCA	Assesses emerging technologies or systems under anticipated future conditions.	Partially incorporated through the forecast-oriented and scenario-based extension of the framework.	Future maritime activity, selected fuel pathways and regulatory conditions are represented through forecasts and scenarios. Future foreground and background systems are not comprehensively reconstructed; results therefore represent conditional future scenarios rather than a complete ex-ante LCA or deterministic prediction.	van der Giesen et al. (2020); Sacchi et al. (2022); Ingwersen et al. (2025)

Accordingly, the framework established in this thesis is best described as an attributional WTW maritime LCA with a forward-looking scenario extension. The attributional component establishes a framework for comparing specified fuel-production and onboard-use pathways within defined WTT and TTW system boundaries. Additionally, forecasting and scenario analysis broaden the evaluation to encompass future maritime activities and regulatory environments. The framework fails to account for the wider market-mediated effects necessary for consequential LCA and does not adequately reconstruct future foreground and background systems, which are essential for a thorough ex-ante evaluation. The results should be interpreted as specific to pathways and contingent upon the established production, operational, demand, and regulatory assumptions.

Methodological basis: *The proposed framework is grounded in the principles and requirements of ISO 14040 and ISO 14044 for life cycle assessment, while the maritime WTT, TTW, and WTW GHG accounting follows the IMO Guidelines on Life Cycle GHG Intensity of Marine Fuels (ISO, 2006a, 2006b; IMO, 2024).*

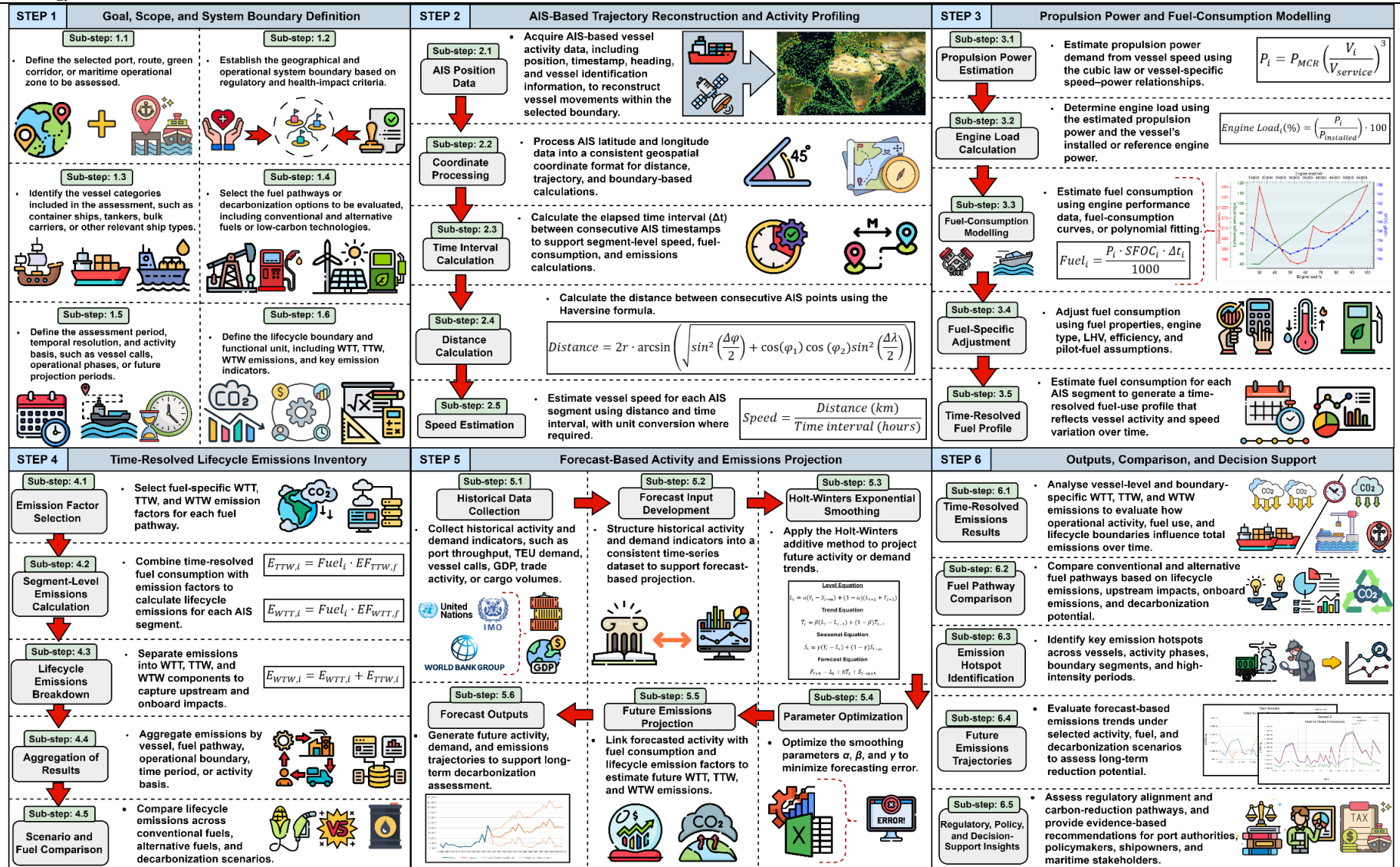


Figure 4-1. Generalized framework for time-resolved and forecast-based maritime life cycle assessment, comprising six sequential steps and their associated sub-steps.

4.1 Step1: Goal, Scope, and System Boundary Definition

The initial phase of the proposed methodology delineates the objective, scope, and system boundaries of the assessment. It defines the maritime system for evaluation, including geographical and operational boundaries, vessel categories and fuel pathways considered, assessment period and temporal resolution, as well as the life cycle boundary and functional unit. Figure 4-2 illustrates that this step consists of six sequential sub-steps that form the methodological foundation for the subsequent activities, including AIS-based activity reconstruction, fuel-consumption modeling, life cycle emissions calculation, forecasting, and decision-support analysis.

4.1.1 Sub-step 1.1: Maritime System Selection

The methodology is structured to be relevant across various maritime contexts, encompassing individual ports, shipping routes, green corridors, and broader maritime operational zones. The chosen context delineates the spatial and operational parameters of the assessment. For instance, a port-based application may concentrate on vessel movements within a specified port boundary, whereas a route- or corridor-based application may analyze emissions related to an entire voyage between multiple ports. This flexibility enables the framework to be tailored to various research objectives, data availability, and policy requirements.

4.1.2 Sub-step 1.2: Geographical and Operational System Boundary Definition

After selecting the assessment context, the geographical and operational system boundary is defined. The geographical boundary delineates the physical area encompassing vessel activity, whereas the operational boundary specifies the activities or phases of operation included in the analysis. Regulatory requirements or policy priorities, and health-impact considerations may determine boundaries. In port-related studies, the boundary is crucial as emissions near populated coastal areas can directly impact air quality and human exposure. In route or green corridor applications, the boundary may reflect the operational scope of the voyage and the corresponding decarbonization pathway.

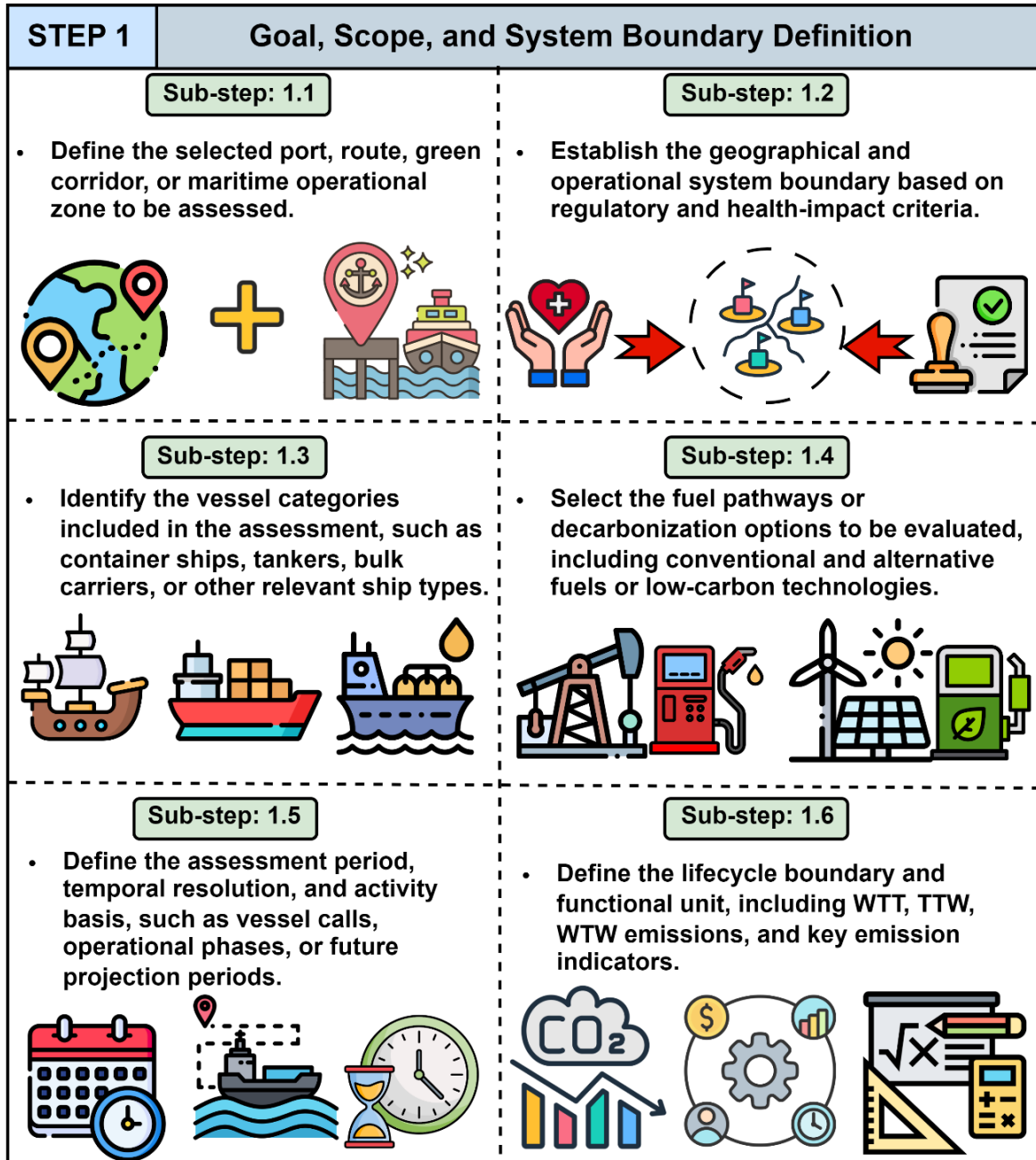


Figure 4-2. Goal, scope, and system boundary definition through six sequential sub-steps.

4.1.3 Sub-step 1.3: Vessel Category Selection

The subsequent component of this sub-step involves identifying the vessel categories included in the assessment. Various ship types, including container ships, tankers, bulk carriers, passenger vessels, and service vessels, exhibit distinct operational profiles, power characteristics, fuel consumption patterns, and emissions intensities. Defining the relevant vessel categories ensures that subsequent modeling stages align with the technical and operational characteristics of the fleet under investigation. This permits the disaggregation of results by vessel type, facilitating the identification of categories that significantly contribute to total emissions.

4.1.4 Sub-step 1.4: Fuel Pathway and Decarbonization Option Selection

The fuel pathways and decarbonization options are established at this sub-step. The selection is crucial as lifecycle performance relies on the fuel utilized onboard as well as factors including feedstock, production technology, electricity source, hydrogen-production method, and upstream supply chain. Thus, fuels characterized by low onboard emissions may still demonstrate considerable well-to-wheel emissions when generated via carbon-intensive methods.

In this thesis, fuel selection was guided by a comprehensive literature review, its significance to maritime decarbonization and regulation, diversity of production pathways, availability of data, and the practical development of alternative fuel infrastructure and investment within the case study contexts. Attention was focused on current and planned production, bunkering, and infrastructure developments pertinent to Singapore and Rotterdam. This process resulted in the evaluation of MDO, bio-methanol, and e-methanol

within the Singapore–Rotterdam context, whereas the Busan application expanded the comparison to include MDO, natural-gas-derived methanol, e-methanol, natural-gas-derived ammonia, and e-ammonia. The chosen pathways are thus representative, not exhaustive.

4.1.5 Sub-step 1.5: Assessment Period, Temporal Resolution, and Activity Basis

The assessment period, temporal resolution, and activity basis are then specified. The assessment period delineates the duration encompassed by the analysis, which may align with a representative operational timeframe, a complete year, or a prospective projection horizon. The temporal resolution defines the detail at which vessel activity and emissions are assessed, including AIS segment level, vessel-call level, operational phase level, daily or annual aggregation, or projected future periods. The activity basis delineates the unit of operational activity employed to organize the assessment, including vessel calls, nautical miles traveled, operational phases, cargo transported, energy demand, or future activity indicators. These choices affect the details of the emissions inventory and the analysis of the results.

4.1.6 Sub-step 1.6: Life Cycle Boundary, Functional Unit, and Emission Indicators

Finally, the lifecycle boundary and functional unit have been established. The lifecycle boundary delineates the emissions considered in the assessment, including WTT, TTW, and/or WTW emissions. WTT emissions encompass upstream processes such as fuel

production, processing, transport, and distribution. TTW emissions denote the emissions produced onboard during the operation of a vessel. WTW emissions encompass both components, offering a comprehensive representation of the total climate impact associated with a fuel pathway. The functional unit establishes a uniform framework for comparison among vessels, fuels, scenarios, or operational contexts. Depending on the study's objective, the functional unit may be defined as total emissions within a specified boundary, emissions per vessel call, emissions per voyage, emissions per unit of transported cargo, or emissions per unit of energy consumed.

This step guarantees that the assessment is well-defined, reproducible, and methodologically consistent. By defining the study context, system boundary, vessel categories, fuel pathways, temporal scope, lifecycle boundary, and functional unit, the framework establishes a clear foundation for the subsequent reconstruction of vessel activity utilizing AIS data.

4.2 Step 2: AIS-Based Trajectory Reconstruction and Activity Profiling

The second step of the proposed methodology entails the reconstruction of vessel trajectories and the development of time-resolved activity profiles utilizing AIS data. Figure 4-3 illustrates that this step consists of five sequential sub-steps: acquisition of AIS position data, processing of coordinates, calculation of time intervals, calculation of distances, and estimation of segment-level speeds. Together, these procedures convert raw vessel-position records into a structured operational dataset that supplies the necessary

inputs for subsequent calculations of propulsion power, fuel consumption, and life cycle emissions.

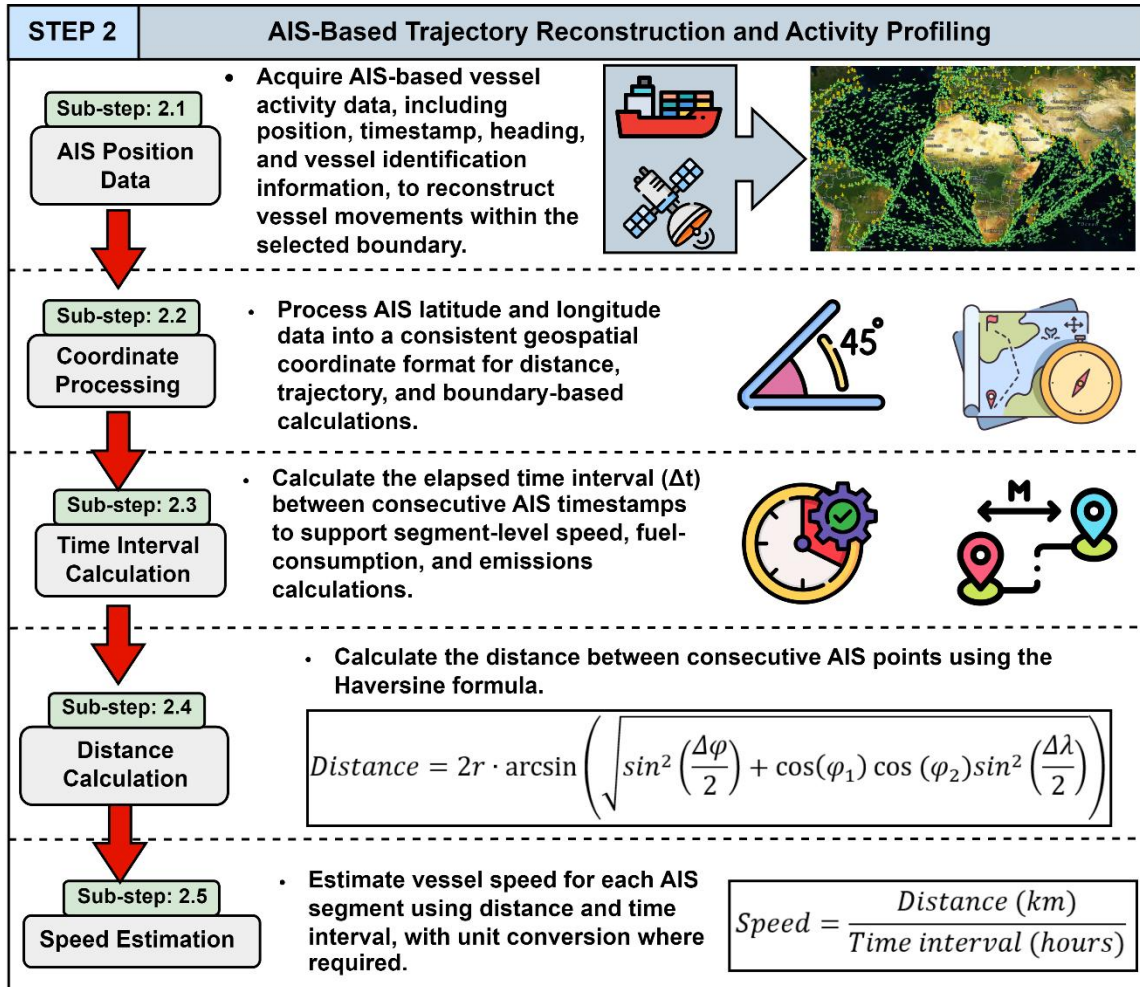


Figure 4-3. AIS-based trajectory reconstruction and activity profiling through five sequential sub-steps.

4.2.1 Sub-step 2.1: AIS Position Data Acquisition

The starting point of this sub-step entails the acquisition of AIS-based vessel activity data within the defined geographical and operational boundaries. AIS records contain data on vessel position, timestamp, heading, and identification, facilitating the tracking of vessel movements over time. Depending on the study's scope, the AIS dataset may encompass all

vessels operating within a port boundary, vessels traversing a designated route, or specific vessel categories linked to a green corridor or maritime operational zone. Each AIS record serves as a time-stamped observation of vessel activity, which is fundamental for trajectory reconstruction.

4.2.2 Sub-step 2.2: Coordinate Processing

After data acquisition, AIS latitude and longitude values are converted into a standardized geospatial coordinate format. Raw AIS position data are initially converted to decimal degrees and then transformed into radians, as the Haversine distance calculation necessitates angular values in radians. When AIS coordinates are presented in raw encoded form, latitude and longitude can be transformed into decimal degrees as follows:

$$\phi_{\text{deg}} = \frac{Lat_{\text{raw}}}{6 \cdot 10^5}, \quad \lambda_{\text{deg}} = \frac{Lon_{\text{raw}}}{6 \cdot 10^5} \quad \text{Eq. (4-1)}$$

where ϕ_{deg} and λ_{deg} represent latitude and longitude in decimal degrees, respectively, while Lat_{raw} and Lon_{raw} represent the raw AIS latitude and longitude values. The factor $6 \cdot 10^5$ reflects the AIS coordinate resolution, where coordinates are commonly encoded in units of 1/10000 of a minute. If the AIS dataset already provides latitude and longitude in decimal degrees, this initial conversion step is not required.

The decimal-degree coordinates are then converted into radians using:

$$\phi_{\text{rad}} = \phi_{\text{deg}} \cdot \frac{\pi}{180}, \quad \lambda_{\text{rad}} = \lambda_{\text{deg}} \cdot \frac{\pi}{180} \quad \text{Eq. (4-2)}$$

where ϕ_{rad} and λ_{rad} are the latitude and longitude values expressed in radians.

This coordinate processing step ensures that vessel positions can be accurately used for distance, trajectory, and boundary-based calculations. It facilitates the identification of consecutive vessel positions and allows for the reconstruction of movement segments between AIS points. Each segment denotes the movement of a vessel between two successive AIS records and constitutes the fundamental unit for time-resolved activity modeling.

4.2.3 Sub-step 2.3: Time-Interval Calculation

The interval between successive AIS records is subsequently calculated. For each vessel movement segment, the elapsed time interval Δt , is defined as the difference between two successive AIS timestamps in seconds.

$$\Delta t_i = t_{i+1} - t_i \quad \text{Eq. (4-3)}$$

where Δt_i is the elapsed time for segment i , t_i is the timestamp of the first AIS record, and t_{i+1} is the timestamp of the following AIS record.

This time interval is significant as it establishes the temporal resolution for each vessel movement segment, which is subsequently utilized in calculations of speed, fuel consumption, and emissions.

4.2.4 Sub-step 2.4: Distance Calculation

Following the calculation of the elapsed time, the distance between consecutive AIS points is determined using the Haversine formula, which calculates the great-circle distance between two points on the Earth's surface based on their latitude and longitude coordinates.

For each AIS segment, the distance can be represented as follows:

$$d = 2R \cdot \arcsin \left(\sqrt{\sin^2 \left(\frac{\Delta\phi}{2} \right) + \cos(\phi_1) \cdot \cos(\phi_2) \cdot \sin^2 \left(\frac{\Delta\lambda}{2} \right)} \right) \quad \text{Eq. (4-4)}$$

where d represents the distance between two points (km), R is the Earth's radius (6,378 km), $\Delta\phi$ denotes the difference in latitude, and $\Delta\lambda$ represents the difference in longitude. This approach facilitates the precise reconstruction of vessel trajectories and the distance traversed within the port boundary. The processed dataset, shown in radians, underpins future calculations of vessel speed consistency, time-in-mode allocation, and energy demand estimation.

4.2.5 Sub-step 2.5: Speed Estimation

Once distance and time interval have been calculated, vessel speed is estimated for each AIS segment. Segment-level speed is calculated by dividing the distance travelled by the elapsed time interval, with appropriate unit conversions applied to obtain speed in both km/h and knots:

$$V = \frac{d}{\Delta t} \quad \text{Eq. (4-5)}$$

Segment-level speed estimation is crucial as vessel speed serves as a primary input for propulsion power estimation in the following stage of the methodology. Propulsion power is significantly affected by speed; thus, the precision of the speed profile directly impacts the accuracy of subsequent fuel consumption and emissions calculations.

In summary, this step transforms unprocessed AIS position records into a structured, time-resolved profile of vessel activity. Through the calculation of coordinate positions, time intervals, traveled distances, and segment-level speeds, the methodology establishes the

operational foundation for modeling propulsion power demand and fuel consumption. The outputs from this stage are subsequently transmitted to the next step of the framework, where vessel speed and activity data are utilized to estimate propulsion power and fuel consumption.

4.3 Step 3: Propulsion Power and Fuel-Consumption Modelling

The third stage of the proposed methodology translates the AIS-based activity profile created in the preceding step into propulsion power demand, engine load, and fuel consumption. This step is crucial as vessel emissions correlate directly with the quantity of fuel utilized during operation. Utilizing segment-level vessel speed and time-interval data, the methodology quantifies fuel consumption in a time-resolved manner, enabling the incorporation of variations in vessel activity and speed into the subsequent lifecycle emissions inventory.

4.3.1 Sub-step 3.1: Propulsion-Power Estimation

The first element of this step involves estimating the propulsion power demand based on vessel speed. In maritime applications, the correlation between vessel speed and propulsion power is typically represented by the cubic law, which posits that propulsion power varies with the cube of vessel speed. This demonstrates the significant impact of speed on hydrodynamic resistance and the power requirements of the engine.

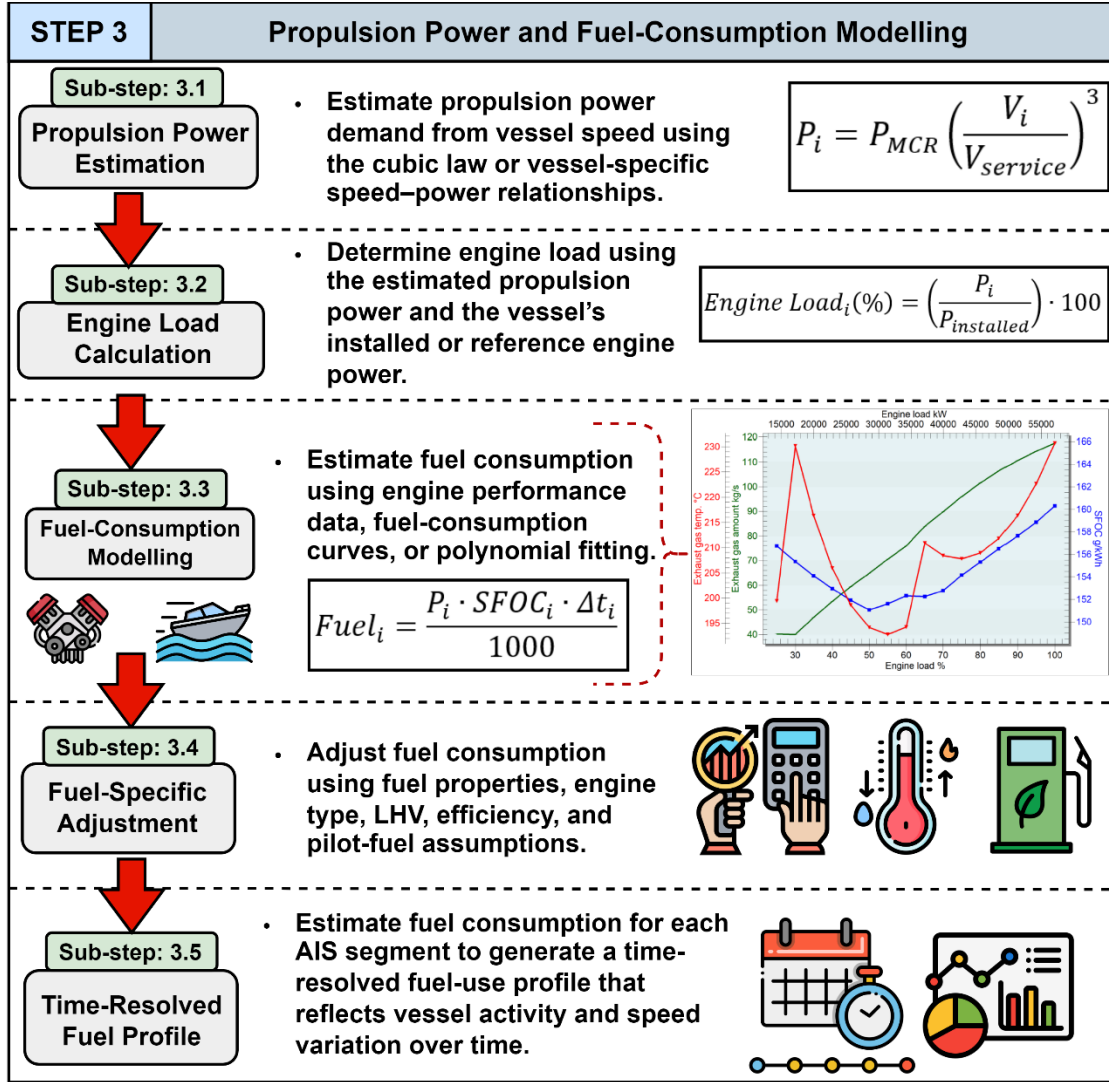


Figure 4-4. Propulsion-power and fuel-consumption modelling through five sequential sub-steps.

In the proposed methodology, the propulsion power for each AIS segment is estimated as follows (Berthelsen & Nielsen, 2021):

$$P \propto V^3$$

or, in normalized form,

$$P_i = P_{MCR} \left(\frac{V_i}{V_{service}} \right)^3 \quad \text{Eq. (4-6)}$$

where P_i is the estimated propulsion power for AIS segment i , P_{MCR} is the maximum continuous rating or reference engine power, V_i is the estimated vessel speed for segment i , and $V_{service}$ is the vessel service speed. Vessel-specific speed–power curves or manufacturer data, when available, can be utilized in place of the simplified cubic-law relationship to enhance the precision of power estimation.

4.3.2 Sub-step 3.2: Engine-Load Calculation

After estimating propulsion power, engine load is determined for each AIS segment. Engine load indicates the ratio of installed or reference engine power necessary to satisfy the projected propulsion power requirements. It establishes a connection between vessel activity and engine operating conditions, serving to facilitate fuel consumption estimation. Engine load is determined by the following calculation:

$$Engine\ Load_i(\%) = \frac{P_i}{P_{MCR}} \times 100 \quad \text{Eq. (4-7)}$$

where $Engine\ Load_i$ is the engine load percentage for segment i , P_i is the estimated propulsion power, and P_{MCR} is the main engine's maximum continuous rating (Seithe et al., 2020)

This calculation enables the model to represent how different vessel speeds correspond to different engine operating loads.

4.3.3 Sub-step 3.3: Fuel-Consumption Modeling

Fuel consumption modeling is conducted by integrating propulsion power, specific fuel oil consumption, and the time interval of each AIS segment. Fuel consumption can be estimated through engine performance data, fuel-consumption curves, manufacturer

information, or polynomial relationships fitted between engine load and specific fuel consumption. In the proposed framework, fuel consumption at the segment level can be articulated as follows:

$$FC_i = \frac{P_i \cdot SFOC_i \cdot \Delta t_i}{10^3} \quad \text{Eq. (4-8)}$$

where FC_i is the fuel consumed during AIS segment i , P_i is the estimated propulsion power in kW, $SFOC_i$ is the specific fuel oil consumption for the relevant engine load in g/kWh, and Δt_i is the time interval of the AIS segment in hours. The division by 10^3 converts fuel consumption from grams to kilograms when $SFOC_i$ is expressed in g/kWh. This formulation enables fuel consumption to be estimated at the same temporal resolution as the AIS activity data.

4.3.4 Sub-step 3.4: Fuel-Specific Adjustment

Following the acquisition of the initial fuel-consumption estimate, adjustments specific to each fuel type are implemented as necessary to ensure that various fuel pathways are represented on a comparable energy and operational basis. These adjustments consider variations in fuel properties, engine technology, lower heating value, fuel energy density, conversion efficiency, combustion behavior, and any auxiliary or pilot-fuel requirements. This is especially significant when comparing conventional marine fuels to alternative fuels, as the same propulsion power demand may necessitate varying quantities of fuel based on the fuel's energy content and the efficiency of the onboard conversion system. Fuels characterized by lower volumetric or gravimetric energy density necessitate a greater mass or volume to achieve equivalent useful energy output. Additionally, fuels including ammonia, methanol, and e-fuels demand pathway-specific considerations pertaining to

engine type, combustion mode, storage system, pilot fuel, or fuel-cell conversion. Thus, this adjustment step guarantees that fuel consumption is evaluated not merely as a mass-based comparison but as a calculation dependent on energy and technology, accurately reflecting the operational characteristics of each fuel pathway. This facilitates a more uniform comparison of conventional and alternative fuels before the calculation of lifecycle emissions in the subsequent phase.

4.3.5 Sub-step 3.5: Time-Resolved Fuel-Use Profile

The final product of this step is a time-resolved fuel-use profile for each vessel or vessel category. This profile evaluates fuel consumption for each AIS segment and accounts for the impact of vessel speed variation, operating time, and engine load on fuel demand. The time-resolved fuel-use profile serves as the direct input for the subsequent stage of the methodology, wherein fuel consumption is integrated with fuel-specific emission factors to compute WTT and TTW emissions.

4.4 Step 4: Time-Resolved Lifecycle Emissions Inventory

The fourth stage of the proposed methodology transforms the time-resolved fuel-use profile created in the preceding step into a lifecycle emissions inventory. This step connects segment-level fuel consumption with fuel-specific emission factors to estimate emissions across various lifecycle boundaries. By calculating emissions at the AIS-segment level, the methodology effectively captures the influence of vessel activity, speed variation, fuel use, and operational time on emissions within the defined boundary. This offers a more comprehensive depiction of maritime emissions compared to methods relying solely on annual fuel totals or generalized operating assumptions.

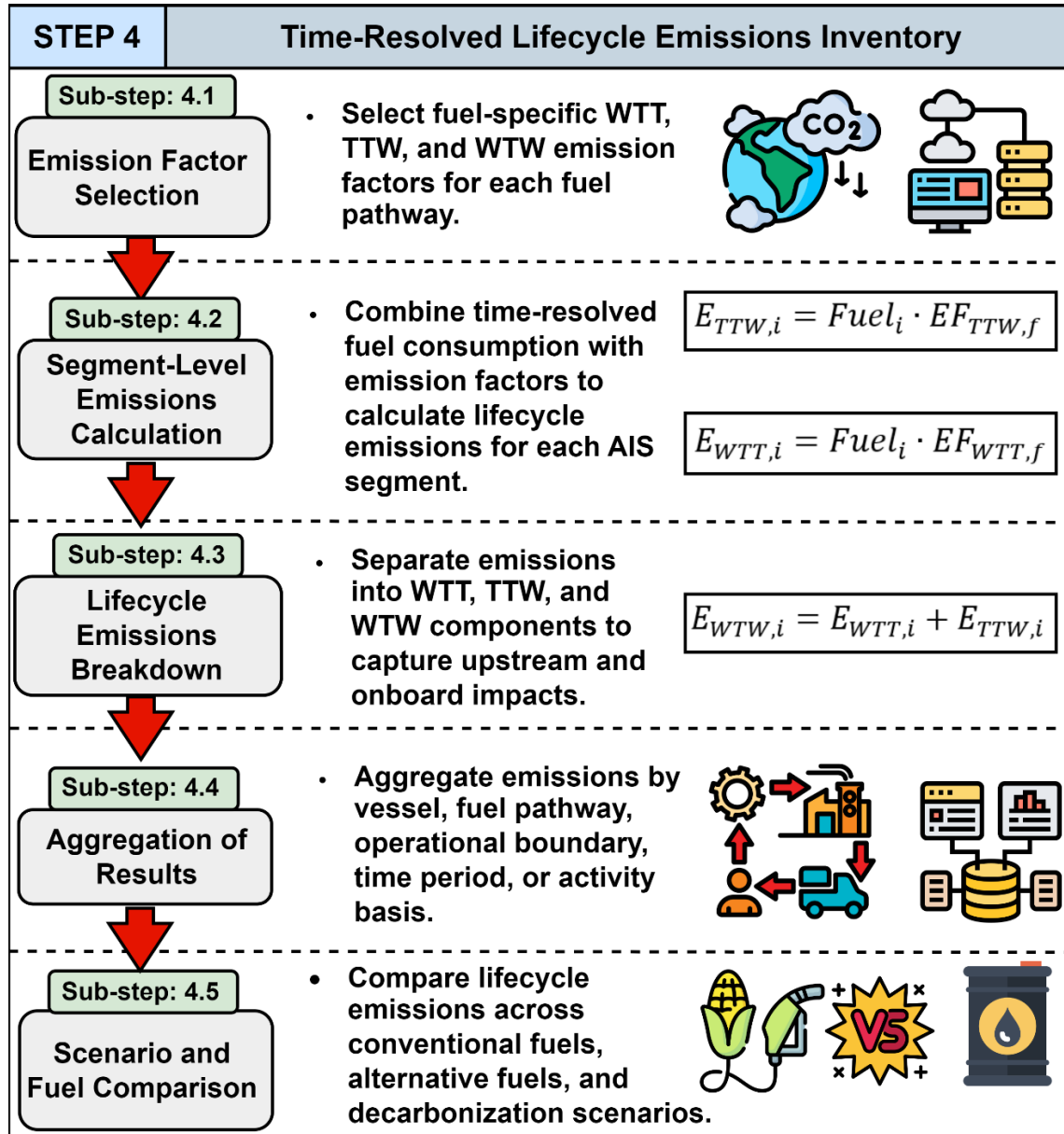


Figure 4-5. Development of the time-resolved life cycle emissions inventory through five sequential sub-steps.

4.4.1 Sub-step 4.1: Emission-Factor Selection

The initial component of this step involves selecting emission factors specific to the fuel type and identifying relevant impact assessment indicators. Emission factors are determined based on the specific fuel pathway under evaluation and the defined lifecycle boundary. In this methodology, emissions are categorized into WTT, TTW, and WTW

phases. WTT emission factors denote the upstream emissions linked to fuel production, processing, transportation, storage, and distribution. TTW emission factors denote the emissions generated by vessels during their operational phase. WTW emission factors integrate both upstream and onboard emissions, offering a comprehensive view of the fuel cycle. Alongside direct GHG emission factors, the methodology may integrate lifecycle impact assessment indicators derived from established methods, such as Centrum voor Milieukunde Leiden (CML) 2001, to assess relevant broader environmental impact categories. Impact factors may encompass indicators such as GWP, AP, EP, and additional midpoint impact categories, contingent upon the assessment's goal and scope. This distinction is crucial when comparing conventional and alternative fuels, as fuels characterized by low onboard emissions may still generate considerable upstream emissions or other environmental impacts, contingent upon their production pathways, feedstocks, energy sources, and supply chain assumptions.

4.4.2 Sub-step 4.2: Segment-Level Emissions Calculation

After selecting the appropriate emission factors, segment-level emissions are determined by multiplying the estimated fuel consumption for each AIS segment by the relevant fuel-specific emission factor. TTW emissions can be articulated for each segment as follows:

$$E_{TTW,i} = FC_i \cdot EF_{TTW,f} \quad \text{Eq. (4-9)}$$

where $E_{TTW,i}$ represents the TTW emissions for the AIS segment i , FC_i is the fuel consumed during segment i , and $EF_{TTW,i}$ is the TTW emission factor for the fuel pathway f (IMO, 2024).

Similarly, WTT emissions are calculated as:

$$E_{WTT,i} = FC_i \cdot EF_{WTT,f} \quad \text{Eq. (4-10)}$$

where $E_{WTT,i}$ represents the upstream emissions associated with the fuel consumed during the AIS segment i , and $EF_{WTT,f}$ is the WTT emission factor for the selected fuel pathway (IMO, 2024). These equations facilitate the calculation of emissions at the same temporal resolution as the activity and fuel-consumption profiles derived from AIS data.

4.4.3 Sub-step 4.3: Life Cycle Emissions Breakdown

The lifecycle emissions breakdown is then developed by combining the WTT and TTW components. WTW emissions for each AIS segment are calculated as:

$$E_{WTW,i} = E_{WTT,i} + E_{TTW,i} \quad \text{Eq. (4-11)}$$

where $E_{WTW,i}$ represents the total lifecycle emissions for the AIS segment i .

This breakdown allows the methodology to differentiate between upstream emissions and onboard emissions, which is crucial for assessing the actual environmental performance of various fuel pathways. For instance, a fuel may decrease TTW emissions while still exhibiting elevated WTT emissions if its production process relies on fossil energy sources. In contrast, fuels derived from renewable energy or sustainable feedstocks may result in reduced WTW emissions, even though their use on board still generates some emissions.

4.4.4 Sub-step 4.4: Aggregation of Results

Following the calculation of segment-level emissions, the results are aggregated based on the assessment's objective and boundary. Emissions can be aggregated according to vessel, vessel category, fuel pathway, operational boundary, time, voyage, port call, or activity basis. This aggregation step facilitates the conversion of detailed AIS-segment emissions into interpretable outputs, including total emissions within a port boundary, emissions per voyage, emissions per vessel category, and emissions under a specific fuel scenario. Aggregation facilitates the identification of activities, vessels, or fuel pathways that significantly contribute to total lifecycle emissions.

4.4.5 Sub-step 4.5: Scenario and Fuel Comparison

The final component of this sub-step involves comparing lifecycle emissions across various fuels and scenarios. Conventional fuels, alternative fuels, and decarbonization options can be evaluated using a standardized WTT, TTW, and WTW framework. This is significant as fuel comparisons that rely solely on onboard emissions may yield an incomplete or misleading evaluation of decarbonization potential. Incorporating both upstream and onboard emissions, the methodology facilitates a comprehensive evaluation of fuel-switching strategies, low-carbon technologies, and future maritime decarbonization scenarios.

This step generates a time-resolved lifecycle emissions inventory that links vessel activity, fuel consumption, and fuel-specific emission factors. The resulting inventory establishes a clear foundation for assessing current emissions performance, comparing fuel pathways, and identifying vessels, operations, or scenarios with high emissions intensity. Subsequent

stages of the methodology utilize these outputs to connect historical activity and emissions data with forecasting methods, enabling projections of future activity and emissions trajectories.

4.5 Step 5: Forecast-Based Activity and Emissions Projection

The fifth step of the proposed methodology expands the time-resolved lifecycle emissions inventory to include a forecast-based evaluation of future maritime activity and emissions. While the previous stages quantify vessel activity, fuel consumption, and lifecycle emissions for the selected assessment period, this step incorporates a temporal projection component to assess how future changes in activity, demand, and fuel pathways may affect long-term emissions trajectories. This is crucial for studies on maritime decarbonization, as factors such as port throughput, cargo demand, vessel calls, trade activity, economic growth, fuel availability, and regulatory targets are anticipated to change over time.

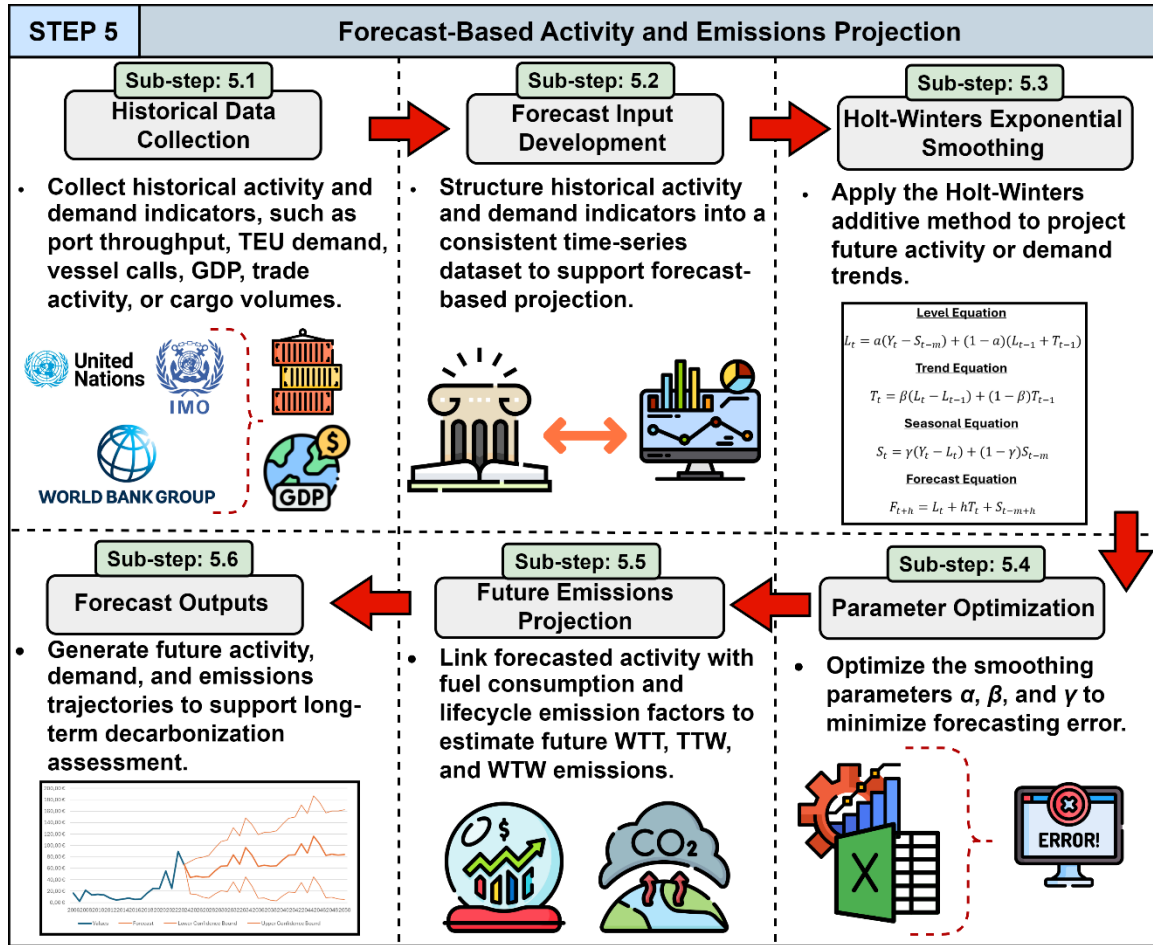


Figure 4-6. Forecast-based activity and emissions projection through six sequential sub-steps.

4.5.1 Sub-step 5.1: Historical Data Collection

The initial component of this sub-step entails gathering historical activity and demand indicators pertinent to the chosen maritime system. In this thesis, the forecasting input emphasizes three primary indicators: TEU demand or port throughput, GDP, and population. TEU demand or throughput signifies maritime transport activity and cargo movement, whereas GDP and population serve as broader socioeconomic indicators that may affect trade demand and long-term transport needs. Data can be obtained from recognized international and sector-specific databases, including including the United

Nations Conference on Trade and Development (UNCTAD), the World Bank, the IMO, port authority statistics, and other official statistical sources. The chosen historical indicators serve as the empirical foundation for recognizing temporal trends and formulating forecast-based projections of future maritime activity and emissions.

4.5.2 Sub-step 5.2: Forecast Input Development

In instances where various historical activity or demand indicators exist, statistical screening may be employed to assist in the selection of forecasting variables. In this study, correlation and regression analyses will be utilized to investigate the relationship between TEU demand or throughput, GDP, and population. This screening process assesses the significance of the chosen socioeconomic and transport-demand indicators, thereby enhancing the transparency of the justification for the forecasting inputs. In the general methodology, this step serves as a procedure for variable selection and validation, while the detailed correlation results, regression relationships, and justification of specific indicators are provided in the corresponding case study application.

Upon the collection and screening of relevant historical indicators, they are organized into a coherent time-series dataset. This necessitates the organization of data using a standardized temporal resolution, such as annual, monthly, quarterly, or daily values, contingent upon data availability and the forecasting objective. Missing values, inconsistent time intervals, and discontinuities must be resolved before the application of forecasting techniques. This step facilitates the utilization of the historical data set to discern the underlying level, trend, and seasonal behavior of the chosen activity or demand

indicator. The resulting forecast input dataset serves as the foundation for projecting future maritime activity.

4.5.3 Sub-step 5.3: Forecasting Method Selection and Holt–Winters Exponential Smoothing

Before selecting the forecasting method, alternative approaches identified in the literature were considered in relation to the characteristics of the available historical data, the long-term forecasting objective, model transparency, and compatibility with the subsequent scenario-based LCA calculations. Table 4-2 summarises the principal forecasting approaches considered and the methodological basis for selecting Holt–Winters exponential smoothing.

The comparison presented in Table 4-2 suggests that multiple forecasting methodologies may be applicable for projecting maritime activity. Holt–Winters exponential smoothing was chosen due to its parsimonious, transparent, and reproducible representation of historical levels and trends, facilitating easy integration with subsequent LCA scenario calculations. ARIMA and machine-learning methods provide enhanced modeling flexibility; however, they typically necessitate more comprehensive model identification, data, and validation. In contrast, econometric models rely on the long-term stability of explanatory relationships. In this study, regression analysis serves as a supplementary method for investigating the relationships between socioeconomic indicators and container demand, whereas exponential smoothing is utilized for the primary time-series forecasting. The resulting forecasts are utilized as scenario trajectories instead of deterministic predictions.

Table 4-2. Comparison of forecasting approaches considered for long-term maritime activity projection

Forecasting approach	Main characteristics	Advantages	Limitations for the present study	Relevance to model selection	Relevant literature
Naïve/benchmark forecasting	Uses recent historical observations as the basis for subsequent forecasts.	Simple, transparent and useful as a basic reference for forecast-error interpretation.	Does not explicitly represent evolving level or trend and is therefore limited for long-term scenario generation.	Used conceptually as a benchmark; MASE provides comparison with the corresponding naïve forecast.	Hyndman & Athanasopoulos (2021)
ARIMA	Represents autoregressive, differencing, and moving-average structures in time-series data.	Flexible statistical framework capable of modelling autocorrelation and stochastic temporal behavior.	Requires model identification and sufficient observations for reliable parameter estimation and validation; less transparent for integration into the scenario-based LCA framework.	Considered a relevant alternative but not selected as the principal forecasting method.	Hyndman & Athanasopoulos (2021)
Econometric / regression forecasting	Relates the forecast variable to explanatory variables such as GDP, population, or transport demand.	Provides interpretable relationships between socioeconomic indicators and maritime activity.	Long-term projections remain dependent on assumptions regarding explanatory variables and structural stability.	Used in this thesis to support indicator screening and demand relationships, rather than as the sole time-series forecasting method.	Chalaris et al. (2025)

Machine-learning approaches	Learn potentially complex and nonlinear relationships from historical data.	Can capture nonlinear behavior and interactions among multiple variables.	Generally, require larger datasets and may reduce model transparency and interpretability for relatively short annual time series.	Not selected because the present framework prioritizes transparent and reproducible scenario generation using limited annual observations.	Literature reviewed in Appendix C
Holt–Winters / exponential smoothing	Applies greater weight to recent observations and represents underlying level and trend, with a seasonal component where identifiable.	Parsimonious, transparent, reproducible and suitable for projecting persistent temporal trends; easily integrated with scenario-based LCA calculations.	Relies on continuation of historical patterns and may not capture structural shocks or abrupt policy, technological or market changes.	Selected approach because it provides a transparent and parsimonious forecasting layer consistent with the available historical data and the scenario-based objectives of the thesis.	Holt (2004a); Winters (1960); Hyndman & Athanasopoulos (2021); Dantas et al. (2017); Chalaris et al. (2025)

A comprehensive multi-model out-of-sample or rolling-origin comparison was not conducted in this study; thus, assessing alternative forecasting models is recognized as a key area for future research.

The forecasting component of the methodology employs the Holt-Winters exponential smoothing technique. The Holt-Winters technique is derived from the advancement of exponential smoothing methods, specifically Holt's (2004a) contributions to forecasting

trends and seasonality, followed by Winters' (1960) extension for seasonal time-series forecasting. Exponential smoothing generates forecasts by allocating higher weights to recent observations and systematically diminishing the impact of older data points. This weighting structure enables the method to adapt to recent changes in the time series while maintaining information from historical behavior. Holt-Winters forecasting is particularly effective for time-series datasets that display systematic temporal patterns, particularly when both trend and seasonality are evident (Raza et al., 2026).

In the sphere of maritime LCA, the application of Holt-Winters forecasting represents a significant enhancement to traditional LCA methodologies. Traditional LCA is predominantly static, as it typically assesses environmental impacts using current or historical inventories and established assumptions. Maritime decarbonization is inherently dynamic, influenced by changes in vessel activity, cargo demand, port throughput, fuel availability, energy systems, and regulatory targets over time. Integrating Holt-Winters forecasting with lifecycle emission factors allows for the estimation of future emissions based on projected activity and demand trends. This enables the assessment to progress from static emissions accounting to a dynamic and predictive emissions modeling approach.

The significance of this integration has been proven in research on maritime decarbonization. Chalaris et al. (2025) integrated LCA with Holt-Winters exponential forecasting and econometric parameters to project the future greenhouse gas intensity of alternative fuels along the Singapore–Rotterdam green corridor. This approach illustrates the connection between time-series forecasting and lifecycle emission factors, facilitating

informed decision-making regarding long-term operations, regulatory compliance, and fuel transitions. Similar forecasting applications have been documented in transport demand and energy forecasting, where Holt-Winters and related exponential smoothing methods have been employed to produce reliable projections. In certain hybrid applications, these methods have enhanced forecasting accuracy relative to traditional benchmark approaches (Dantas et al., 2017).

The Holt–Winters formulation effectively captures level, trend, and seasonality when a discernible seasonal pattern is present in historical data. However, the primary forecasting datasets utilized in the case studies are documented at an annual resolution. Due to the limitation of having only one observation per year, it is not possible to empirically identify an intra-annual seasonal cycle. For these annual series, the forecasting implementation is regarded as a non-seasonal Holt trend formulation, which captures the underlying level and trend without incorporating an explicit seasonal component. The seasonal extension of Holt–Winters is applicable only when data are available at a high temporal resolution and exhibit a consistent seasonal pattern.

However, the Holt-Winters method has limitations that should be recognized. Given that the method relies on smoothed historical patterns, it posits that the level, trend, and seasonal behavior observed in the past offer valuable insights for future predictions. Consequently, the predictive performance may diminish when the underlying system experiences abrupt structural changes, significant policy shocks, technological disruptions, extreme market volatility, or pronounced irregular fluctuations (Dutt Attri et al., 2026). Consequently, Holt-Winters forecasting should be viewed as a systematic projection derived from

historical patterns, rather than a definitive prediction of future maritime activity. This methodology provides a transparent and reproducible forecasting layer that supports scenario-based emissions assessment.

The Holt-Winters additive method comprises three smoothing equations and a single forecast equation. These equations estimate the level, trend, and seasonal components of historical time series and subsequently combine them to project future values. The additive form is suitable when seasonal variations maintain a relatively stable magnitude over time. If the chosen time series lacks a distinct seasonal pattern, a non-seasonal Holt linear trend formulation may be applied, or the seasonal component may be excluded based on the forecasting objective and data structure (Holt, 2004a; Hyndman & Athanasopoulos, 2021a; Winters, 1960).

The level component is estimated as:

$$L_t = \alpha(Y_t - S_{t-m}) + (1 - \alpha)(L_{t-1} + T_{t-1}) \quad \text{Eq. (4-12)}$$

where L_t is the estimated level of the series at time t , Y_t is the observed value at time t , S_{t-m} is the seasonal component from the equivalent period in the previous season, T_{t-1} is the trend component from the previous time step, and m is the seasonal period. The smoothing parameter α regulates the model's responsiveness to recent observations during level updates. A higher value of α assigns greater importance to recent activity data, thereby enhancing the forecast's responsiveness to short-term fluctuations. A lower value of α assigns greater importance to the historical level of the series, resulting in a more stable forecast.

The trend component is estimated as:

$$T_t = \beta(L_t - L_{t-1}) + (1 - \beta)T_{t-1} \quad \text{Eq. (4-13)}$$

where T_t is the estimated trend at time t , $L_t - L_{t-1}$ represents the most recent change in the level, and T_{t-1} is the previous trend estimate. The smoothing parameter β controls how quickly the trend component is updated. A higher value of β increases the model's sensitivity to recent changes in the direction or slope of the time series, whereas a lower value of β results in a more stable trend estimate. In maritime activity, this parameter is significant as it dictates the extent to which recent fluctuations in demand, throughput, or vessel calls affect future projections.

The seasonal component is estimated as:

$$S_t = \gamma(Y_t - L_t) + (1 - \gamma)S_{t-m} \quad \text{Eq. (4-14)}$$

where S_t is the seasonal component at time t , $Y_t - L_t$ represents the current seasonal deviation from the estimated level, and S_{t-m} is the seasonal component from the corresponding period in the previous seasonal cycle. The smoothing parameter γ regulates the extent to which the seasonal pattern is adjusted over time. A higher value of γ enables the model to rapidly adjust to variations in seasonal behavior, whereas a lower value of γ presumes that the seasonal structure remains largely stable. This parameter is pertinent when historical data exhibit recurring seasonal patterns, including monthly variations in port activity, trade flows, or cargo demand.

The future forecast is then calculated as:

$$F_{t+h} = L_t + hT_t + S_{t-m+h} \quad \text{Eq. (4-15)}$$

where F_{t+h} is the forecast value h periods ahead, L_t is the estimated level at time t , T_t is the estimated trend, and S_{t-m+h} represents the relevant seasonal component for the forecast horizon. This equation indicates that the future value is determined by integrating the current level, the anticipated trend over the forecast period, and the relevant seasonal adjustment.

4.5.4 Sub-step 5.4: Parameter Optimization

The smoothing parameters α , β , and γ are constrained within the range of 0 to 1 and are chosen to minimize forecasting error. Parameter optimization is a crucial component of the forecasting process. If the parameters are inadequately chosen, the model may either overreact to short-term fluctuations or fail to accurately represent significant changes in the historical trend or seasonal structure. In this methodology, the smoothing parameters are determined through an optimization procedure aimed at minimizing forecasting errors, which may include techniques such as minimizing the sum of squared errors, mean absolute error, root mean square error, or mean absolute percentage error. This can be executed utilizing statistical software or spreadsheet applications. Alternatively, when the Holt-Winters equations are applied explicitly, optimization tools such as *Microsoft Excel Solver* can be utilized to determine the values of α , β , and γ that minimize the chosen forecasting error metric.

4.5.5 Sub-step 5.5: Future Emissions Projection

Upon forecasting the future activity or demand indicator, the projected activity is integrated with the fuel-consumption and lifecycle emissions framework established in prior stages. This enables the estimation of future emissions by integrating projected activity levels with assumptions about vessel operations, fuel consumption, fuel pathways, and emission factors. Future emissions can be projected for WTT, TTW, and WTW boundaries. This sub-step allows the methodology to progress beyond historical emissions accounting and assess the potential impacts of future maritime activity and fuel-transition scenarios on long-term decarbonization outcomes.

4.5.6 Sub-step 5.6: Forecast Outputs

The outcome of this stage is a collection of forecast-driven trajectories for activity, demand, and emissions. These outputs facilitate the assessment of future emissions trends, the comparison of alternative scenarios, the evaluation of the potential impact of fuel switching, and the examination of the alignment of projected emissions pathways with long-term decarbonization objectives. Integrating forecasting into the LCA framework offers a proactive approach for evaluating maritime decarbonization strategies amidst evolving operational, economic, and technological conditions.

4.6 Step 6: Output, Comparison, and Decision Support

The sixth and final stage of the proposed methodology emphasizes the interpretation of results, comparison of fuel pathways, identification of emissions hotspots, evaluation of future emissions trajectories, and the development of decision-support insights. This stage

converts the time-resolved and forecast-based emissions outputs from previous stages into information that aids in maritime decarbonization planning. It serves as the interpretative stage of the framework, connecting quantitative emissions modeling with practical insights for port authorities, policymakers, shipowners, fuel suppliers, and other maritime stakeholders.

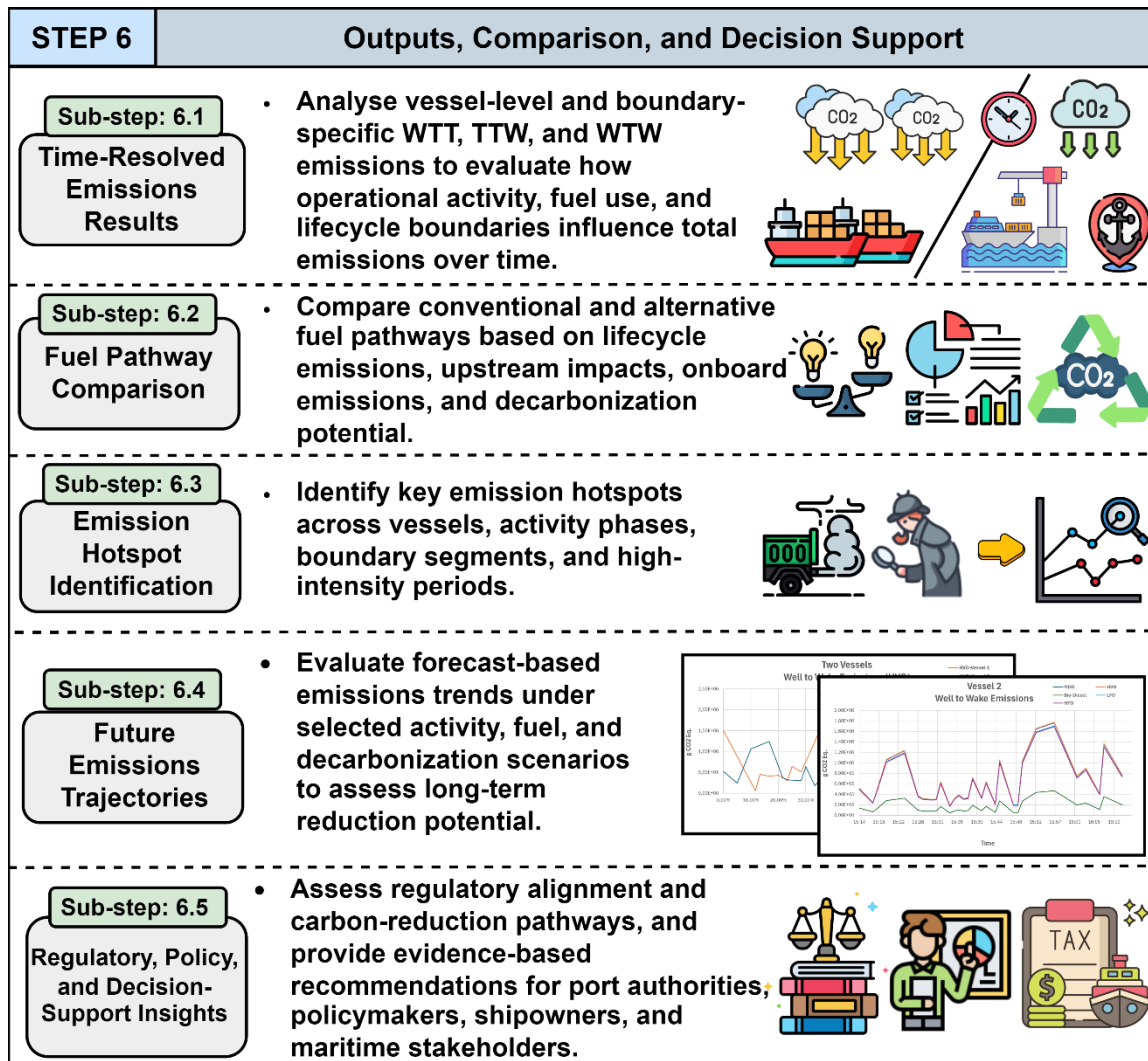


Figure 4-7. Outputs, comparison, and decision support through five sequential sub-steps.

4.6.1 Sub-step 6.1: Time-Resolved Emissions Results

The initial component of this step involves the analysis of time-resolved emissions results. The outputs from the lifecycle emissions inventory are analyzed at the vessel, boundary, and temporal levels to assess variations in emissions related to operational activity, fuel consumption, and lifecycle boundaries. Emissions can be categorized into WTT, TTW, and WTW components, allowing for a separate assessment of upstream and onboard emissions contributions. This distinction is significant as it enables the framework to ascertain whether emissions are primarily influenced by onboard vessel operations or by upstream fuel production and supply-chain processes. By analyzing emissions over time, the methodology facilitates the identification of periods characterized by higher emissions intensity, including high-traffic periods, congestion events, or operational phases linked to increased fuel demand.

4.6.2 Sub-step 6.2: Fuel Pathway Comparison

The second component entails a comparison of fuel pathways. Conventional and alternative fuels are analyzed in terms of lifecycle emissions, upstream impacts, onboard emissions, and overall potential for decarbonization. This comparison is conducted using a uniform lifecycle framework, ensuring that fuels are evaluated beyond their direct onboard emissions. Such an approach is crucial as certain alternative fuels may lower TTW emissions while still generating considerable WTT emissions, influenced by factors such as feedstock, production technology, electricity source, and supply-chain assumptions. In contrast, fuels generated from renewable energy or sustainable feedstocks may offer greater WTW reduction potential. This stage facilitates a more thorough evaluation of fuel-

switching strategies and prevents erroneous conclusions derived solely from tank-to-wake performance.

4.6.3 Sub-step 6.3: Emission Hotspot Identification

Furthermore, emission hotspot identification is conducted to ascertain which vessels, operational phases, boundary segments, time periods, or fuel pathways contribute most significantly to total emissions. Hotspots can be categorized as operational, spatial, or temporal. Operational hotspots may pertain to vessel categories, maneuvering activities, waiting times, berthing, or high-load operations. Spatial hotspots may arise within designated areas of a port boundary, route, or maritime operational zone. Temporal hotspots may correlate with specific days, seasons, or periods of heightened activity. Identifying these hotspots is crucial as it enables the targeting of mitigation measures to areas where they are expected to have the most significant impact. Hotspot analysis can inform decisions regarding port electrification, speed management, alternative fuel deployment, operational optimization, and the prioritization of high-emitting vessel categories.

4.6.4 Sub-step 6.4: Future Emissions Trajectories

In addition, the methodology evaluates future emissions trajectories established during the forecasting stage. Forecast-based outputs are utilized to analyze the potential evolution of emissions under specific activity, fuel, and decarbonization scenarios. This allows the framework to evaluate the likelihood of changes in projected emissions over time and to determine if alternative fuel pathways or operational measures can achieve significant long-term reductions. Future emissions trajectories may be evaluated in relation to

decarbonization objectives, regulatory targets, or policy scenarios. This forward-looking capability is crucial as maritime decarbonization decisions necessitate long-term planning, especially concerning fuel infrastructure, fleet renewal, port investment, and adherence to future emissions regulations.

4.6.5 Sub-step 6.5: Regulatory, Policy, and Decision-Support Insights

The final component of this step involves the development of insights related to regulation, policy, and decision support. The results are analyzed in relation to pertinent emissions targets, carbon-reduction pathways, and decarbonization objectives. This may involve evaluating the alignment of chosen fuels, operational strategies, or prospective scenarios with climate objectives, lifecycle emissions reduction mandates, or decarbonization strategies for ports and shipping. The methodology can thus facilitate evidence-based recommendations for maritime stakeholders. For port authorities, the findings may guide infrastructure planning, shore power implementation, emissions monitoring, and local air quality management. For shipowners and operators, the output may facilitate fuel selection, enhance operational optimization, and aid fleet transition planning. For policymakers, the findings may offer support for regulation, incentives, and sustainable decarbonization strategies.

Finally, this final step converts the outputs of the methodology into practical knowledge. By integrating time-resolved emissions data, lifecycle fuel analyses, hotspot identification, forecast-based emissions trajectories, and regulatory interpretation, the framework facilitates technical assessment and strategic decision-making. This ensures that the

proposed methodology extends beyond emissions quantification, contributing to the assessment of practical pathways for the reduction of maritime emissions over time.

4.7 Closing Remarks

This chapter developed the methodological framework used to address the research objectives of the thesis. The principal methodological points can be summarised as follows:

- The proposed methodology establishes a single overarching maritime LCA framework that integrates WTW lifecycle accounting with maritime activity modelling, forecasting, scenario analysis, and decision-support interpretation. Its modular structure allows the same methodological principles to be adapted to different spatial, temporal, and operational contexts.
- The Singapore–Rotterdam application represents the strategic and forecast-oriented implementation of the framework. It uses a representative 8,000 TEU containership and annual activity basis to connect alternative fuel pathways with lifecycle emissions, future transport demand, vessel requirements, FuelEU Maritime compliance, and EU ETS exposure. AIS trajectory reconstruction is not required for this application because its purpose is long-term corridor-level assessment.
- The Port of Busan application represents the operational and time-resolved implementation of the framework. AIS-derived trajectories from seven container vessels within a defined 20 NM boundary are converted into vessel-specific speed, propulsion demand, fuel consumption, and WTW emissions, allowing operational variability and emission hotspots to be examined before extending the results to future port-activity scenarios.

- The two applications intentionally employ different functional units, operational boundaries, activity bases, and temporal resolutions because they address different decision contexts. Their absolute numerical emissions results are therefore not directly comparable. Instead, synthesis is undertaken through their common methodological logic, relative fuel-pathway performance, treatment of lifecycle emissions, and contribution to strategic and operational decision support.
- The robustness of the framework is supported through explicit assumptions, consistent within-case fuel comparisons, forecast-error assessment, sensitivity analysis, and transparent acknowledgement of validation constraints. The methodological framework is transferable to other maritime applications, whereas its numerical outputs remain dependent on the specific corridor, port, vessel population, fuel pathways, and data used.

Table 4-3. Application of the proposed methodology in Chapters 5 and 6.

Methodological step	Chapter 5: Singapore– Rotterdam green corridor	Chapter 6: Port of Busan
Step 1: Goal, Scope, and System Boundary Definition	Fully applied to define the corridor, representative vessel, fuel pathways, life cycle boundary, functional unit, assessment period, and regulatory scope.	Fully applied to define the port boundary, vessel sample, fuel pathways, vessel-hour functional unit, life cycle boundary, and temporal scope.
Step 2: AIS-Based Trajectory Reconstruction and Activity Profiling	Not applied, as the corridor assessment uses representative operational profiles and forecast-	Fully applied through AIS acquisition, coordinate processing, time-interval calculation, Haversine

	based activity rather than AIS trajectories.	distance calculation, and speed estimation.
Step 3: Propulsion Power and Fuel-Consumption Modelling	Applied in an aggregated operational-mode form using representative power, specific fuel consumption, operating time, and fuel-specific assumptions.	Fully applied at the AIS-segment level using vessel-specific speed–power relationships, engine load, fuel-consumption curves, and fuel-specific adjustments.
Step 4: Time-Resolved Life Cycle Emissions Inventory	Adapted to calculate and compare WTT, TTW, and WTW emissions at operational-mode, fuel-pathway, and future-fleet levels.	Fully applied at the AIS-segment level, followed by aggregation by vessel, fuel pathway, and port-boundary activity.
Step 5: Forecast-Based Activity and Emissions Projection	Fully applied to forecast corridor TEU demand, vessel requirements, life cycle emissions, and regulatory exposure to 2050.	Fully applied to forecast GDP-driven container throughput, capacity-equivalent vessel demand, and future port-boundary emissions to 2050.
Step 6: Outputs, Comparison, and Decision Support	Applied to fuel-pathway comparison, future emissions trajectories, FuelEU Maritime compliance, EU ETS costs, and strategic decision support.	Applied to time-resolved emissions analysis, fuel comparison, operational variation, future emissions trajectories, and port-decarbonisation decision support.

Source: Developed by the author.

While the two case-study applications utilize the same overarching methodological framework and WTW lifecycle perspective, they vary in functional unit, operational system boundary, temporal resolution, and activity basis due to their distinct decision contexts. The Singapore–Rotterdam application utilizes a fuel-energy-based functional unit (g CO₂-eq/MJ) and presents an annual, forecasting-oriented model of a representative containership. In contrast, the Port of Busan application employs a vessel-time-based functional unit (kg CO₂-eq/vessel-hour) and incorporates AIS-derived, time-resolved vessel activity within a specified 20 NM port boundary. These differences are intentional methodological choices that align with the objectives, scale, and available data of each application. The implications for synthesis across the two case studies are summarized in Figure 4-8.

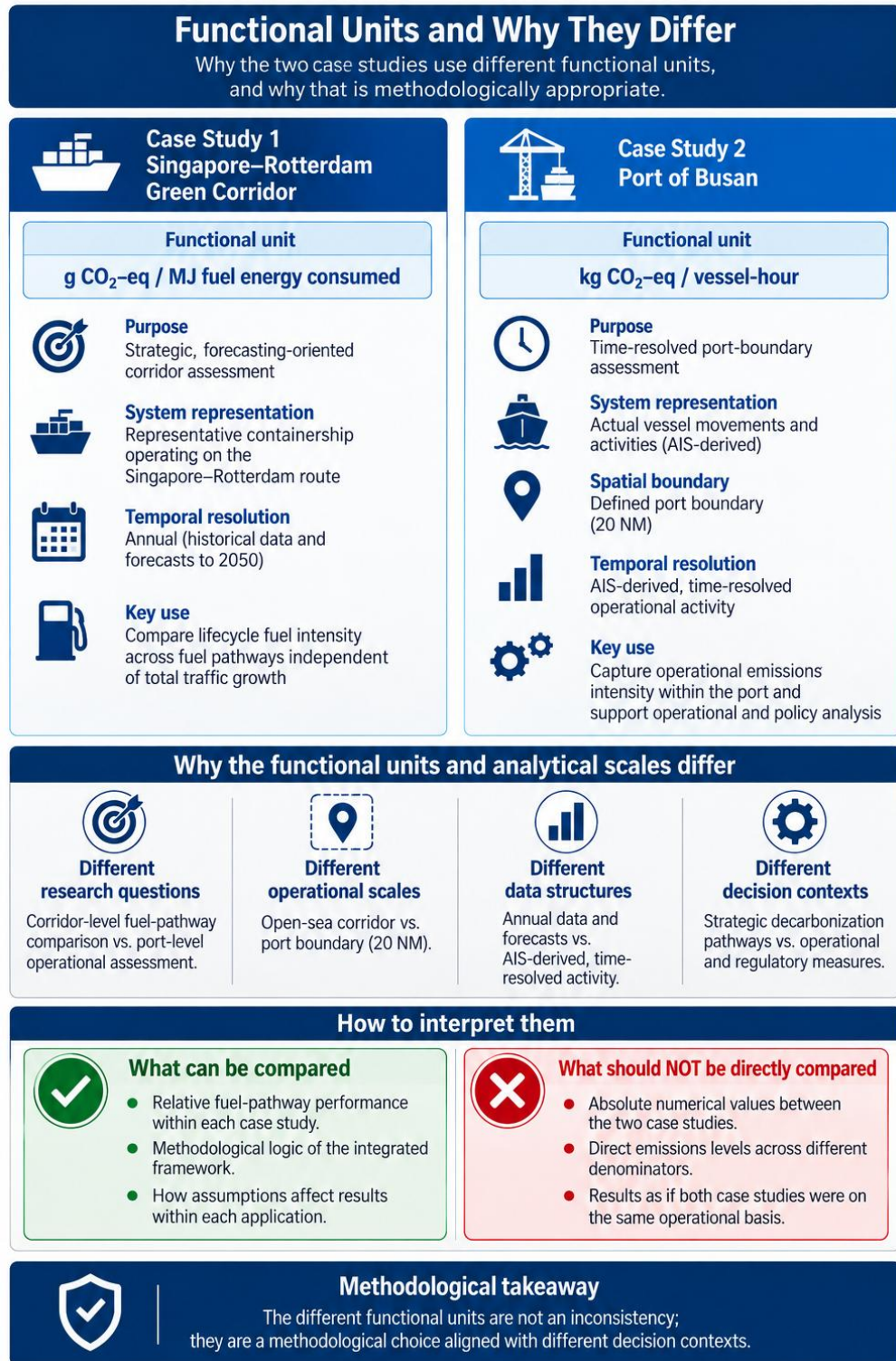


Figure 4-8: Comparison of functional units, operational system boundaries, temporal resolution, and interpretation across the two case-study applications.

5 Case Study 1: Strategic Forecasting of GHG Intensity for the Singapore–Rotterdam Containership Green Corridor

5.1 Introduction

Chapter 4 outlined a comprehensive methodology for maritime LCA, incorporating operational modelling, fuel consumption estimation, life cycle emissions accounting, forecasting, and decision-support analysis. Chapter 5 utilizes the forecast-oriented components of this methodology in the analysis of the first case study of the thesis: the Singapore–Rotterdam containership green corridor. The case study assesses the long-term GHG performance and regulatory implications of MDO, bio-methanol, and e-methanol utilized by a representative 8,000 TEU containership operating along the corridor.

This case study is derived from the published article by Chalaris, I., Jeong, B., and Jee, J. (2025), titled “*Strategic forecasting of GHG intensity: Econometrically enhanced LCA for the Singapore–Rotterdam containership green corridor*,” which appears in *Results in Engineering*. The study combines LCA with historical TEU demand, GDP, population data, statistical screening, and Holt–Winters forecasting to assess the future performance of specific marine fuel pathways through 2050.

The Singapore–Rotterdam corridor was chosen due to its strategic significance in international container shipping and maritime decarbonization. The green and digital corridor initiative, established by the Port of Rotterdam and the Maritime and Port Authority of Singapore, aims to facilitate the implementation of low- and zero-carbon fuels, relevant infrastructure, digital technologies, and synchronized decarbonization efforts. The

carbon performance is influenced by onboard fuel consumption, upstream production pathways, energy sources, future transport demand, and regulatory requirements.

The focus of Chapter 5 is on strategic and forecast-oriented aspects, rather than being based on AIS and operationally time-resolved elements. In Step 1 of the Chapter 4 methodology, the corridor, representative vessel, selected fuels, assessment period, functional unit, and life cycle boundary are comprehensively defined. Step 2 is not implemented because the case study utilizes a representative annual operating profile instead of AIS-derived vessel trajectories. Steps 3 and 4 are modified to assess fuel consumption and the emissions associated with WTT, TTW, and WTW by operating mode, fuel pathway, representative vessel, and projected fleet. Step 5 is comprehensively implemented and serves as the core element of the case study, connecting historical demand indicators with projections of future TEU demand, vessel requirements, and fleet emissions. Step 6 is utilized for comparing fuel pathways, analyzing future emissions trajectories, ensuring compliance with FuelEU Maritime, assessing FuelEU penalties, evaluating EU ETS allowance costs, and providing strategic decision support.

The methodology's effectiveness is evidenced by its adaptability to a corridor-level assessment, while maintaining a consistent WTW basis. The case study illustrates the integration of representative vessel operation, fuel-production pathways, future transport demand, life cycle emissions, and regulatory costs within a unified analytical framework. The application of the relevant steps and sub-steps is detailed in the following sections, while the AIS-based and time-resolved application of the methodology is demonstrated in Chapter 6.

5.2 Description of the Singapore–Rotterdam Green Corridor

Green corridors aim to reduce the burden of coordinating fuel infrastructure and ships throughout the value chain and across national boundaries, making them more manageable while retaining scale (ABS, 2024a).

In November 2021, during the 26th Conference of the Parties (COP 26) to the United Nations Framework Convention on Climate Change (UNFCCC) in Glasgow, UK, the Clydebank Declaration was established and endorsed by 19 member countries. As of September 2022, the number of nations that have joined the Clydebank Declaration has risen to 24, with Italy, Morocco, Palau, Singapore, and Spain as the new members (B. Jeong et al., 2022a). The signatories have pledged to create six green corridors by 2025, completely decarbonized maritime routes (including land-side infrastructure and vessels) connecting two or more ports, to expedite the advancement of zero-emission fuels, low-carbon enabling infrastructure, and effective legislation and regulation. The objective is to expand the six pilot corridors by establishing more routes, extending existing routes, and/or increasing the number of vessels traversing them (Watson Farley & Williams LLP, 2022a). The promise of green corridors resides in their capacity to streamline intricate decisions and navigate through ambiguity, while the growing clarity about fuel paths indicates that these corridors are realizing this potential. Currently, there is no indication that zero-emission fuels have been officially obtained for use on these corridors (Talalasova et al., 2023)

The transportation of containers between Asia and Europe is among the most fuel-intensive routes in the shipping sector. In August 2022, the Port of Rotterdam and Singapore's

Maritime and Port Authority announced the development of the world's longest green maritime corridor. The corridor seeks to accelerate the decarbonization of the shipping industry by partnering to provide low- or zero-carbon fuels and bunkering infrastructure in Singapore and Rotterdam, aiming to implement solutions at scale by 2030. The corridor would function as a digital shipping corridor, aimed at creating trade routes for the sharing of vital information and data among stakeholders to enhance port operations and cargo transportation (Svendsen et al., 2023a).

This green and digital corridor brings together over 20 partners from the shipping industry's value chain, led by two major bunkering centers worldwide. The corridor connects one of the world's biggest trade routes, with involvement from all major container lines. This entails establishing and aligning methanol and ammonia bunkering standards in Rotterdam and Singapore, exploring diminished port fees for zero- and net-zero emission vessels, and executing joint pilots and demonstrations (Talalasova et al., 2023)

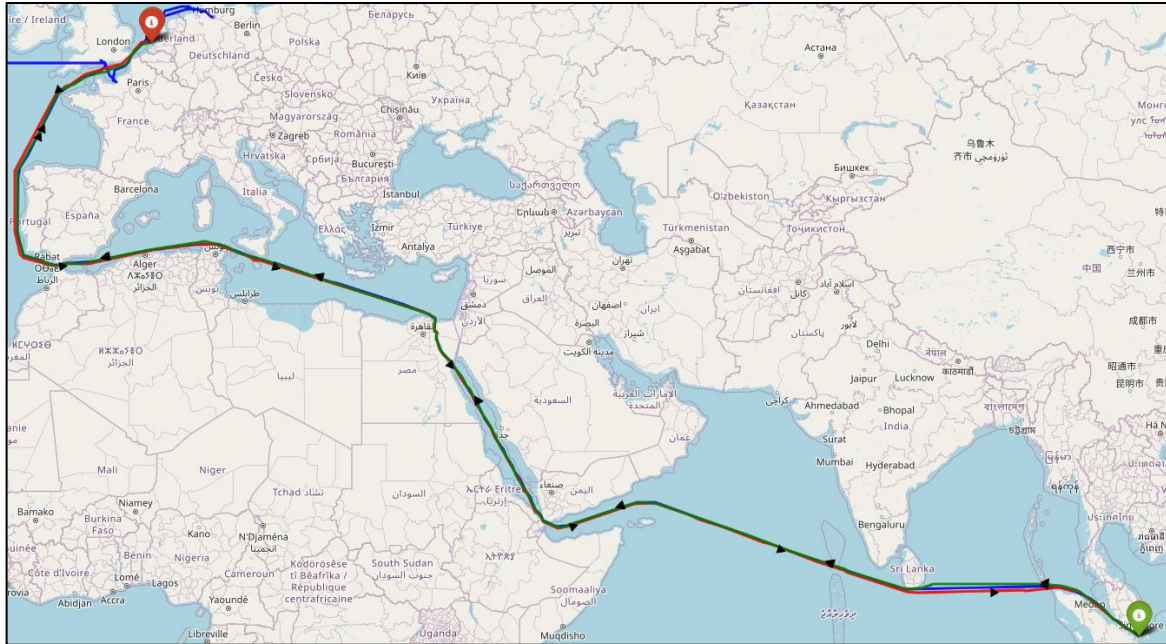


Figure 5-1. The Singapore–Rotterdam green corridor. Source: adapted by the author using Google Maps. © Google.

In this thesis, the Singapore–Rotterdam green corridor is chosen as the initial case study due to its significance in the decarbonization of long-distance container shipping. The corridor integrates significant transport demand, pertinent international regulations, the development of alternative-fuel infrastructure, and proactive stakeholder involvement. It provides a suitable context for applying the forecast-oriented components of the methodology outlined in Chapter 4 to evaluate the potential of selected alternative fuel pathways in facilitating the long-term decarbonization of green shipping corridors.

5.3 Step 1: Goal, Scope, and System Boundary of the Case Study

The initial step implements the goal, scope, and system-boundary definitions established in Chapter 4 within the context of the Singapore–Rotterdam green-corridor case study. It delineates the chosen maritime system, geographical and operational scope, representative

vessel category, fuel pathways, assessment period, activity basis, life cycle boundary, functional unit, and emissions indicators employed in the ensuing analysis.

5.3.1 Sub-step 1.1: Maritime System Selection

The maritime system chosen for this case study is the Singapore–Rotterdam System Selection. The maritime system chosen for this case study is the Singapore–Rotterdam containership green corridor. The case study evaluates and forecasts the GHG intensity of MDO, bio-methanol, and e-methanol utilized by a representative containership operating along the corridor until 2050.

The corridor exemplifies the application of forecast-oriented components of the methodology by integrating significant container-transport demand, long-distance vessel operation, the development of alternative-fuel infrastructure, and compliance with emerging maritime decarbonization regulations. The assessment focuses on the long-term environmental and regulatory implications of selected fuel pathways within a strategically significant container-shipping corridor.

5.3.2 Sub-step 1.2: Geographical and Operational System Boundary Definition

The geographical boundary includes containership activity between the ports of Singapore and Rotterdam. The operational boundary represents the activity of a containership serving the corridor through sailing, maneuvering, anchoring, and berthing.

The operational assessment encompasses the main engine, auxiliary engines, and boiler, evaluated under the pertinent operating conditions. In contrast to the AIS-based application

discussed in Chapter 6, this case study employs a representative annual operating profile instead of reconstructing individual vessel trajectories.

Multiple exclusions are implemented to ensure a well-defined and manageable scope. Emissions related to bunkering infrastructure, fuel storage, and logistics are not included, based on the assumption that the necessary fuel-handling infrastructure is either currently available or will be established during the corridor transition. Operational measures such as slow steaming, hull retrofits, weather routing, and other efficiency improvements are also excluded because the case study focuses primarily on fuel-pathway performance, life cycle GHG intensity, future transport demand, and regulatory compliance.

5.3.3 Sub-step 1.3: Vessel Category Selection

The chosen vessel category comprises containerships engaged in long-distance international routes. A representative containership with a capacity of 8,000 TEU serves as the technical foundation for the assessment.

The vessel model encompasses the main engine, auxiliary engines, and boiler, with power demand and fuel consumption illustrated across the chosen operating modes. The representative vessel provides a standardized technical framework for evaluating the chosen fuel pathways and subsequently adjusting vessel-level emissions in line with anticipated future fleet needs.

5.3.4 Sub-step 1.4: Selection of Fuel Pathway and Decarbonization Options

Three primary fuel alternatives are evaluated: MDO, bio-methanol, and e-methanol. MDO serves as the conventional fossil-fuel reference case, while bio-methanol and e-methanol are evaluated as alternative pathways for marine fuel.

These fuels were selected because they represent different production pathways, upstream energy requirements, and potential investments in the ports of Rotterdam and Singapore. The bio-methanol and e-methanol cases encompass various production processes and electricity sources, facilitating the assessment of the impact of natural gas, wind, and solar electricity on upstream emissions where relevant.

The selected fuel scope facilitates comparison between onboard emissions reductions and complete life cycle performance. This distinction is important because a fuel may reduce emissions during vessel operations while generating substantial upstream emissions during feedstock preparation, electricity generation, carbon capture, processing, or fuel production.

The chosen methanol pathways were guided by current and planned production, investment, and bunkering developments pertinent to Singapore and Rotterdam, as detailed in Appendix APPENDIX A. They are thus regarded as indicative of feasible supply pathways for the corridor, rather than as speculative fuel configurations. However, they are not designed to forecast the precise future fuel supply mix, as actual availability will be contingent upon project implementation, feedstock and renewable electricity availability, production capacity, certification, and future bunkering infrastructure.

5.3.5 Sub-step 1.5: Assessment Period, Temporal Resolution, and Activity Basis

The assessment period extends to 2050 and combines historical transport-demand and socioeconomic data with future activity projections. An annual temporal resolution is employed, aligning with the available historical datasets and the long-term strategic objectives of the case study.

TEU demand functions as the primary indicator of maritime activity, whereas GDP and population are first assessed as socioeconomic factors that could influence future container demand. Forecasted TEU demand is subsequently converted into the requisite number of containerships needed to service the corridor.

Three scenarios are analyzed to illustrate uncertainty in future economic development and transport demand: a forecast scenario grounded in historical trends, a lower-confidence scenario indicating more conservative growth, and a higher-confidence scenario reflecting stronger growth. These scenarios serve as the foundation for forecasting future vessel requirements and fleet-level emissions.

5.3.6 Sub-step 1.6: Life Cycle Boundary, Functional Unit, and Emission Indicators

The case study follows a WTW life cycle boundary comprising WTT and TTW components. The WTT boundary includes upstream emissions associated with fuel production, processing, energy supply, carbon capture where relevant, and the included production-chain activities. The TTW boundary includes onboard emissions generated by the main engine, auxiliary engines, and boiler during the selected operating modes. The combined WTW boundary represents the total life cycle GHG performance of each fuel pathway.

The functional unit is defined as the GHG intensity per unit of fuel energy consumed by the representative 8,000 TEU containership operating along the Singapore–Rotterdam corridor. Results are expressed in grams of CO₂-eq per MJ of fuel energy consumed. This functional unit facilitates consistent comparisons among fuels with varying energy contents, production processes, and onboard combustion characteristics, while also allowing for direct comparison with the GHG intensity requirements of FuelEU Maritime.

The primary emissions indicators consist of TTW, WTT, and WTW GHG emissions and intensities. Projected outputs encompass vessel demand forecasts, anticipated fleet-level emissions, compliance outcomes and penalties related to FuelEU Maritime, and costs associated with EU ETS allowances. These indicators facilitate the environmental, regulatory, and strategic comparison of MDO, bio-methanol, and e-methanol.

Table 5-1. Key modeling assumptions applied in the Singapore–Rotterdam case study.

Category	Assumption	Justification	Reference
Functional Unit	GHG intensity per MJ fuel for an 8,000 TEU container ship operating in the Singapore–Rotterdam corridor	Functional Unit is defined to normalize across fuels	-
System Boundaries	WTT + TTW included; bunkering infrastructure and bunkering logistics excluded	Assumed existing MDO infrastructure and future investment in e-methanol and bio-methanol	-
Fuel Scope	Only MDO, bio-methanol, and e-methanol are considered	Selected as representative alternative fuels with available data	-
Operational Context	Operational measures such as slow steaming, hull retrofits, and routing were excluded	Focus is on fuel performance, not operational practices	-
Forecasting	Holt-Winters additive method used; α , β , γ optimized automatically; MASE & SMAPE reported	Minimization of forecast error	(Holt, 2004a; Hyndman & Athanasopoulos, 2021a)
Explanatory Variables	GDP and population growth used to estimate TEU demand (2000–2023)	Supported by Pearson correlation and regression analysis	-
ETS Modeling	ETS allowance ramp-up: 40% (2024), 70% (2025), 100% (2026–2050); CO ₂ only (2024–25), CO ₂ -eq. from 2026	EU ETS regulation	(European Union, 2023)
FuelEU Penalties	Onshore Power Supply (OPS) penalty = 0 (case vessel insufficient port power demand)	FuelEU Maritime regulation	(European Union, 2018; IMO, 2024)
Electricity Mix	Rotterdam methanol production: natural gas or wind; Singapore: solar	Literature and regulatory assumptions	(International Energy Agency, 2024b, 2024a)
Emission Factors	TTW factors as in Table 5-5; CH ₄ and N ₂ O for methanol assumed = 0	Intergovernmental Panel on Climate Change (IPCC) defaults/study assumption	(IPCC, 2006b)
Scenario Design	Three scenarios: forecast, lower-confidence, higher-confidence	Used to capture uncertainty in demand	-
Sensitivity Analysis	±10% and ±20% variations on ETS carbon prices and FuelEU penalties	Robustness check of results	-

5.4 Step 2: AIS-Based Trajectory Reconstruction and Activity Profiling

Step 2 of the methodology outlined in Chapter 4 is not implemented in the Singapore–Rotterdam green-corridor case study. The assessment does not utilize AIS position records for the reconstruction of individual vessel trajectories. Therefore, Sub-step 2.1 involves the acquisition of AIS position data; Sub-step 2.2 pertains to coordinate processing; Sub-step 2.3 focuses on time-interval calculation; Sub-step 2.4 addresses distance calculation; and Sub-step 2.5 relates to speed estimation, all of which are beyond the scope of this chapter.

The omission of these sub-steps indicates the strategic and predictive intent of the case study. Chapter 5 does not aim to quantify short-term variations in vessel speed, propulsion demand, fuel consumption, or emissions across individual voyage segments. Rather, the assessment employs a representative annual operational profile for an 8,000 TEU containership, which includes the operating modes of sailing, maneuvering, anchoring, and berthing. This aggregated activity profile establishes the operational foundation necessary for the subsequent estimation of propulsion requirements, fuel consumption, and life cycle emissions.

The application of representative operating modes is justified, as the primary aim of the case study is to integrate vessel-level life cycle emissions with forecasts of future container demand, necessary vessel quantities, and fleet-level emissions through 2050. The AIS-based and time-resolved components of the methodology are not necessary for the corridor-level forecasting objective discussed in this chapter. Their application is illustrated independently in the case study of the Port of Busan discussed in Chapter 6.

5.5 Step 3: Propulsion Power and Fuel-Consumption Modelling

Step 3 utilizes the propulsion-power and fuel-consumption modeling procedure outlined in Chapter 4 for the representative 8,000 TEU containership. In this case study, AIS-derived vessel speeds and individual voyage segments are not utilized; therefore, the procedure is modified from segment-level modeling to a representative operational-mode approach. Power demand and fuel consumption are assessed for sailing, maneuvering, anchoring, and berthing by utilizing manufacturer specifications, engine modeling outputs, operating durations, and literature-based assumptions regarding auxiliary engines and boilers.

5.5.1 Sub-step 3.1: Propulsion Power and Engine Load Estimation

In Chapter 4, the general methodology estimates propulsion power and engine load for each AIS segment by utilizing vessel speed, the vessel's installed or reference engine power, and the relevant speed–power relationship. These calculations are not directly applicable in the current case study, as Step 2 does not reconstruct a speed profile derived from AIS.

Instead, the vessel's propulsion and onboard power requirements are depicted through established operating modes. The technical parameters are derived from a representative 8,000 TEU containership and encompass the main engine, auxiliary engines, and boiler. Manufacturer specifications and engine modeling outputs characterize the main engines, while the auxiliary engine and boiler power requirements are derived from the operational assumptions reported by IMO (2021).

The chosen operational modes include at sea, maneuvering, anchoring, and at berth. The power requirements for the auxiliary engine and boiler fluctuate based on the relevant operating conditions, as detailed in Table 5-2.

The cubic speed–power relationship and segment-level engine-load calculation presented in Chapter 4 are therefore not repeated in Chapter 5. Instead, the relevant engine operating conditions are represented through manufacturer-derived main-engine performance data and predefined auxiliary-engine and boiler power requirements. This adaptation is consistent with the strategic scope of the case study, which evaluates representative annual vessel operation rather than variations between individual AIS segments.

Table 5-2. Power outputs (kW) under different operational modes.

	At Berth	Anchored	Maneuvering	At Sea	Reference
Boiler	590	580	550	0	(IMO, 2021a)
Auxiliary Engines	1,100	1,400	2,800	1,450	

5.5.2 Sub-step 3.2: Fuel-Consumption Modelling

Fuel consumption is estimated by integrating the relevant engine or equipment power, specific fuel consumption, operating duration, and quantity of units. Distinct calculations are performed for the primary engine, auxiliary engines, and boiler.

For MDO operation, the chosen main engine is the 6G80ME-C10.5-HPSCR, according to the specifications provided by MAN Energy Solutions (2023). The engine is modeled using the Computerised Engine Application System (CEAS) software, which provides the

specific fuel oil consumption necessary for estimating main-engine fuel demand under the chosen operating conditions.

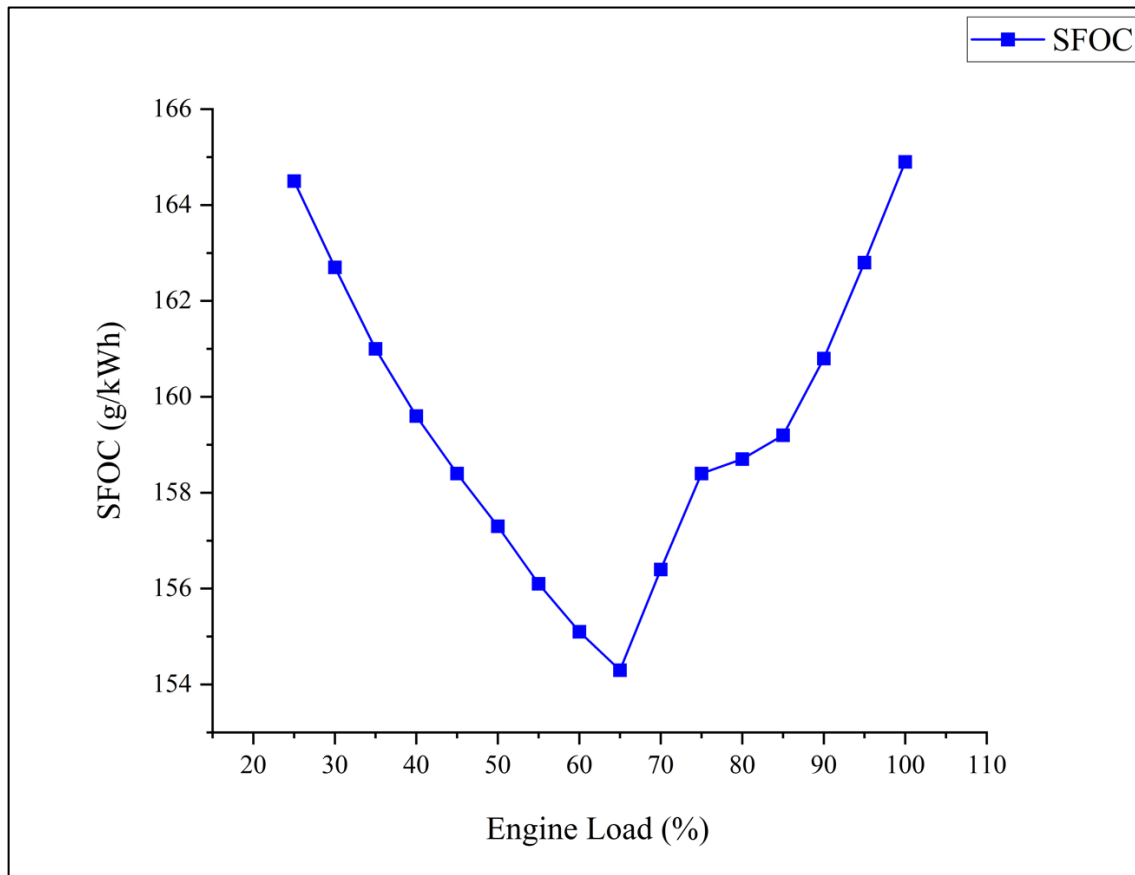


Figure 5-2. Specific fuel oil consumption of the selected diesel engine operating in Tier III mode, obtained using CEAS software.

For methanol operation, a dual-fuel main-engine configuration is applied. The selected engine is the 8G60ME-C10.5-LGIM-HPSCR, based on the specifications provided by MAN Energy Solutions (2023). The CEAS outputs provide the specific gas consumption of methanol and the specific pilot-oil consumption of MDO required to support methanol combustion.

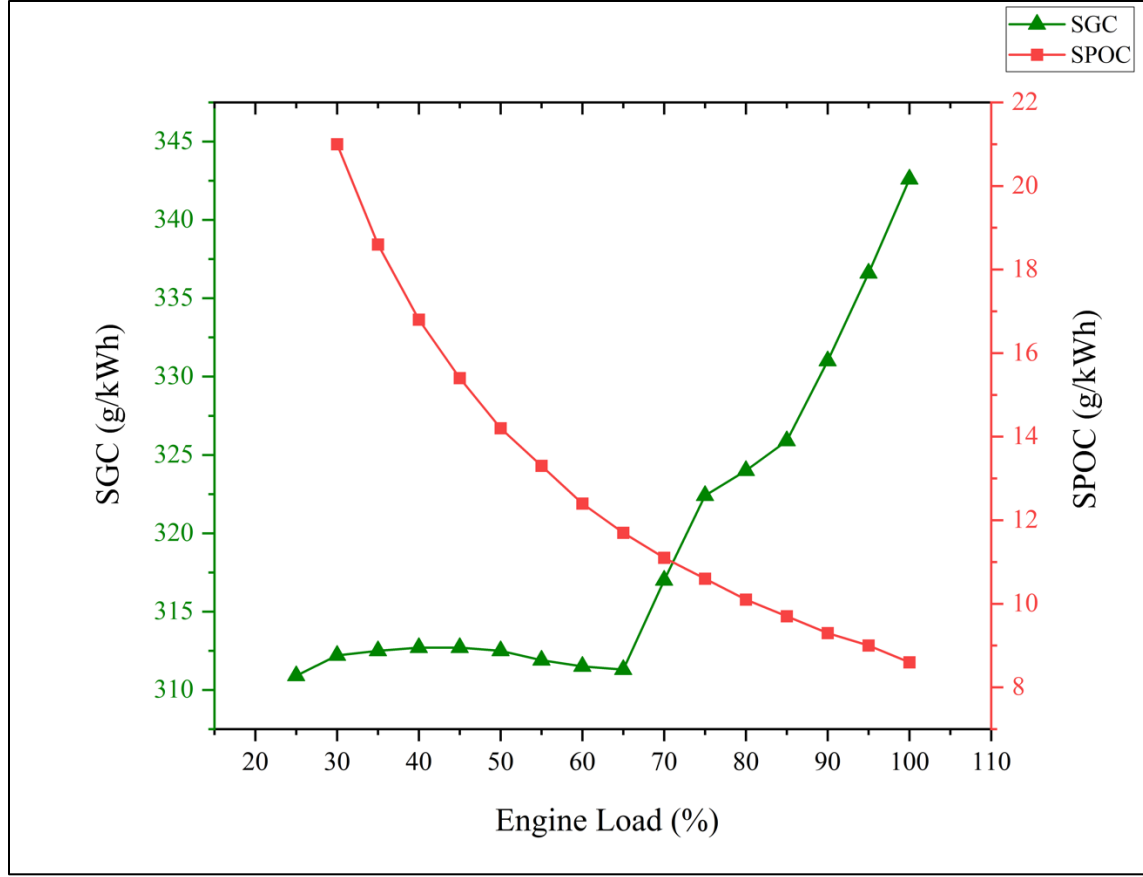


Figure 5-3. Specific gas consumption (SGC) of methanol and specific pilot-oil consumption of the selected dual-fuel engine operating in Tier III mode, obtained using CEAS software.

Fuel consumption for the main engine is calculated as follows:

$$FC_f = \sum_{op}^n \left(\frac{P_{op,f} \times Sfof_f \times t_{op,f}}{10^6} \right) \quad \text{Eq. (5-1)}$$

where FC_f is the total fuel consumption in tons across all operational profiles, op is the operational profile (sailing, maneuvering, berth), P_{op} is the propulsion power in kW used in each operational profile, $SFOC$ in g/kWh is the specific fuel oil consumption of the fuel, t_{op} is the time spent in each operational profile in hours, and the conversion factor 10^6 converts grams to tons. In methanol engines, an additional parameter is necessary to

characterize the pilot fuel required for combustion, influencing overall fuel consumption and emissions. The combustion of methanol generally produces lower CO₂ emissions per unit of energy in comparison to traditional fuels; however, the possibility of methanol slip (unburned fuel) and other secondary emissions warrants consideration.

The auxiliary engines and boilers are represented separately because their installed units, power requirements, and specific fuel-consumption values differ from those of the main engine. The assumptions applied to the boiler are presented in Table 5-3.

Table 5-3. Data assumptions for the boiler.

	Parameter	Value	Unit	Reference
Boiler	Number of units	1	-	(IMO, 2021a)
	Type of fuel	MDO	-	
	Fuel Consumption	320	(g/kWh)	

The boiler is represented by one MDO-fueled unit with a specific fuel consumption of 320 g/kWh, based on IMO (2021a). The corresponding auxiliary-engine assumptions are presented in Table 5-4.

Table 5-4. Data assumptions for auxiliary engines.

	Parameter	Value	Unit	Reference
Auxiliary Engines	Number of units	3	-	(IMO, 2021a)
	Power (per unit)	1,890	kW	
	Type of fuel	MDO	-	
	Fuel Consumption	185	(g/kWh)	

The auxiliary power system consists of three units, each rated at 1,890 kW, with a specific fuel consumption of 185 g/kWh, according to IMO (2021a). Fuel consumption for the auxiliary engines and boilers is determined as follows:

$$FC_{f,d} = \sum_{op}^n \left[\frac{(P_{op,f} \times N_{unit,f}) \times Sfof \times t_{op,f}}{10^6} \right] \quad \text{Eq. (5-2)}$$

where N_{unit} is the number of auxiliary engines or boilers needed. The equation accounts for the combined fuel consumption of the operating units during each applicable operational mode.

5.5.3 Sub-step 3.3: Fuel-Specific Adjustment and Time-Resolved Fuel Profile

After the initial fuel-consumption calculation, adjustments specific to each fuel type are implemented to address the varying engine technologies and operational demands linked to MDO and methanol. These adjustments ensure that the chosen fuel pathways are not regarded as direct mass-based substitutes and that their respective fuel consumption characteristics are consistently represented.

MDO operation is modeled using the SFOC of the chosen diesel engine. Methanol operation is modeled utilizing the SGC of the chosen dual-fuel engine alongside its specific pilot-oil consumption. The necessary amount of pilot MDO is thus factored into the methanol fuel-consumption calculation and subsequently integrated into the TTW emissions inventory.

The time-resolved fuel-use profile outlined in Chapter 4 is adapted in this case study to reflect an operational-mode fuel-use profile. Fuel consumption is not assessed for specific AIS time intervals. It is instead aggregated across sailing, maneuvering, anchoring, and berthing based on power requirements, operating duration, specific fuel consumption values, and the number of units relevant to each mode.

This procedure generates an annual fuel consumption profile for the representative containership. The quantities of MDO, methanol, and pilot MDO serve as the activity inputs for Step 4, where they are integrated with the corresponding TTW and WTT emission factors to compute the life cycle emissions of the chosen fuel pathways.

5.6 Step 4: Time-Resolved Life Cycle Emissions Inventory

Step 4 implements the life cycle emissions inventory procedure outlined in Chapter 4 for the chosen fuel pathways. Since the Singapore–Rotterdam case study does not utilize AIS-derived vessel segments, the time-resolved inventory is modified to align with operational modes and production stages. TTW emissions are assessed for sailing, maneuvering, anchoring, and berthing, whereas WTT emissions are evaluated for the specific stages within each fuel-production pathway.

The inventory includes MDO, bio-methanol, and e-methanol, integrating onboard fuel consumption with fuel-specific emission factors, upstream production assumptions, electricity-source considerations, carbon-capture inputs, and GWP100 impact factors. The WTT and TTW emissions are combined to assess the WTW GHG performance of each pathway.

5.6.1 Sub-step 4.1: Emission Factor and Impact Indicator Selection

Data on fuel pathways were gathered for MDO, bio-methanol, and e-methanol. MDO is utilized as the standard reference fuel, while bio-methanol and e-methanol are assessed via distinct upstream production pathways. The necessary parameters encompass direct-combustion emission factors, electricity emission factors, production energy requirements, feedstock assumptions, carbon-capture assumptions, gasification inputs, methanol-synthesis parameters, and production efficiencies.

The selected TTW emission factors for MDO and methanol are detailed in the table below.

Table 5-5. Emission factors for MDO and methanol.

Fuel	Emission Factor	CO₂	CH₄	N₂O	Reference
MDO	gr pollutant/ gr fuel	3.206	0.00005	0.00018	(European Union, 2023)
Methanol	gr pollutant/ gr fuel	1.375	0	0	

Complete combustion of methanol is not anticipated to yield CH₄. Incomplete combustion or secondary reactions under certain operating conditions, such as low combustion temperatures or insufficient fuel–air mixing, can lead to restricted CH₄ formation (Brynnolf et al., 2014). Due to the lack of adequately established CH₄ and N₂O emission factors for the chosen methanol-engine configuration, these factors are assumed to be zero in this case study.

Electricity supply is a significant factor influencing the WTT performance of bio-methanol and e-methanol. The case study examines various electricity sources, such as natural gas, wind, and solar power, to illustrate alternative production conditions in Rotterdam and Singapore and to evaluate the impact of electricity carbon intensity on fuel-production emissions. The emission factors for the selected electricity sources are detailed in the table below.

Table 5-6. Emission factors for selected electricity sources (g CO₂-eq./ kWh) (United Nations Economic Commission for Europe, 2022a)

Natural Gas	Coal	Oil	Biofuels	Wind	Solar	Waste	Nuclear
490	820	0	230	12	27	0	12

The life cycle impact assessment focuses on global warming potential. The CML 2001 impact-assessment approach is applied using GWP100 characterization factors for CO₂, CH₄, and N₂O. These factors are applied consistently to emissions arising from both the WTT and TTW stages. The selected impact factors are presented in the table below.

Table 5-7. CML 2001 impact factors for MDO and methanol.

Fuel	Impact Factor	CO₂	CH₄	N₂O	Reference
MDO	GWP 100	1	28	273	(IPCC, 2006b)
Methanol					

5.6.2 Sub-step 4.2: Segment-Level Life Cycle Emissions Calculation

The segment-level calculation described in Chapter 4 is adapted in this case study because individual AIS segments are not available. Emissions are instead calculated at two corresponding levels:

- by operational mode for the TTW stage; and
- by production and supply-chain stage for the WTT stage.

This retains the disaggregated character of the general methodology while reflecting the annual, corridor-level scope of the present case study.

5.6.2.1 Tank-to-Wake Emissions Calculation

The TTW phase encompasses emissions produced during vessel operation. Onboard emissions are calculated for the main engine, auxiliary engines, and boiler across sailing, maneuvering, anchoring, and berthing.

Following the estimation of fuel consumption in Step 3, the quantity of each GHG emitted is calculated as follows:

$$E_{i,f} = FC_f \times EF_{i,f} \quad \text{Eq. (5-3)}$$

where $E_{i,f}$ is the amount of emissions in tons from each operational profile, FC_f is the total fuel consumption in tons, and $EF_{i,f}$ is the emission factor for each GHG in ton of emissions/ton of fuel.

For the methanol cases, the calculation includes emissions associated with both methanol consumption and the pilot MDO required by the selected dual-fuel engine. The auxiliary engines and boilers remain MDO-fueled according to the assumptions presented in Step 3.

5.6.2.2 Well-to-Tank Fuel-Pathway Calculation

The WTT phase encompasses upstream emissions related to fuel production and supply. In this case study, the WTT calculation varies by fuel pathway due to the distinct feedstocks, conversion processes, electricity sources, and carbon capture assumptions associated with bio-methanol and e-methanol production. Pathway-specific WTT equations are employed for bio-methanol derived from municipal solid waste, biogas/biomass, and renewable e-methanol.

The pathway-specific calculations adhere to a stage-based emissions accounting framework, wherein the activity data for each production stage are multiplied by the relevant emission factor:

$$WTT_f = \sum_{st} (A_{extst,f} \times EF_{extst,f}) \quad \text{Eq. (5-4)}$$

where WTT_f is the total well-to-tank emissions in ton CO₂-eq. across all stages, st is the supply chain stage (extraction, processing, transport, distribution), A_{extst} is the activity data (e.g., energy consumed, fuel transported) for each stage, EF_{extst} is the emission factor per unit of activity, and the conversion factor 10^6 converts grams to tons.

5.6.2.2.1 Bio-Methanol from Municipal Solid Waste (MSW)

For bio-methanol derived from municipal solid waste, the WTT emissions are determined by analyzing the specific upstream processes, including municipal solid waste collection, treatment, gasification, and transportation.

$$\begin{aligned} WTT_{MSW} = & (MSW_{Collection} \times EF_i) + (MSW_{Treatment} \times EF_i) \\ & + (Gasification_{Total} \times EF_i) + (Trasnpotation \times EF_i) \end{aligned} \quad \text{Eq. (5-5)}$$

Four primary phases, $MSW_{Collection}$, $MSW_{Treatment}$, $Gasification_{Total}$, and $Trasnpotation$, affect the WTT emissions in this study associated with MSW-derived bio-methanol. Each step i corresponds to a specific emission factor EF_i . The collection of MSW encompasses the gathering of refuse from commercial, industrial, and urban sources at the Amsterdam Metropolitan Region (AMR) facility. Emissions result from the fuel utilized by collection vehicles and the logistics involved in waste management. Several variables, such as fuel type, collection efficiency, and distance traveled, are represented in the corresponding EF_i . Sorting, drying, and preprocessing are integral steps in the municipal solid waste treatment

process that consume energy and contribute to emissions; the emission factor EF_i depends on the energy source and the efficiency of the treatment equipment. The energy-intensive gasification process converts solid waste into syngas at elevated temperatures. In this context, the EF_i accounts for process efficiency, the carbon intensity of the heat source, and any implemented emission mitigation measures.

The transportation of intermediate and final methanol products represents the final source of transportation emissions; the emission factor EF_i varies based on the mode of transportation, distance traveled, and fuel utilized. Emissions from this pathway can be minimized by optimizing processes, which include improving waste management, reducing transportation distances, and utilizing cleaner energy sources.

Table 5-8. Characteristics of the trucks used for fuel transportation.

Vehicle Model	Trailer Model	Capacity (Tons)	Tank Material	Features	Reference
Kenworth T880	Polar Tank Trailer	29.98	Stainless Steel	Insulated tanks, multiple compartments, vapor recovery systems	(SafeRack, 2024)

Transportation is included as a common stage within the selected WTT fuel pathways. Where road transport is required, identical truck and trailer specifications are assumed for the transportation of bio-methanol and e-methanol. The principal vehicle characteristics used in the calculation are presented in the table above.

Table 5-9. Data and assumptions for the production of bio-methanol in Rotterdam through the Gidara and Lowlands pathway.

Parameter	Value	Unit	Reference
Annual Bio-methanol Production Target	125.48	tons/day	-
Syngas Production rate	19,78	Nm ³ /hour	
Methanol Production Efficiency	3,784.61	Nm ³ /ton MeOH	
Syngas Required Annually	1.73E+08	Nm ³ /year	
Lower heating value (LHV) of MSW	13.2	MJ/kg	
LHV of Syngas	12	MJ/Nm ³	(Lee et al., 2023a)
Cold Gas Efficiency	0.85	-	(B. Wang et al., 2023a)
Carbon Conversion Efficiency	0.95	-	(Moghaddam, 2022)
Syngas Energy Needed Daily	5.70E+06	MJ/day	
MSW Needed Daily	507.90	tons/day	-
Emission Factor CO ₂ (Gasification)	53	kg/ton MSW	
Emission Factor CH ₄ (Gasification)	0.0064	kg/ton MSW	(Ouedraogo et al., 2021)
Emission Factor N ₂ O (Gasification)	0.00223	kg/ton MSW	
Electricity for MSW sorting	0.059	kWh/ton MSW	

Electricity for MSW size reduction and shaping	91.5	kWh/ton MSW	
Electricity for field devices	25.58	kWh/ton MSW	
Electricity (Wind) for MSW sorting	1.31E+02	kg CO ₂ -eq.	
Electricity (Wind) for MSW size reduction and shaping	2.04E+05	kg CO ₂ -eq.	-
Electricity (Wind) for field devices	5.69E+04	kg CO ₂ -eq.	
CO ₂ Emissions (Gasification)	9.83E+06	kg/year	
CH ₄ Emissions (Gasification)	1.19E+03	kg/year	
N ₂ O Emissions (Gasification)	4.13E+02	kg/year	
Total GHG Emissions from Gasification	9.97E+06	kg CO ₂ -eq./year	
Total Production GHG Emissions via Wind	1.02E+07	kg CO ₂ -eq.	
Total Production GHG Emissions via Natural Gas	2.06E+07	kg CO ₂ -eq.	

Note: Values without an individual reference are calculated by the author.

5.6.2.2.2 Bio-methanol from Biogas/Biomass

The equation below outlines the primary phases involved in the production of bio-methanol from biogas.

$$\begin{aligned} WTT_{Biogas} = & (Biomass_{Collection} \times EF_i) + (Biomass_{Treatment} \times EF_i) \\ & + (Methanol\ Synthesis \times EF_i) \\ & + (Transportation \times EF_i) \end{aligned} \quad \text{Eq. (5-6)}$$

To produce biogas-derived bio-methanol, the emission factor EF_i plays a vital role in every phase of biomass collection, treatment, conversion for methanol synthesis, and transportation, influencing WTT emissions. The process of gathering organic feedstocks, including forestry waste, is referred to as *Biomass_{Collection}*. Cultivation, fuel consumption, and transportation collectively contribute to emissions. The efficiency of machinery and the distance to processing facilities are two factors influencing the EF_i in this context. The energy intensity associated with the preprocessing stages of *Biomass_{Treatment}*, including drying, grinding, and enzymatic breakdown, is represented by the EF_i . Emissions associated with thermal requirements and catalyst efficiency are critical in the primary phase of *Methanol Synthesis*, which converts biogas, predominantly methane, into methanol. The energy source utilized significantly influences the EF_i during this phase. It incorporates fuel type, logistics efficiency, and travel distances. *Transportation* emissions result from the movement of methanol and its intermediates. The carbon intensity of this method can be significantly diminished through the potential implementation of carbon capture in methanol synthesis, reduction of transport emissions, and enhancement of biomass sources. Emissions from biomass transportation and other

upstream transport operations are omitted, as their proportional impact is anticipated to be negligible compared to the primary lifecycle phases. These exclusions are recognized as constraints of the current scope.

Table 5-10. Data and assumptions for the production of bio-methanol in Rotterdam through the OCI/BioMCN pathway.

Production Phase	Parameter	Value	Unit	Reference
Methanol Synthesis and Gasification	Emission Factor for Processing	0	gr CO ₂ .eq./ MJ	(European Union, 2018)
	Combined Energy Demand for Gasification and Methanol Synthesis	0.53	MWh/ tons MeOH	(Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2022)
	Combined Energy Demand for Gasification and Methanol Synthesis	24,27	MWh/ year	-
	Electricity via Wind	291,28	kg CO ₂ .eq./ year	
	Electricity via Natural Gas	1.19E+07	kg CO ₂ .eq./ year	
Woody Biomass Production	Biomass Emission Factor	0.09	tons CO ₂ .eq./ tons biomass	(Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2022)

	Conversion Efficiency	0.5	-	-
	Biomass Energy Content	18	MJ/ kg	(Ontario, 2023)
	Total Production Energy Required per year	9.11E+08	MJ	-
	Energy Required from Biomass per year	1.82E+09	MJ	
	Amount of Biomass required per year	101,26	tons	
	Emission Factor for cultivation	2.5	gr CO ₂ .eq./ MJ	(European Union, 2018)
	Cultivation Emissions	4,557.08	tons CO ₂ .eq.	-

Note: Values without an individual reference are calculated by the author.

5.6.2.2.3 E-methanol from Renewable Sources

The phases considered for calculating the WTT emissions for e-methanol are detailed in the equation and interpretation provided below:

$$\begin{aligned} WTT_{E-methanol} = & (Electrolysis_{Total\ Electricity} \times EF_i) \\ & + (Carbon\ Capture_{DAC\ \&\ PS} \times EF_i) \\ & + (Methanol\ Synthesis \times EF_i) + (Transportation \times EF_i) \end{aligned} \quad \text{Eq. (5-7)}$$

The four main processes affecting e-methanol WTT emissions in this study are electrolysis, carbon capture, methanol synthesis, and transportation. Each process i is associated with a specific emission factor EF_i . The energy mix employed significantly influences the efficiency of *electrolysis*, a process that utilizes electricity to dissociate water into hydrogen. Emissions from renewable energy sources are minimal, particularly solar and wind, which are considered. The next phase, *carbon capture*, involves the extraction of CO₂ from either direct air capture or point-source emissions. DAC typically exhibits a higher energy factor EF_i due to its substantial energy requirements. *Methanol synthesis* occurs in the presence of hydrogen and CO₂, and emissions are affected by catalyst efficiency, thermal requirements, and the energy sources utilized during the process. The EF_i incorporates these factors alongside waste heat recovery and emission reduction strategies. *Transportation* of methanol to distribution centers or end customers results in emissions. Trip distances, fuel efficiency, and transportation methods all influence the EF_i .

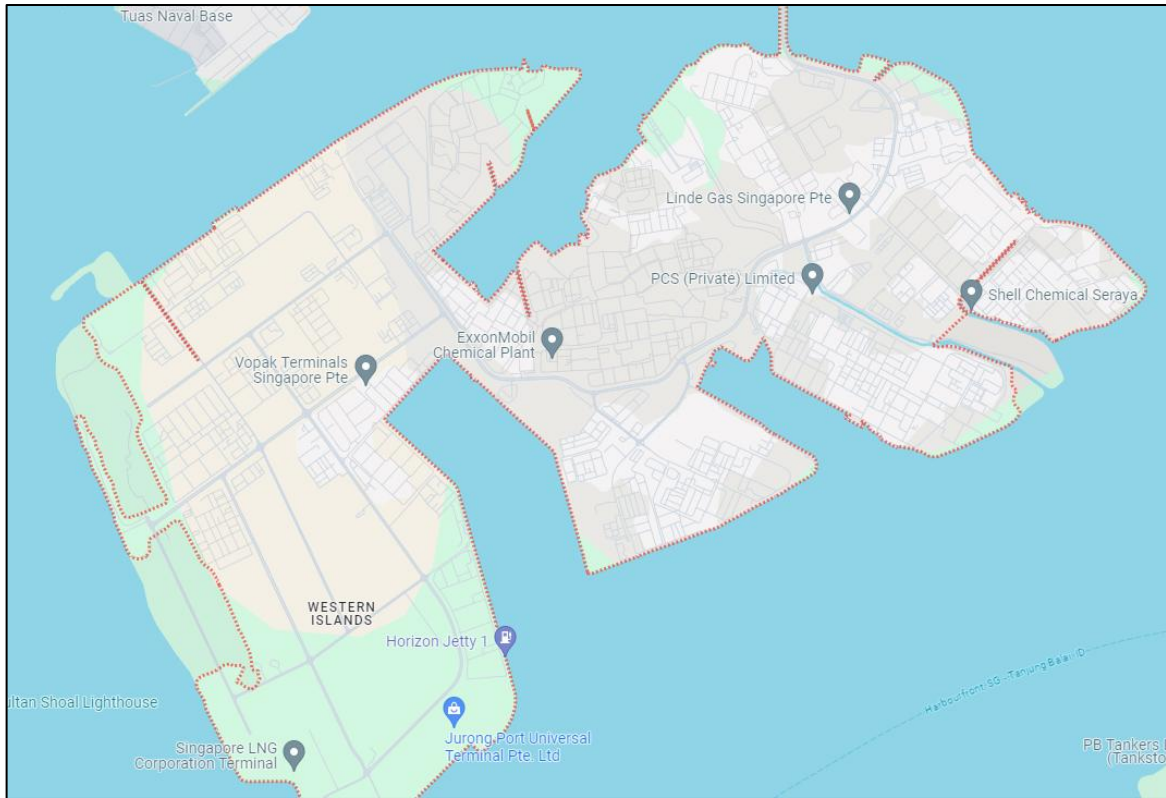


Figure 5-4. Jurong Island. Source: Google Maps. © Google.

To reduce emissions in this pathway, it is essential to enhance the utilization of renewable energy, improve capture efficiency, and ensure the availability of sustainable mobility options.

Table 5-11. Data and assumptions for fuel production of e-methanol in Singapore (PTTEP, Air Liquide, YTL Power Seraya, Oil Tanking, Kenoil Marine Services, Maersk).

Parameter	Value	Unit	Reference
Molar Mass of CO ₂	44.01	gr/mol	-
Molar Mass of H ₂	2.02	gr/mol	
Molar Mass of CH ₃ OH	32.04	gr/mol	
Moles of Methanol	1.4E+09	-	
Mass of CO ₂ Required	62,910.4	tons	

Mass of H ₂ Required	4.3E+09	tons	
Total Production Energy Required	7.2E+08	MJ	
Electrolysis	53.4	kWh/kg H ₂	(Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2022)
Electricity via solar photovoltaic (PV)(Hydrogen)	1.25E+07	kg CO ₂ -eq.	-
Electricity via Natural Gas (Hydrogen)	2.27E+08	kg CO ₂ -eq.	
Conversion efficiency	15.81	MJ/kg CH ₃ OH	(Kajaste et al., 2018)
Efficiency of CO ₂ capture from biomass	0.5	-	-
Biomass Required	125,820.7	tons	-
Emission Factor for Biomass Cultivation	0.2	kg CO ₂ -eq./ kg biomass	(IPCC, 2006b)
Cultivation Emissions	25,164.1	ton CO ₂ -eq.	-
Emission Factor for Biomass Processing	0.3	kg CO ₂ -eq./ kg biomass	(Edwards et al., 2011)
Electricity needed for Hydrogen Production per year	4.63E+08	kWh	-
DAC Energy Consumption	3	MWh/ ton CO ₂	(Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2022)
DAC Energy Needed	1.89E+05	MWh	-

Carbon capture (DAC and PS)	-1.38	ton CO ₂ -eq./ ton MeOH	(Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, 2022)
Carbon capture (DAC and PS)	-6.90E+07	kg CO ₂ -eq.	-
Electricity via Natural Gas (DAC)	9.25E+07	kg CO ₂ -eq.	
Electricity via Solar PV (DAC)	5.10E+06	kg CO ₂ -eq.	
Total Production GHG Emissions via Natural Gas	2.75E+08	kg CO ₂ -eq.	
Total Production GHG Emissions via Solar PV	-2.62E+07	kg CO ₂ -eq.	

Note: Values without an individual reference are calculated by the author.

5.6.2.3 Well-to-Wake Emissions and Life Cycle Impact Calculation

The total WTW emissions of each fuel pathway are obtained by combining the calculated WTT and TTW components. This distinction permits the upstream effects of fuel production to be evaluated separately from the emissions generated onboard the vessel.

The equation used for the calculations of the GWP for this case study can be found below:

$$GWP_{i,f} = E_{i,f} \times IF_{i,f} \quad \text{Eq. (5-8)}$$

where $E_{i,f}$ is the emission factor of each GHG emission in tons of emission/ton of fuel, and $IF_{i,f}$ is the impact factor.

The total GHG emissions are expressed in terms of CO₂-eq. The GHG intensity of each fuel pathway is determined by correlating the total WTW GHG emissions with the useful fuel energy utilized by the vessel. Results are presented in g CO₂-eq/MJ, facilitating consistent comparisons among fuels with varying energy contents, production methods, and combustion properties. This unit aligns with the GHG-intensity basis employed in the subsequent FuelEU Maritime assessment.

5.6.3 Sub-step 4.3: Aggregation, Scenario, and Fuel Comparison

The life cycle emissions are compiled at multiple levels to facilitate the subsequent analysis. TTW emissions are categorized by operating mode and onboard energy systems, which encompass the main engine, auxiliary engines, and boiler. WTT emissions are compiled according to production stage and fuel pathway. The WTT and TTW results are combined to calculate annual WTW emissions for the representative vessel.

Comparisons of fuel pathways are conducted among MDO, bio-methanol, and e-methanol. Additional comparisons are conducted among various production routes, feedstocks, electricity sources, and carbon-capture assumptions within the alternative-fuel cases. At this stage, the scenario comparison focuses on the differences between fuel production and electricity supply configurations. The forecast, along with lower-confidence and higher-confidence demand scenarios, is presented individually in Step 5.

The vessel-level life cycle emissions serve as the foundation for the subsequent forecast-based projections developed in the next step. Projected vessel requirements are integrated with the corresponding WTW results to assess future fleet-level emissions along the Singapore–Rotterdam corridor up to 2050.

5.7 Step 5: Forecast-Based Activity and Emissions Projection

Step 5 implements the forecast-based activity and emissions-projection methodology outlined in Chapter 4 for the Singapore–Rotterdam green corridor. This step is a crucial element of the current case study, as it broadens the vessel-level LCA established in Steps 3 and 4 to encompass a long-term corridor-level assessment projected to 2050.

Historical transport demand and socioeconomic indicators are utilized to forecast future TEU demand and to estimate the requisite number of containerships for the corridor. The projected vessel requirements are subsequently associated with the WTT, TTW, and WTW emissions calculated for the chosen fuel pathways. Three scenarios are analyzed to illustrate uncertainty in future corridor activity: a forecast scenario, a lower-confidence scenario, and a higher-confidence scenario.

5.7.1 Sub-step 5.1: Historical Data Collection

Historical activity, transport demand, and socioeconomic data were gathered to form the empirical foundation of the forecast. TEU demand and port throughput serve as indicators of container transport activity, whereas GDP and population were initially identified as socioeconomic factors that could impact future trade and maritime transport demand.

The historical indicators span the years 2000 to 2023 and were sourced from reputable international and sector-specific entities, including UNCTAD, the World Bank, the IMO, and port authority statistics. The data were organized with an annual temporal resolution to establish a consistent framework for identifying long-term trends and projecting future corridor activity through 2050.

The container throughput values utilized to define the activity context of Singapore and Rotterdam are displayed in Table 5-12.

Table 5-12. Port Throughput in Rotterdam and Singapore.

Port	Containers	Unit	Reference
Singapore	39.01	mTEU	(Maritime and Port Authority of Singapore, 2024)
Rotterdam	13.40	mTEU	(Port of Rotterdam Authority, 2023)

5.7.2 Sub-step 5.2: Indicator Screening and Forecast Input Development

After data collection, Pearson correlation and regression analyses (Appendix A) were conducted to investigate the relationships among TEU demand, GDP, and population. This statistical screening facilitated the evaluation of the chosen socioeconomic indicators and the formulation of the forecasting input necessary for projecting future container demand.

The historical data were structured into a uniform annual time-series dataset. The demand input was integrated with assumptions regarding the proportion of total port throughput linked to the corridor, average vessel capacity, vessel utilization rate, effective carrying capacity, annual vessel requirements, and weekly sailing frequency.

Three scenarios were created to illustrate uncertainty in future corridor activity. The lower-confidence scenario indicates more conservative transport-demand conditions, whereas the

higher-confidence scenario reflects stronger corridor growth. The forecast scenario presents the primary projection derived from historical demand trends, positing that 15% of total port throughput is linked to the Singapore–Rotterdam route. The primary scenario assumptions are outlined in Table 5-13.

Table 5-13. Assumptions applied to the lower-confidence, forecast, and higher-confidence corridor-demand scenarios.

	Lower Confidence	Higher Confidence	Unit	Assumptions
Percentage of Throughput on the Singapore–Rotterdam Route	10%	20%	-	15% for the implementation of the “Forecast Scenario”.
Average Vessel Size	15,000	20,000	TEUs	-
Utilization Rate	80%	90%	-	-
Throughput on the Singapore–Rotterdam Route	3,901	7,802	mTEU	-
Effective Capacity	12,000	18,000	TEUs	-
Number of Vessels Required	325	433	Vessels/ Year	-
Weekly Frequency of Shipments	6	8	Vessels/ Week	-

Note: The lower- and higher-confidence values represent scenario assumptions defined for sensitivity analysis. The forecast scenario assumes that 15% of total port throughput is associated with the Singapore–Rotterdam route. Effective capacity, vessel requirements, and weekly frequency are derived from the stated vessel-size, route-share, and utilization assumptions.

The lower-confidence scenario assumes that 10% port throughput is associated with the corridor, an average vessel size of 15,000 TEU, and an 80% utilization rate. The higher-confidence scenario assumes a corridor share of 20%, an average vessel size of 20,000 TEU, and a 90% utilization rate. These assumptions determine the effective vessel capacity and the number and frequency of containership movements required to serve the route.

5.7.3 Sub-step 5.3: Holt–Winters Exponential Smoothing Method

The Holt–Winters additive exponential smoothing method discussed in Chapter 4 is utilized to forecast future TEU demand through 2050. The exponential-smoothing method discussed in Chapter 4 is applied to forecast future TEU demand through 2050. Because the historical demand dataset is structured at annual resolution, no identifiable intra-annual seasonal component is estimated. The implementation therefore represents the level and trend of the historical series using a non-seasonal Holt trend formulation. The resulting TEU-demand projections are subsequently used to estimate the number of containerships required under the forecast, lower-confidence, and higher-confidence scenarios.

The additive formulation is implemented as per Eq. (4-12)–Eq. (4-15) outlined in Chapter 4. The method prioritizes recent observations while preserving information from earlier values, enabling the forecast to adapt to recent changes without neglecting the longer-term historical demand pattern.

The resulting TEU-demand projections are utilized to estimate the number of containerships needed under the forecast, lower-confidence, and higher-confidence scenarios. This scenario-based application allows for the examination of alternative

assumptions regarding future transport demand, corridor share, vessel size, and vessel utilization.

5.7.4 Sub-step 5.4: Parameter Optimization and Forecast Error Minimization

The Holt–Winters smoothing parameters α , β , and γ were optimized automatically to minimize forecasting error. Parameter optimization mitigates the risk of forecasts either overreacting to transient fluctuations or inadequately capturing significant shifts in the historical demand trajectory.

Performance forecasts were assessed utilizing the error indicators outlined in Table 5.14. These encompass absolute error, relative error, percentage error, mean absolute error, root mean squared error, and standard error utilized in statistical evaluation.

Table 5-14. Forecast-error metrics calculated for the projected demand scenarios.

Scenario	Absolute Error	Relative Error	Percentage Error	Mean Absolute Error (MAE)	Root Mean Squared Error (RMSE)	Standard Error for Statistical Analysis
Higher Confidence	1.70E+07	37.0%	36.98	1.74E+07	1.90E+07	1.73E+06
Forecast	1.40E+06	4.0%	4.01	1.37E+06	1.70E+06	1.77E+06
Lower Confidence	1.70E+06	5.3%	5.27	1.67E+06	2.08E+06	8.95E+05

Source: Author's calculations based on the Holt–Winters demand scenarios described in Sections 5.7.3–5.7.4.

The reported error metrics quantify the discrepancies between the observed historical demand data and the corresponding fitted values utilized in the development of demand trajectories. Absolute error quantifies the magnitude of deviation, whereas relative and percentage errors normalize this deviation in relation to the observed value. Meanwhile, MAE and RMSE provide a summary of the average magnitude of fitting errors. These indicators describe the historical alignment of the forecasting procedure and should not be viewed as direct measures of uncertainty regarding the projections for 2050.

Differences among the forecast, lower-confidence, and higher-confidence trajectories arise from intentionally varied scenario assumptions related to corridor throughput share, vessel size, and vessel utilization. Thus, the variation among the three future trajectories indicates scenario uncertainty rather than solely forecast-model error. The central forecast serves as the reference trajectory, while the lower- and higher-confidence cases are utilized to explore alternative future demand scenarios.

5.7.5 Sub-step 5.5: Future Emissions Projection and Forecast Outputs

The projected TEU demand is converted into the number of containerships required to serve the corridor using the scenario assumptions concerning corridor throughput share, average vessel size, effective carrying capacity, and vessel-utilization rate. The resulting vessel projections are presented in the figure below.

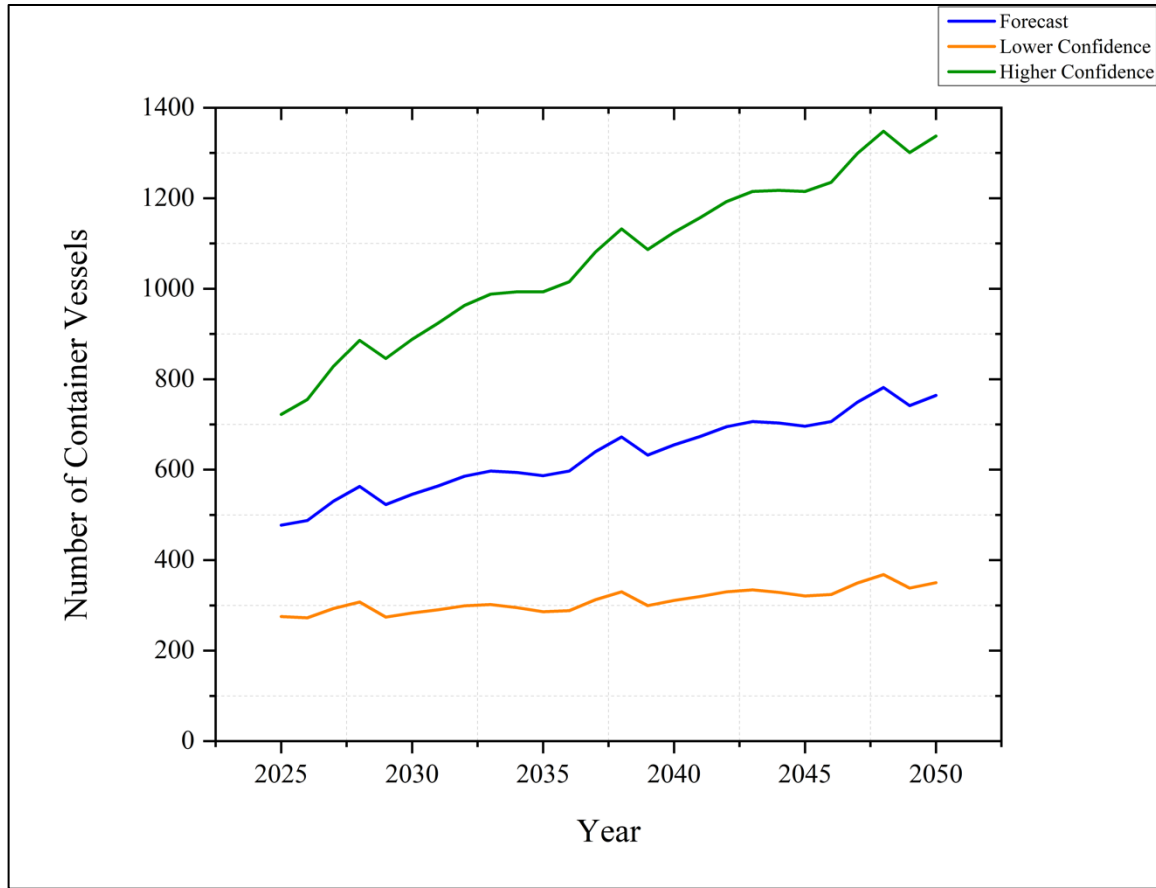


Figure 5-5. Projected number of containerships required on the Singapore–Rotterdam green corridor under the lower-confidence, forecast, and higher-confidence scenarios to 2050.

Each scenario has its own number of containerships that are needed to carry the required demand until 2050. Starting from the higher confidence scenario, in 2025, the demand will be 8.668 mTEU with 722 vessels required, while in 2050, the demand will rise to 16.050 mTEU with 1337 vessels required. For the lower confidence scenario, demand in 2025 will be 3.306 mTEU, with 275 containerships required, while demand in 2050 will be 4.203 mTEU, with 350 vessels needed. The forecast scenarios seem to be the most realistic, with 477 vessels covering the demand of 5.730 mTEU in 2025 and 764 ships responding to 9.171 mTEU in 2050.

After estimating future vessel requirements, the projected activity is associated with the life cycle emissions determined in Step 4. The annual emissions from the representative vessel are adjusted based on the anticipated number of containerships operating within the corridor. This calculation is performed for MDO, bio-methanol, and e-methanol based on the chosen production pathway and electricity source assumptions.

The procedure produces future fleet-level WTW emissions trajectories for each fuel pathway. The emissions projections, fuel-pathway comparisons, and regulatory implications are analyzed and discussed in Step 6.

5.8 Step 6: Outputs, Comparison, and Decision Support

Step 6 analyzes and contrasts the operational-mode, life cycle, forecast, and regulatory outputs produced in the previous steps. It assesses TTW emissions by operating mode, compares the WTT and WTW performance of the chosen fuel pathways, identifies key emission hotspots, analyzes future fleet-level emissions trajectories, and converts the findings into regulatory and decision-support insights.

The outputs encompass the annual TTW emissions of the representative containership, the WTT performance of the chosen production pathways, projected corridor-level WTW emissions through 2050, FuelEU Maritime compliance and penalty outcomes, EU ETS allowance costs, and the findings from the regulatory sensitivity analysis. Together, these outputs illustrate the impact of fuel selection, production pathway, electricity source, projected transport demand, and regulatory conditions on the long-term decarbonization performance of the Singapore–Rotterdam green corridor.

5.8.1 Sub-step 6.1: Time-Resolved Emissions Results

The time-resolved output outlined in Chapter 4 is applied in this case study for an operational-mode emissions assessment. TTW emissions are categorized by sailing, maneuvering, anchoring, and berthing, facilitating an analysis of how each operational condition affects the annual onboard emissions of the representative containership.

The TTW results demonstrate the greenhouse gas emissions produced by the main engine, auxiliary engines, and boiler during vessel operation. The results present an initial comparison between MDO and methanol-based operations.

In MDO, CO₂ emissions during sailing represent the most significant contribution to the overall TTW impact. CO₂ emissions significantly exceed those of CH₄ and N₂O during berthing, anchoring, and maneuvering.

Table 5-15. Total annual TTW emissions from MDO by operating mode.

Fuel	Emissions	Sailing	Berth	Anchored	Maneuvering
MDO	CO ₂ (gr)	9.19E+10	5.32E+07	6.03E+07	4.71E+07
	CH ₄ (gr)	1.43E+06	8.30E+02	9.41E+02	7.34E+02
	N ₂ O (gr)	5.16E+06	2.99E+03	3.39E+03	2.64E+03
	Total kg CO ₂ -eq.	9.34E+07	5.41E+04	6.13E+04	4.78E+04
	Total kg CO ₂ -eq.	9.40E+07			

For methanol operation, the evaluation encompasses both methanol consumption and the pilot MDO necessary for the dual-fuel main engine. The auxiliary engines and boilers persist in consuming MDO as per the assumptions outlined in Step 3. Sailing serves as the primary source of TTW emissions, similar to the MDO case.

Table 5-16. Total annual TTW emissions for methanol.

Fuel	Emissions	Sailing		Berth	Anchored	Maneuvering
		MeOH	Pilot MDO			
Methanol	CO ₂ (gr)	6.30E+10	1.18E+10	5.32E+07	6.03E+07	4.71E+07
	CH ₄ (gr)	0	1.84E+05	8.30E+02	9.41E+02	7.34E+02
	N ₂ O (gr)	0	6.61E+05	2.99E+03	3.39E+03	2.64E+03
	Total kg CO ₂ -eq.	6.30E+07	1.20E+07	5.41E+04	6.13E+04	4.78E+04
	Total kg CO ₂ -eq.	7.51E+07				

Source: Author's calculations using the operational assumptions, fuel-consumption modelling and emission factors presented in Sections 5.5–5.6.

Overall, the total TTW emissions from MDO are 9.40E+07 kg CO₂-eq., while from methanol are 7.51E+07 kg CO₂-eq. When methanol (bio-methanol or e-methanol) is used instead of MDO, TTW emissions are reduced by 20%.

5.8.2 Sub-step 6.2: Fuel Pathway Comparison

The fuel-pathway comparison broadens the TTW assessment to include the upstream production stage. This distinction is essential, as reduced onboard emissions do not inherently equate to lower total life cycle emissions. The WTT performance of bio-methanol and e-methanol is significantly influenced by the production process, feedstock, electricity source, carbon-capture method, and supply-chain assumptions.

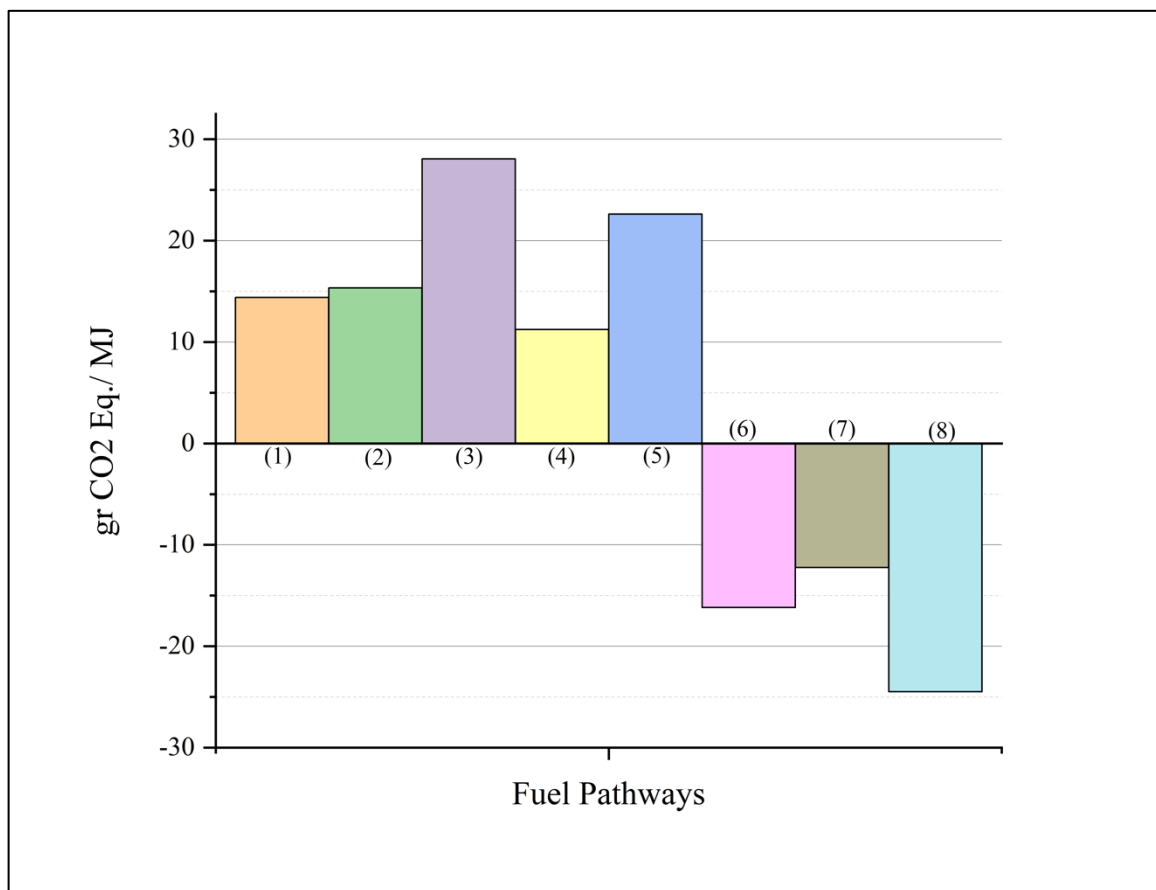


Figure 5-6. Well-to-Tank emissions for MDO, bio-methanol, and e-methanol, 1. MDO, 2. Bio-methanol (OCI/BioMCN) (Wind), 3. Bio-methanol (OCI/BioMCN) (Natural Gas), 4. Bio-methanol (Gidara & Low Lands) (Wind), 5. Bio-methanol (Gidara & Low Lands) (Natural Gas), 6. E-methanol (Consortium Nouryon/ Gasunie/ BioMCN) (Wind), 7. E-methanol (Consortium Nouryon/ Gasunie/ BioMCN) (Solar), 8. E-methanol (PTTEP, Air Liquide, YTL PowerSeraya, Oiltanking, Kenoil Marine Services, Maersk) (Solar).

The GHG intensity of marine diesel oil in the well-to-tank phase is 14.4 g CO₂-eq/MJ. The e-methanol pathway linked to Maersk and its partners exhibits the lowest calculated WTT value of −24.49 g CO₂-eq/MJ. In contrast, bio-methanol generated via the OCI/BioMCN pathway utilizing natural-gas electricity shows a WTT value of 28.06 g CO₂-eq/MJ.

The comparison highlights the significance of the electricity source utilized in methanol production. Bio-methanol generated from wind electricity exhibits a reduced upstream carbon impact compared to the analogous process utilizing natural-gas electricity. In a similar vein, e-methanol generated from renewable electricity demonstrates superior life cycle performance compared to pathways reliant on fossil-based electricity.

The findings indicate that the assessment of alternative fuels should not be limited to their combustion emissions during operation. While methanol decreases TTW emissions compared to MDO, its overall environmental impact is contingent upon the upstream production pathway. Renewable electricity, sustainable feedstocks, efficient production processes, and effective carbon-capture systems are crucial for attaining significant WTW reductions.

5.8.3 Sub-step 6.3: Emission Hotspot Identification

The operational-mode results indicate that sailing is the primary TTW emission hotspot for both MDO and methanol operations. The longer duration and increased main-engine power demand associated with sailing contribute significantly more than maneuvering, anchoring, or berthing. Auxiliary engine and boiler emissions during non-sailing modes are significant, especially when considering the annual activity of the projected corridor fleet.

At the life cycle level, the primary hotspots occur during upstream fuel production. The electricity needed for feedstock treatment, gasification, and methanol synthesis significantly influences the total WTT emissions of bio-methanol. Pathways that depend on natural-gas electricity exhibit higher emissions compared to those supplied by wind electricity.

In the production of e-methanol, hydrogen generation via electrolysis and the electricity needed for direct air capture constitute significant upstream energy requirements. The carbon intensity of the electricity supply is the primary factor influencing pathway performance. Renewable electricity derived from wind or solar sources significantly enhances the WTW performance of e-methanol. In contrast, electricity generated from fossil fuels can negate a considerable portion of the advantages realized during onboard operation.

The hotspot assessment identifies two primary priorities for emissions reduction: reducing operational emissions during sailing and ensuring that methanol production is powered by low-carbon electricity and efficient upstream production systems.

5.8.4 Sub-step 6.4: Future Emissions Trajectories

The annual WTW emissions calculated for the representative vessel are combined with the projected number of containerships developed in Step 5. This produces corridor-level emissions trajectories for MDO, bio-methanol, and e-methanol under the forecast scenario for 2050.

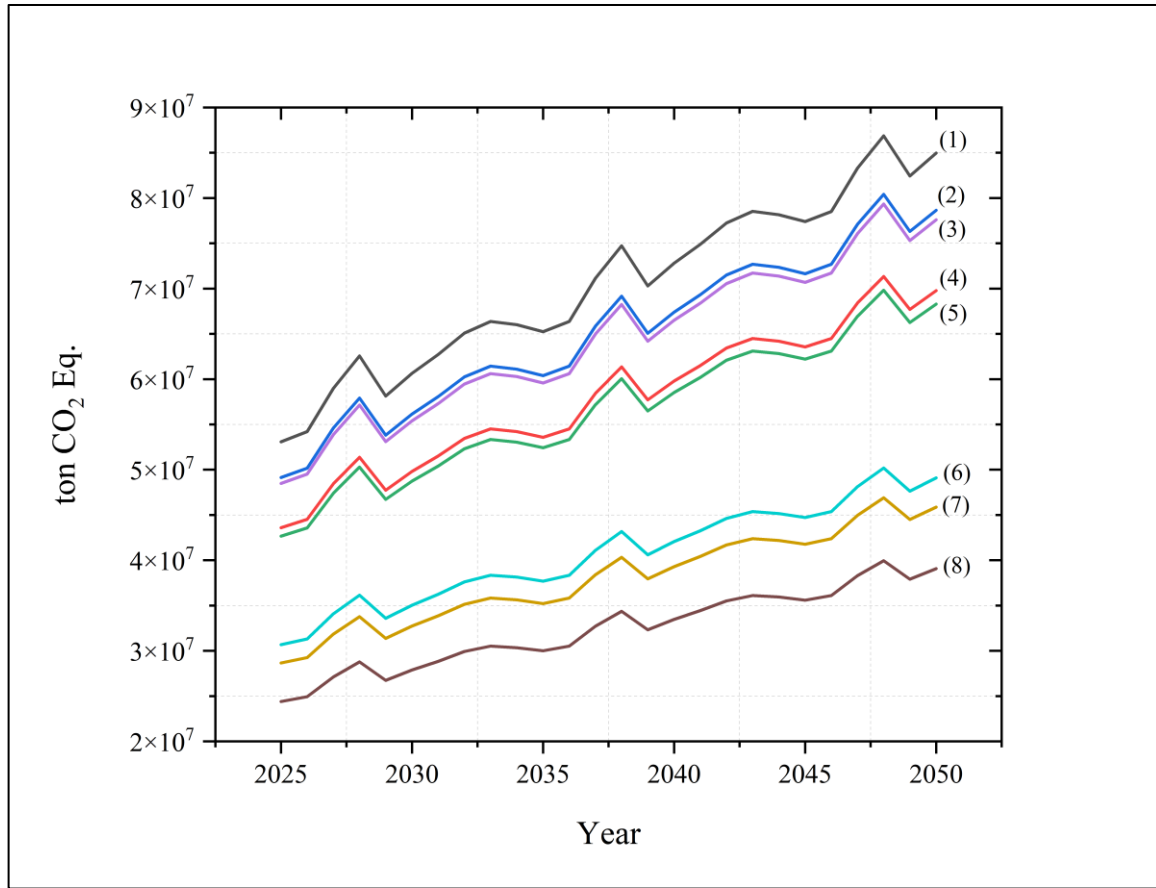


Figure 5-7. Projection of Well-to-Wake emissions of bio-methanol, e-methanol, and MDO (forecast scenario), 1. MDO, 2. Bio-methanol (OCI/BioMCN) (Natural Gas), 3. Bio-Methanol (Gidara & Low Lands) (Natural Gas), 4. Bio-methanol (OCI/BioMCN) (Wind), 5. Bio-methanol (Gidara & Low Lands) (Wind), 6. E-methanol (Consortium Nouryon/ Gasunie/ BioMCN) (Solar), 7. E-methanol (Consortium Nouryon/ Gasunie/ BioMCN) (Wind), 8. E-methanol (PTTEP, Air Liquide, YTL PowerSeraya, Oiltanking, Kenoil Marine Services, Maersk) (Solar).

The figure above represents the total GHG impact of the fleet that is projected to correspond to the TEU demands that are revealed until 2050. MDO has the highest GHG emissions compared to bio-methanol and e-methanol, starting from 5.31E+07 tons CO₂-eq. in 2025 and reaching 8.50E+07 tons CO₂-eq. in 2050. Following MDO, bio-methanol from natural gas has a significantly high GHG footprint with 4.92E+07 tons CO₂-eq. and 4.85E+07 tons CO₂-eq. in 2025, values that grow to 7.86E+07 tons CO₂-eq. and 7.76E+07 tons CO₂-eq. in 2050. The influence of the source of electricity during the production phase of bio-

methanol can be observed easily above because the bio-methanol produced from wind has a lower carbon impact.

Specifically, in 2025, the GHG emissions are 4.36E+07 tons CO₂-eq. and 4.27E+07 tons CO₂-eq, hitting the values of 6.98E+07 tons CO₂-eq. and 6.83E+07 tons CO₂-eq. in 2050. The most carbon-favorable fuel is e-methanol produced from renewable sources of wind and solar. The GHG intensity in 2025 is 3.07E+07 tons CO₂-eq., 2.87E+07 tons CO₂-eq., and 2.44E+07 tons CO₂-eq., reaching 4.59E+07 tons CO₂-eq., 4.91E+07 tons CO₂-eq., and 3.91E+07 tons CO₂-eq. in 2050. Concluding, e-methanol based on 2050 values can reduce the GHG impact by 26% compared to 2025 MDO values and 54% compared to 2050 MDO values.

5.8.5 Sub-step 6.5: Regulatory, Policy, and Decision-Support Insights

This section delineates the regulatory assessment framework employed in the Singapore–Rotterdam green corridor case study. Alongside the evaluation of life cycle GHG emissions, the case study examines the efficacy of the chosen fuel pathways in relation to two major European maritime decarbonization initiatives: FuelEU Maritime and the EU ETS. This section delineates the process by which the calculated GHG intensity and TTW emissions are converted into regulatory compliance indicators and their corresponding financial implications.

5.8.5.1 FuelEU Maritime Assessment

FuelEU Maritime is utilized in this case study to assess the compliance of MDO, bio-methanol, and e-methanol with forthcoming GHG intensity targets through 2050. This comparison enables the case study to determine which fuel pathways maintain compliance over time and which pathways result in a compliance deficit.

The FuelEU Maritime penalty mechanism is designed to discourage non-compliance with the required GHG intensity targets. To calculate the amount that a non-complier needs to pay, it is mandatory to know the Carbon Intensity Factor, as can be seen in the following equation (European Union, 2023).

$$C_B = (GHG_{i,target} - GHG_{i,actual}) \times Total\ Energy_{onboard} \quad \text{Eq. (5-9)}$$

where $GHG_{i,target}$ is the GHG intensity target of Fuel EU in g CO₂ eq./MJ, $GHG_{i,actual}$ is the actual GHG intensity of the vessel in g CO₂ eq./MJ, and $Total\ Energy_{onboard}$ is the total energy used on board in MJ. After that, the penalty can be calculated as:

$$\text{Fuel EU Penalty} = \frac{|C_B|}{GHG_{i,actual} \times 41000} \times 2400 \quad \text{Eq. (5-10)}$$

where C_B in absolute value is the carbon intensity factor as mentioned before, $GHG_{i,actual}$ is the actual GHG intensity of the vessel in g CO₂ eq./MJ, 41000 is 1 metric ton of VLSFO that is equivalent to 41000 MJ, and 2400 is the amount to be paid in EUR per equivalent metric ton of VLSFO. The sum multiplied by $1 + (n - 1)/10$, where n is the number of consecutive reporting periods for which the corporation is subject to a Fuel EU penalty for

that ship, will be applied if a ship has a compliance deficit for two or more consecutive reporting periods (European Union, 2023).

Consequently, a fuel characterized by low onboard emissions may encounter regulatory obstacles if its upstream production process results in elevated WTT emissions. This renders FuelEU Maritime particularly pertinent for the comparison of MDO, bio-methanol, and e-methanol, as their compliance performance is significantly influenced by the electricity source, production method, and overall WTW GHG intensity.

Figure 5-8 represents a holistic comparison between the Fuel EU GHG intensity targets until 2050 and the actual GHG intensity of bio-methanol, e-methanol, and diesel that are available and produced in Singapore and Rotterdam. Every line presents a fuel, a production method, and the main source of electricity, which is mainly natural gas, wind, and solar. It is vital to mention at that stage that from 2030 onwards, the OPS will be applied to all the cases that are about to be analyzed. Details related to the assumption used for each case, the LCA results, and the investments in Rotterdam and Singapore are already discussed in previous chapters.

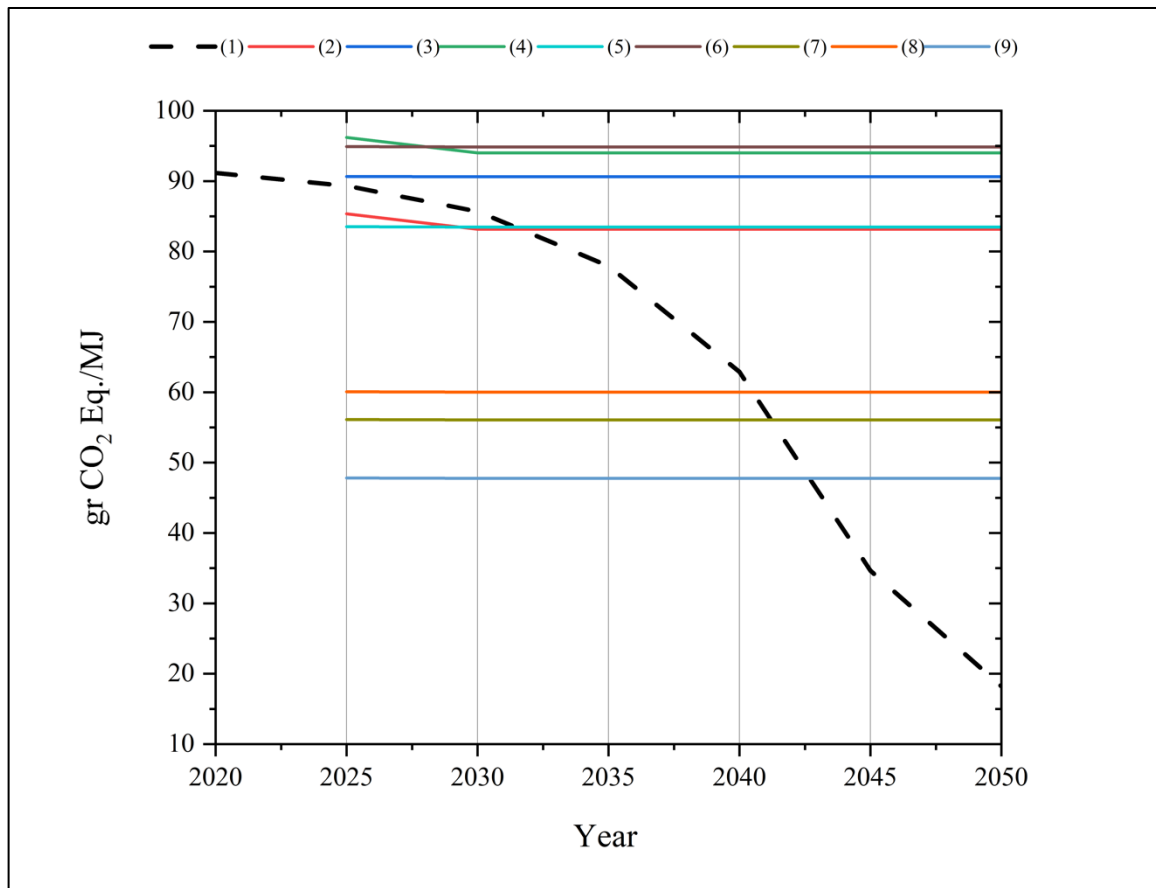


Figure 5-8. Comparison of Fuel EU GHG intensity targets and bio-methanol, e-methanol, and diesel GHG intensity values, 1. Fuel EU Targets, 2. Bio-methanol (OCI/BioMCN) (Wind), 3. MDO, 4. Bio-methanol (OCI/BioMCN) (Natural Gas), 5. Bio-methanol (Gidara & Low Lands) (Wind), 6. Bio-methanol (Gidara & Low Lands) (Natural Gas), 7. E-methanol (Consortium Nouryon/ Gasunic/ BioMCN) (Wind), 8. E-methanol (Consortium Nouryon/ Gasunic/ BioMCN) (Solar), 9. E-methanol (PTTEP, Air Liquide, YTL PowerSeraya, Oiltanking, Kenoil Marine Services, Maersk) (Solar).

By observing the figure above, the fuel with the highest GHG intensity is bio-methanol using natural gas as the main feedstock for electricity, with 94.87 g CO₂-eq./MJ and 94.01 g CO₂-eq./MJ. MDO is also in the highest rankings with 90.62 g CO₂-eq./MJ. Comparing these values with the first target of Fuel EU, which is 89.34 g CO₂-eq./MJ in 2025, MDO and bio-methanol utilizing natural gas cannot align with the current restrictions.

However, bio-methanol produced from electricity using wind has a different character. Particularly, bio-methanol via wind emits 83.48 g CO₂-eq./MJ and 83.17 g CO₂-eq./MJ,

values that align with the Fuel EU regulation from 2025 until 2035, since the restrictions are 89.34 g CO₂-eq./MJ in 2025 and 77.94 g CO₂-eq./MJ in 2035. After 2035, a penalty must be issued to the current vessel by 2050.

The most promising fuel for this green corridor seems to be e-methanol. To produce e-methanol, renewable energy is required, so only wind and solar energy have been considered as sources of electricity. This fuel presents a GHG intensity of 60.01 g CO₂-eq./MJ, 56.07 g CO₂-eq./MJ, and 47.76 g CO₂-eq./MJ as the lowest possible values. That means that it complies with the current FuelEU regulation until 2045, with the restriction target of 34.64 g CO₂-eq./MJ. Eventually, only five years until 2050 are left, so the penalty for this option will be considerably lower than the other fuel choices.

After assessing the carbon impact of bio-methanol, e-methanol, and MDO, it is essential to calculate the overall amount of euros that needs to be paid under the Fuel EU penalty scheme from the year of non-compliance until 2050.

According to Figure 5-9 bio-methanol sourced with electricity from natural gas and MDO have the highest amount to pay, with 641.970.461,0 € and 640.669.251,51 € for bio-methanol and 678.584.810,3 € for MDO. Bio-methanol via wind follows with 338.890.646,5 € and 340.909.249,4 €. E-methanol is considered not only the most carbon-friendly choice but also the most financially attractive since the overall penalty is 112.170.920,2 €, 103.534.789,4 €, or 80.673.138,5 €, depending on the source of electricity, between wind and solar.

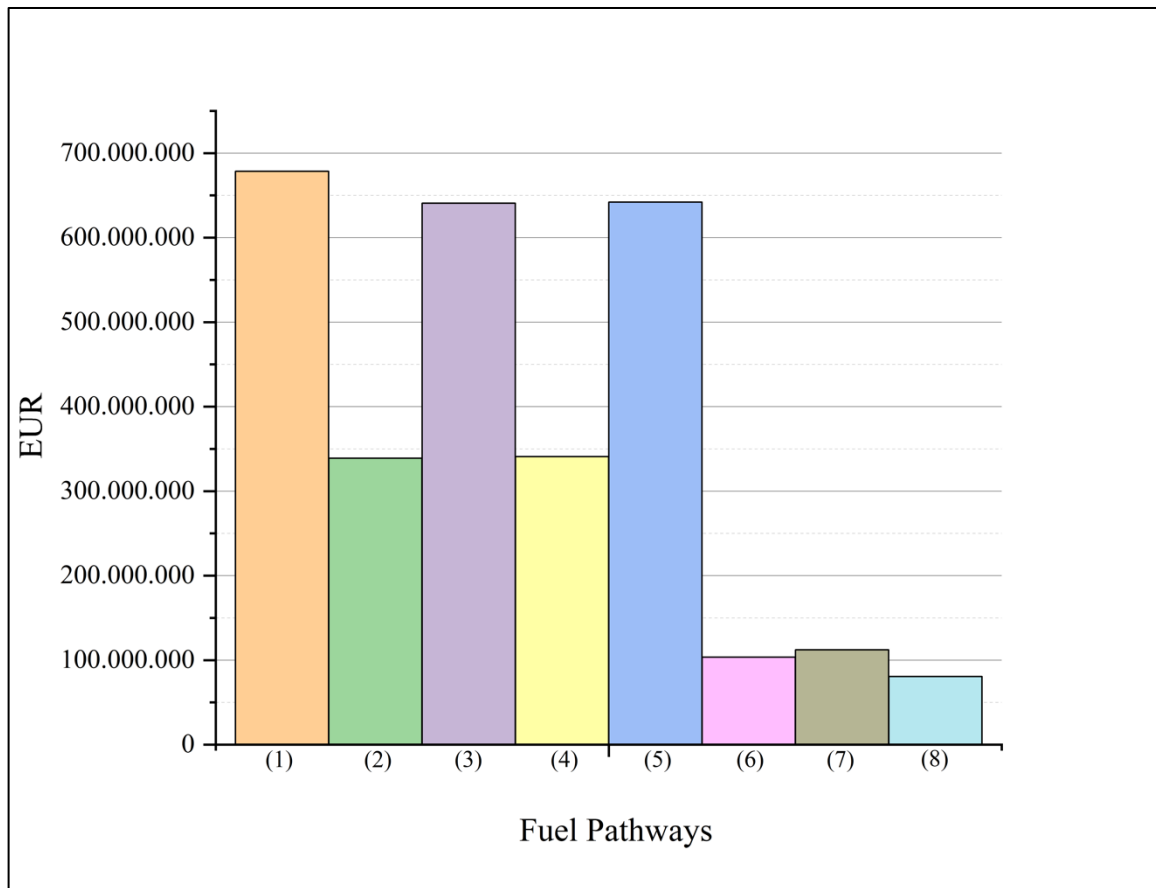


Figure 5-9. Total Fuel EU Penalties until 2050, 1. MDO, 2. Bio-methanol (OCI/BioMCN) (Wind), 3. Bio-methanol (OCI/BioMCN) (Natural Gas), 4. Bio-methanol (Gidara Energy) (Wind), 5. Bio-methanol (Gidara Energy) (Natural Gas), 6. E-methanol (Consortium Nouryon/ Gasunie/BioMCN) (Wind), 7. E-methanol (Consortium Nouryon/ Gasunie/ BioMCN) (Solar), 8. E-methanol (PTTEP, Air Liquide, YTL Power Seraya, Oiltanking, Kenoil Marine Services, Maersk) (Solar).

Another penalty is the one that refers to the non-compliance of the vessel with the OPS requirements during its time at berth. In this case study, there is no such penalty due to the power needs of this containership in the port of Rotterdam. However, in case of non-compliance, the penalty according to the guidelines of Fuel EU would be 30.037,50 € for the diesel engine and 25.560,00 € for the methanol dual-fuel engine. These values are considered an “extra penalty” in addition to the one that is already presented, every time the vessel does not meet the port-call requirements of the Fuel EU (European Union, 2023).

Consequently, a fuel with low onboard emissions may face regulatory challenges if its upstream production process leads to increased WTT emissions. This makes FuelEU Maritime especially pertinent for comparing MDO, bio-methanol, and e-methanol, as their compliance performance is significantly affected by the electricity source, production method, and overall WTW GHG intensity.

5.8.5.2 EU Emissions Trading System Assessment

One of the most crucial regulations that has already been implemented in the maritime industry is the EU ETS. In this case study, the EU ETS is applied to estimate the annual and cumulative cost of the emissions allowances required for vessel operation to 2050. The EU ETS serves as the basis for estimating the costs of emissions allowances related to the operation of the vessel in this case study. In contrast to FuelEU Maritime, which evaluates fuel greenhouse gas intensity on a lifecycle basis, the EU ETS assessment relies on TTW emissions. Consequently, the EU ETS framework is implemented for emissions produced during vessel operation, specifically those related to fuel combustion.

Specifically, for a ship to have permission to emit a certain quantity of GHGs, the shipowner must buy the relevant quantity in EU allowances, starting from 2024. The total GHG emissions that the case vessel emits have already been calculated from the TTW phase and are about to be used for these economic estimations. To forecast the prices of the EU ETS allowances until 2050, Holt-Winters' exponential smoothing methodology is used based on historical data from 2006 to 2024 (Trading Economics, 2024a). Three price scenarios are considered to reflect uncertainty in future carbon-market development: a forecast scenario, a lower-confidence scenario, and a higher-confidence scenario. These

projected prices are then used to calculate the annual and cumulative allowance costs associated with MDO and methanol operation. These results are based on historical data, and a seasonality factor of 11 is used for implementing the projections as accurately as possible.

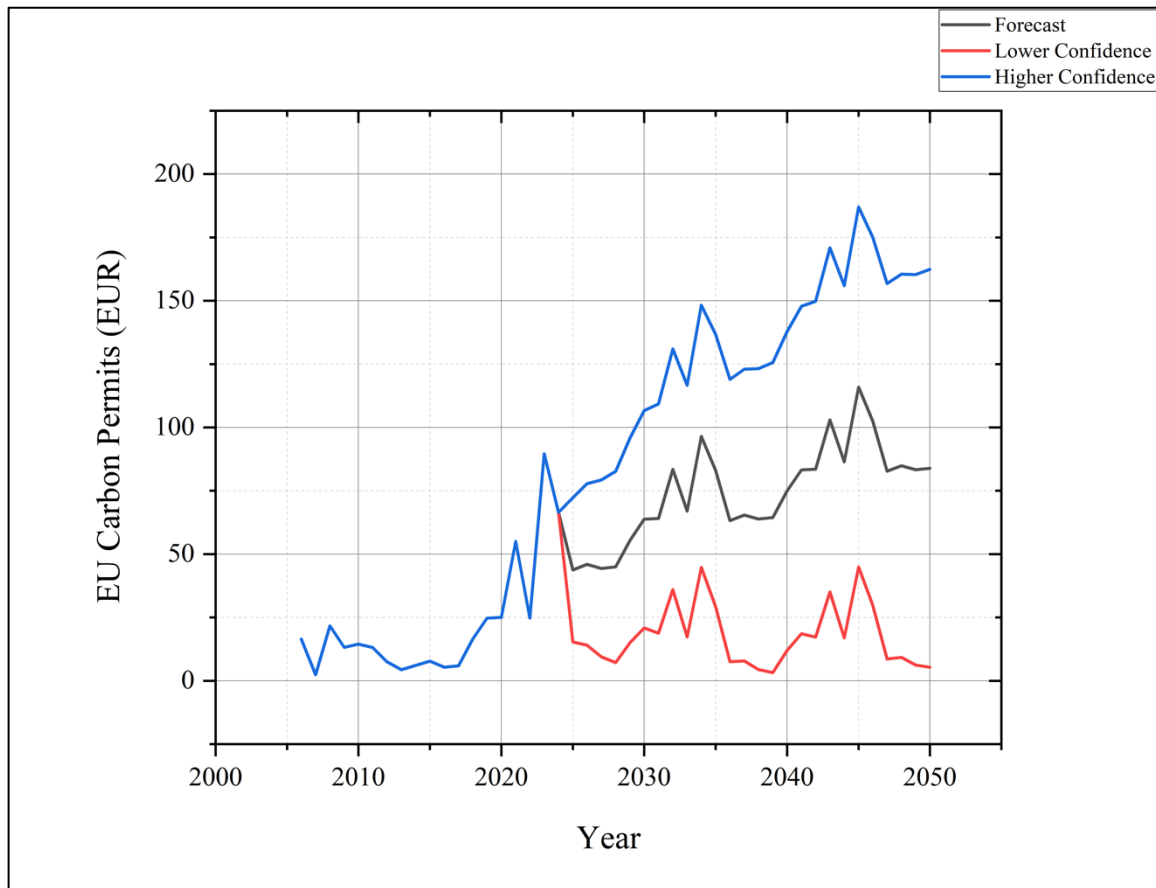


Figure 5-10. Historical and projected EU carbon-permit prices under the lower-confidence, forecast, and higher-confidence scenarios to 2050.

The prices from the different scenarios above are the basis for the calculations that aim to investigate the total amount required to be paid in EU ETS allowances for this case study. After that, there will be an estimation of how much it costs to sail in this green corridor from an EU ETS perspective. It is important to note that in 2024 and 2025, only the CO₂

emissions must be considered, while from 2026 until 2050, the total CO₂-eq. emissions must be taken into consideration.

One of the most crucial regulations that has already been implemented in the maritime industry is the EU ETS. Based on the present case study, results related to the total amount (EUR) that needs to be paid by 2050 are revealed.

Table 5-17. TTW emissions from methanol and MDO, and the share of emissions covered by EU ETS allowances.

Fuel	Year	Share of Emissions covered by EU ETS Allowances (%)	CO ₂	CH ₄	N ₂ O	Total (tons CO ₂ eq.)
Methanol	2024	40%	1.50E+04	-	-	1.50E+04
	2025	70%	2.62E+04	-	-	2.62E+04
	2026 - 2050	100%	3.75E+04	9.30E-02	3.35E-01	3.75E+04
MDO	2024	40%	1.84E+04	-	-	1.84E+04
	2025	70%	3.22E+04	-	-	3.22E+04
	2026 - 2050	100%	4.61E+04	7.18E-01	2.59E+00	4.68E+04

Source: Author's calculations based on the TTW emissions calculated in this study and the EU ETS assumptions described in Section 5.8.5.

As can be seen in Table 5-17 the GHG emissions from the diesel selection need to be covered by a significant amount of EU ETS allowances. To understand the total impact of these emissions, it is mandatory to convert the environmental footprint into financial consequences for the shipowners. Figure 5-11 depicts a comprehensive picture of diesel's financial behavior from the EU ETS viewpoint, based on the prices derived from the current study's prediction and the previously discussed alternative scenarios.

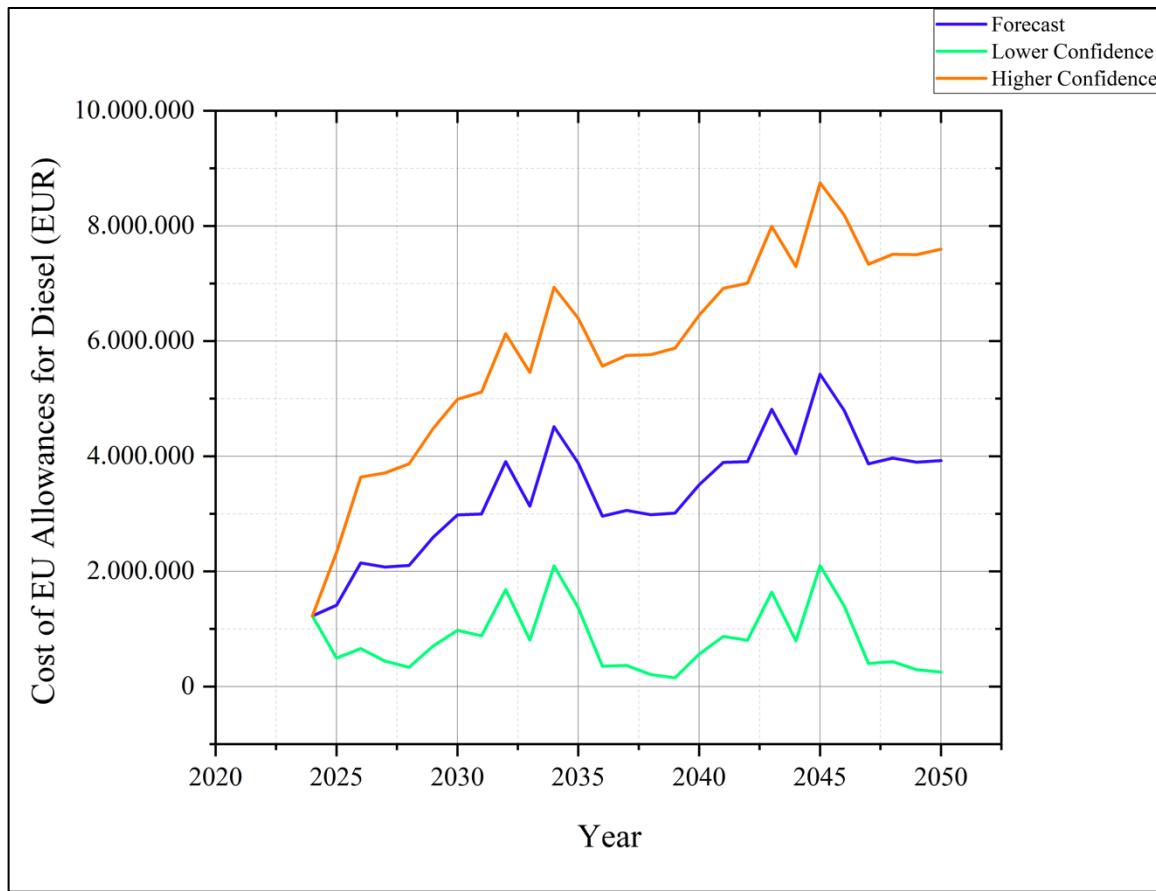


Figure 5-11. Total amount (EUR) of EU allowances for diesel.

The figure above shows that 2045 will have the highest amount that must be paid to be allowed to emit the amount of $4.68\text{E}+04$ tons $\text{CO}_2\text{-eq}$ from diesel. For the higher confidence scenario, the price will be 8.747.746 €, while for the lower confidence scenario, the price is 2.098.980,4 €. Focusing on the most potential forecast scenario, the amount to be paid will be 5.423.363,4 € for this year.

Another crucial observation is that the prices tend to increase every year in every scenario studied. Eventually, the EU allowance price is the primary driver of this fuel investment's financial nature for a certain quantity of TTW.

Since diesel is the fuel that the maritime industry aims to replace, methanol, specifically bio-methanol and e-methanol, could be a potential source of energy for the industry. For that reason, the same work and calculations have been implemented for methanol. Since only the total amount of TTW emissions is in scope for the EU ETS, the differences between e-methanol and bio-methanol in the WTT phase are not taken into consideration.

The TTW emissions resulting from the use of methanol are calculated and shown in Figure 5-12 for each year between 2024 and 2050, considering the pilot fuel (MDO) needed for the combustion of methanol in internal combustion engines. The shipowner is anticipated to pay less than in the diesel fuel scenario since the overall number of emissions is lower.

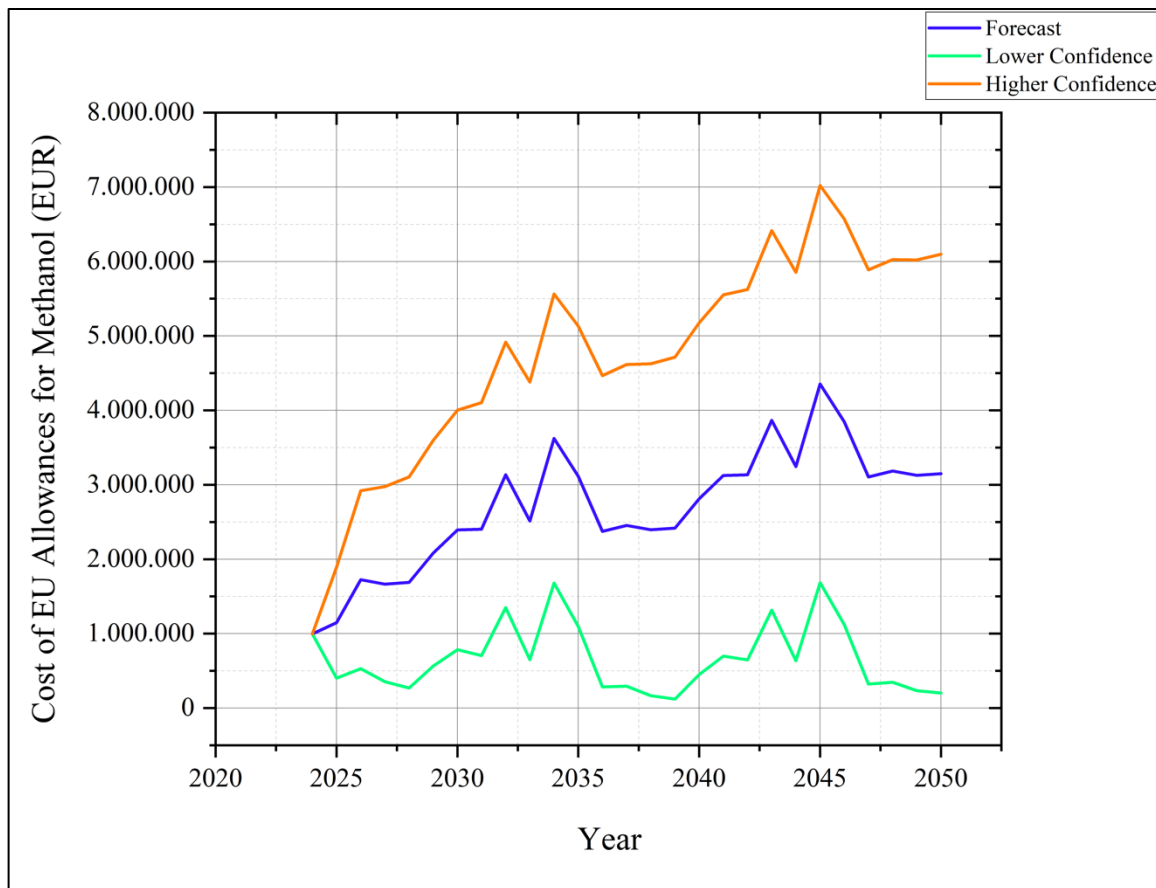


Figure 5-12. Total amount (EUR) of EU allowances for methanol.

The estimate indicates that the largest payment required to release 3.75E+04 tons CO₂-eq. from methanol is in 2045. The price for the higher confidence scenario is 7.021.186 €, whereas for the lower confidence scenario, it is 1.684.700,5 €. Based on the most likely forecast scenario, the amount to be paid this year will be 4.352.943,4 €.

In every scenario examined, prices tend to increase annually, just like with the diesel option. Therefore, the EU permit price is the primary factor that determines the financial character of this fuel investment for a given quantity of TTW emissions.

The EU ETS regulation can play an important role in determining which fuel should be utilized due to the total cost of EU permits a shipowner must pay for that corridor. For this reason, Figure 5-13 compares diesel and methanol in terms of the total amount of money required to pay for EU allowances, under the forecast scenario, since it has the most potential compared to the other two.

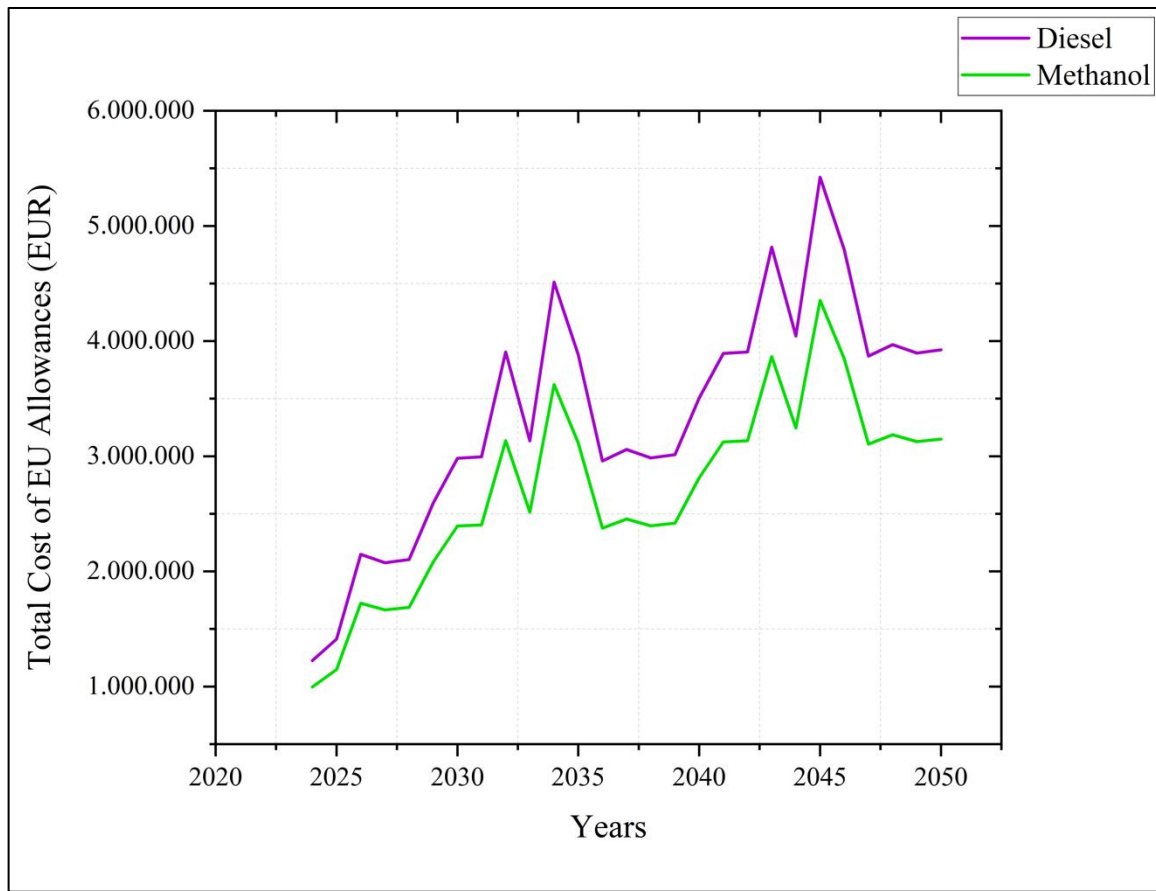


Figure 5-13. EU Allowances cost comparison between diesel and methanol.

The results show a varying pattern in costs for both fuels, with a significant variance in cost trajectories over time. Initially, from 2024 until about 2045, diesel is more expensive than methanol, culminating around 2045 when expenses reach 5.423.363,4 €. This period shows high fluctuation in diesel prices, indicating the influence of strict environmental restrictions and market instability.

In comparison, methanol follows a similar trajectory over the years but with lower prices, never exceeding the 2045 price of 4.352.943,4 €. This is evidence that methanol can be an alternative to diesel and a cost-effective option for the shipowner over the upcoming years.

5.8.5.3 Decision-Support Implications

The assessment of the EU ETS links onboard emissions performance to financial risk. Methanol necessitates fewer allowances than MDO due to its lower calculated TTW emissions, leading to reduced costs associated with the EU ETS. However, the EU ETS focuses on operational emissions and fails to account for the comprehensive upstream carbon performance of each fuel pathway. The findings of the EU ETS should be interpreted in conjunction with the FuelEU Maritime assessment and the WTW life cycle results.

The integrated regulatory assessment allows for the evaluation of the chosen fuel pathways from environmental and financial viewpoints. FuelEU Maritime evaluates compliance through life cycle GHG intensity, while the EU ETS calculates the expenses associated with operational emissions. Together, the two instruments offer complementary insights into the impact of fuel selection on regulatory compliance, carbon costs, and long-term decarbonization strategies for the Singapore–Rotterdam green corridor.

5.8.6 Case-Study-Specific Extension: Sensitivity Analysis

A sensitivity analysis was conducted to assess the robustness of compliance cost forecasts by varying the two primary regulatory parameters, ETS carbon prices and Fuel EU penalty, between a $\pm 10\%$ and $\pm 20\%$ range of the expected values in the forecast scenario utilized in this work. The ETS carbon price fluctuated for each analyzed year (2025–2050), while the Fuel EU, initially established at 2400 € per ton of VLSFO equivalent energy, a key parameter for penalty computation, was similarly modified. The outcomes illustrated by the tornado diagrams below offer a lucid representation of how these variations affect

overall compliance costs for both MDO and e-methanol. Each bar signifies the percentage effect on the overall compliance cost (FuelEU + ETS) when the respective parameter is altered within the specified range. This depiction emphasizes the significance of each parameter in influencing total compliance costs.

The research indicates that compliance costs for MDO are significantly affected by FuelEU penalty criteria, which constitute 60% to 80% of the entire cost, varying by year. When the FuelEU penalty escalates by 10% or 20%, MDO's compliance expenses substantially climb, exacerbating the economic drawbacks of persistent fossil fuel utilization. This tendency intensifies post-2040, since Fuel EU becomes most MDOs' overall compliance expenses, rendering it less competitive. The compliance cost for e-methanol is mostly influenced by EU ETS pricing. Nonetheless, a significant tendency manifests over time: whereas fluctuations in carbon pricing substantially affect e-methanol in the initial years (2025–2035), this effect wanes in subsequent years, especially post-2040. This indicates that as carbon pricing stabilizes and the usage of alternative fuels increases, e-methanol will become a more economically viable choice.

The research reveals that, even under the most adverse situations, characterized by substantial increases in both carbon pricing and Fuel EU penalties, e-methanol continues to be the more economically viable option in the long run. This suggests that more regulatory constraints will expedite the industry's shift from MDO, solidifying e-methanol's status as a sustainable alternative. The increasing financial strain on MDO underscores the efficacy of Fuel EU penalties as a significant tool for phasing out fossil fuels. The costs associated with the EU ETS significantly affect alternative fuels,

highlighting the necessity for further policy assistance, whether carbon credits or tax incentives, to enhance the competitiveness of low-carbon fuels.

These results possess considerable consequences for policymakers and industry stakeholders. Given that FuelEU penalties are the primary cost driver for MDO, augmenting them beyond 2040 might provide a more compelling incentive for the maritime sector to transition to alternative fuels. Conversely, the disproportionate impact of EU ETS costs on e-methanol indicates that regulatory authorities should contemplate ways to mitigate this effect, such as subsidies or preferred carbon credit distributions, to promote broader adoption. Moreover, establishing enough infrastructure for e-methanol production and delivery will be pivotal in stabilizing prices over time, alleviating supply-chain bottlenecks, and bolstering market confidence throughout the transition.

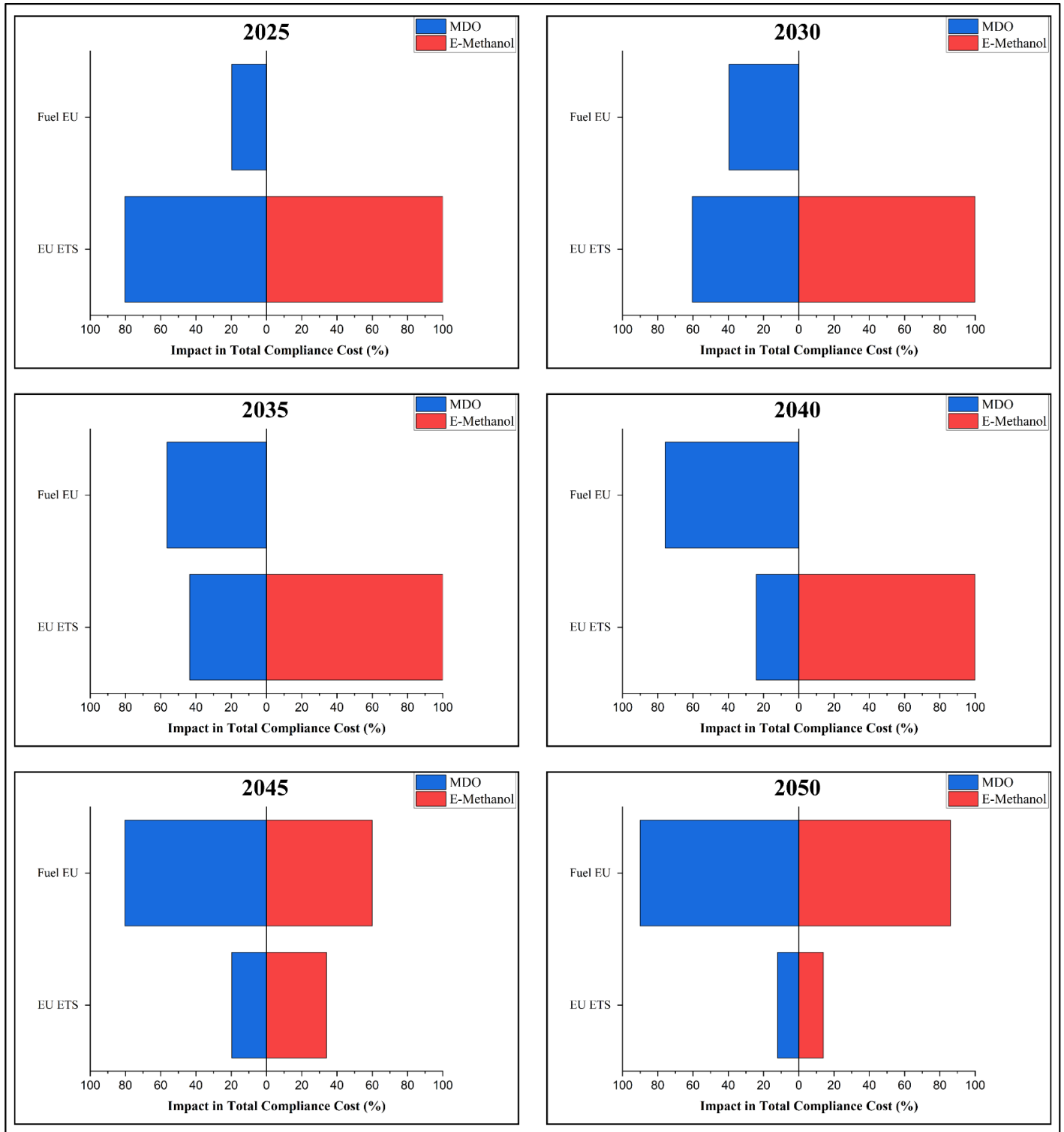


Figure 5-14. Tornado diagrams illustrating the sensitivity of critical factors of FuelEU and ETS on the overall compliance cost between 2025 and 2050.

The sensitivity analysis demonstrates that, within the examined $\pm 10\%$ and $\pm 20\%$ variations, the primary regulatory-cost trends remain largely consistent. FuelEU Maritime penalties constitute a significant long-term cost factor for MDO, while EU ETS carbon prices exert a more substantial impact on the compliance costs related to methanol. These conclusions are contingent upon the regulatory and lifecycle assumptions utilized in this case study. Future modifications in EU ETS allowance prices, FuelEU Maritime targets and penalty mechanisms, emissions coverage, fuel-certification regulations, or lifecycle emission factors may impact the scale and timing of anticipated compliance costs. The results should be interpreted as regulatory outcomes specific to scenarios rather than as fixed predictions of future fuel competitiveness.

5.9 Case Study Limitations

Although this case study offers a thorough forecast-based LCA of the Singapore–Rotterdam green corridor, it is important to recognize several limitations.

The accuracy of the forecast results is contingent upon the quality, availability, and historical behavior of the input data utilized for TEU demand, GDP, population, and carbon-price projections. The Holt–Winters method identifies and extends patterns in historical time-series data. However, future maritime demand and carbon-market prices may be influenced by unforeseen economic, political, technological, or regulatory developments not captured by historical trends. The projections should be viewed as systematic scenario-based estimates rather than definitive predictions of future activity and emissions.

Furthermore, the case study does not incorporate AIS-derived vessel trajectories or segment-level operational data. Instead, it utilizes a representative annual operational profile for an 8,000 TEU containership, encompassing sailing, maneuvering, anchoring, and other operational activities. Thus, the assessment fails to account for variations specific to vessels, including speed, engine load, voyage duration, weather conditions, congestion, waiting time, or operational behavior. The calculated fuel consumption and emissions represent the assumptions of the selected case vessel rather than the performance of all containerships operating on the corridor.

Additionally, certain fuel-production data were obtained from published literature, publicly accessible project information, and plausible assumptions, especially in instances where detailed commercial information was lacking. This limitation is particularly pertinent to planned or emerging bio-methanol and e-methanol production projects for which comprehensive technical and operational data remain undisclosed to the public. The calculated WTT emissions should be interpreted as estimates specific to particular pathways rather than as fixed or universally applicable values.

Another significant limitation pertains to the presumed source of electricity. The life cycle performance of bio-methanol and e-methanol is significantly affected by the carbon intensity of the electricity utilized in their production. Renewable electricity significantly lowers upstream emissions, while electricity from fossil fuels raises the overall greenhouse gas intensity of methanol-based pathways. The results must be interpreted in relation to the electricity source assumptions utilized in the case study. Future modifications in regional electricity systems, availability of renewable energy, production efficiency, and

advancements in carbon-capture technology may impact the environmental performance of the evaluated pathways.

The forecasting component estimates future transport activity and vessel requirements up to 2050, maintaining selected lifecycle emission factors and background-energy assumptions constant within each defined fuel pathway. The resulting assessment should be interpreted as forecast-oriented and prospective regarding activity and scenario development, rather than as a fully prospective LCA in which all future foreground and background systems evolve dynamically. Variations in electricity carbon intensity, fuel production efficiency, hydrogen production, carbon capture, or lifecycle emission factors may impact the future WTW performance of the evaluated pathways.

Furthermore, due to the lack of adequately established CH₄ and N₂O emission factors for the chosen methanol-engine configuration, the associated methanol-combustion emission factors are presumed to be zero. While complete combustion of methanol typically does not yield CH₄, some formation may occur under conditions of incomplete combustion, low temperatures, or insufficient fuel–air mixing. The TTW results may not comprehensively capture all potential secondary emissions linked to methanol combustion.

The defined system boundary excludes specific infrastructure and logistics components, such as detailed emissions from bunkering infrastructure, fuel storage, and certain transportation processes deemed negligible or outside the study's scope. Furthermore, operational efficiency measures such as slow steaming, weather routing, hull retrofits, wind-assist technologies, and various energy-saving strategies remain unassessed. The analysis primarily emphasizes fuel-pathway performance, life cycle GHG intensity,

forecast activity, and regulatory compliance, rather than encompassing the entire spectrum of technical and operational decarbonization measures accessible to shipowners.

The scope of the sensitivity analysis constitutes an additional limitation. The analysis examines variations of $\pm 10\%$ and $\pm 20\%$ in EU ETS carbon prices and FuelEU Maritime penalty rates. While this indicates the robustness of the regulatory-cost outcomes, it does not account for all potential future changes in fuel prices, production efficiencies, renewable electricity availability, fleet activity, technology costs, or regulatory requirements.

Ultimately, the regulatory assessment relies on the provisions and parameters of FuelEU Maritime and the EU ETS as applicable during the study period. Future modifications to GHG-intensity targets, penalty rates, emissions-coverage requirements, allowance prices, life cycle accounting rules, or fuel-certification requirements may influence the assessed compliance and cost outcomes.

Despite these limitations, the case study offers a reliable foundation for comparing MDO, bio-methanol, and e-methanol within an integrated life cycle, forecasting, and regulatory framework. The analysis illustrates the implementation of the forecast-oriented components of the methodology outlined in Chapter 4, whereas the AIS-based and fully time-resolved components are presented independently in Chapter 6.

5.10 Closing Remarks

This chapter applied the forecast-oriented components of the proposed methodology to the Singapore–Rotterdam containership green corridor. The principal findings can be summarized as follows:

- The WTW results demonstrate that alternative marine fuels should be assessed based on the complete production pathway, rather than onboard emissions alone. The performance of bio-methanol and e-methanol is strongly influenced by feedstock, electricity source, production technology, and upstream supply-chain assumptions.
- Within the pathways and assumptions examined, renewable e-methanol produced the lowest lifecycle GHG impacts among the assessed alternatives, while the performance of bio-methanol varied considerably depending on its production and electricity-source assumptions.
- The forecasting analysis shows that reductions in emissions intensity do not necessarily result in reductions in absolute corridor emissions, because future growth in TEU demand and vessel activity can offset part of the benefit achieved through lower-carbon fuels.
- FuelEU Maritime and the EU ETS provide complementary regulatory perspectives. FuelEU Maritime is particularly sensitive to lifecycle GHG intensity, whereas EU ETS exposure is driven primarily by onboard emissions and carbon-allowance prices. The associated cost conclusions remain conditional on future carbon prices, regulatory developments, and lifecycle-emission assumptions.
- Overall, the case study demonstrates how forecasting can extend maritime LCA from a static fuel comparison to a scenario-based assessment of future corridor decarbonization.

The analysis remains forecast-oriented rather than fully prospective, since selected lifecycle emission factors and background-energy assumptions are held fixed within the defined pathways.

Chapter 6 complements this strategic, corridor-level perspective by applying the methodology at the operational scale using AIS-derived, time-resolved vessel activity within the Port of Busan.

6 Case Study 2: Port-LCA Application for AIS-Based Time-Resolved Emissions Assessment in the Port of Busan

6.1 Introduction

The preceding chapter utilized a forecast-based LCA framework for the Singapore–Rotterdam containership green corridor. The case study examined long-distance corridor emissions, anticipated fuel performance, and regulatory implications, considering projected transport demand. Chapter 6 presents the second case study of the thesis, transitioning the analytical focus from a green shipping corridor to an assessment of port-boundary emissions. This chapter analyzes the Port of Busan and employs an AIS-based, time-resolved Port-LCA framework to assess lifecycle GHG emissions from container vessels operating within a specified port boundary.

The objective of this case study is to illustrate the integration of vessel activity data with life cycle assessment for a more detailed evaluation of emissions. Rather than relying solely on static assumptions about vessel operations, the Port-LCA framework uses AIS-derived vessel trajectories to reconstruct movement and estimate distance, speed, propulsion power, fuel consumption, and lifecycle emissions. This allows evaluation of time-resolved variations in vessel activity within the port boundary and facilitates comparison of the performance of different fuel pathways under identical operational conditions.

This case study is derived from the author's revised manuscript intended for resubmission to Ocean Engineering, titled “*Port-LCA for Maritime Decarbonization: AIS-Based Time-Resolved Analysis of Alternative Marine Fuels.*” The research establishes and implements

an AIS-based Port-LCA framework to assess port-boundary WTW emissions associated with alternative marine fuels. The framework integrates AIS trajectory reconstruction, speed–power modeling, fuel consumption estimation, fuel-specific WTT and TTW emission factors, along with Holt–Winters forecasting for future port activity.

The Port of Busan is chosen as the case study due to its status as a major container port and a key maritime hub in East Asia. The port exhibits significant vessel traffic density, strong links to global container trade, and increasing importance in the discourse surrounding port-related air pollution and maritime decarbonization. Recent studies demonstrate that maritime operations in and around Busan significantly impact local air pollution, specifically concerning PM_{2.5}, SO_x, and black carbon. Scenario-based assessments indicate that enhanced regulations about ships and ports could lead to improved air quality in the adjacent port area (Kang et al., 2025; Kwon et al., 2023; Loh et al., 2025).

The case study assesses seven anonymized container vessels functioning within a 20 NM boundary of the Port of Busan. Five marine fuel pathways are analyzed: MDO, methanol, e-methanol, ammonia, and e-ammonia. MDO serves as the conventional fossil-fuel baseline, while methanol and ammonia signify alternative fuel pathways that can be derived from fossil or transitional methods. In contrast, e-methanol and e-ammonia exemplify lower-carbon synthetic fuel pathways grounded in renewable or renewable fuel of non-biological origin (RFNBO)-type production routes. This fuel selection enables the case study to analyze the impact of fuel type and production pathway on lifecycle GHG performance.

This case study should be interpreted as a proof-of-concept application of the Port-LCA framework. The operational analysis is based on seven container-vessel trajectories observed over two days and therefore does not represent annual vessel activity or a complete emissions inventory for the Port of Busan.

The chapter expands the Port-LCA framework from emissions at the vessel level to emissions at the future port boundary. This is accomplished by correlating vessel-level emission intensities with anticipated container-vessel demand at the Port of Busan. Demand scenarios are developed using South Korea's real GDP and Busan container throughput, which are subsequently translated into capacity-equivalent vessel requirements projected until 2050. This allows the case study to assess both current vessel-level emissions and the potential future emissions implications of increased port activity under various macroeconomic scenarios.

Finally, this chapter illustrates the comprehensive application of the six-step methodology outlined in Chapter 4. It delineates the objectives, parameters, functional unit, fuel pathways, and port boundaries; reconstructs vessel trajectories and activity profiles derived from AIS data; estimates propulsion power and fuel consumption; computes time-resolved WTT, TTW, and WTW emissions; forecasts future port activity and emissions; and analyzes the resulting outputs through fuel-pathway comparison, identification of emission hotspots, future emissions trajectories, sensitivity analysis, and decision-support insights. The chapter outlines the main limitations and validation constraints of the case study, with a broader interpretation of the findings and their comparison to the Singapore–Rotterdam case study discussed in Chapter 7.

6.2 Description of the Port of Busan Case Study

The Port of Busan is chosen as the second case study of this thesis due to its strategic significance in global container shipping and its relevance to the assessment of port-related emissions. Busan ranks among the busiest container ports globally and serves as a significant transshipment hub in East Asia (Yoo et al., 2022). The high traffic density, complex vessel movements, and strong connectivity with international trade routes render it an appropriate site for testing an AIS-based Port-LCA framework. Recent trends in container throughput demonstrate continued growth in port activity from 2019 to 2024, bolstered by local and transshipment cargo flows (Ministry of Oceans and Fisheries, 2026).

Busan's strategic significance makes it an appropriate case study, as it allows the Port-LCA framework to integrate three analytical levels: AIS-based vessel activity, vessel-specific technical characteristics, and long-term port-demand forecasting. The availability of container-throughput data and its empirical relationship with South Korea's real GDP facilitate the development of future activity scenarios, which can be associated with vessel-level emission intensities (Busan Port Authority, 2024; World Bank, 2026). This positions Busan as a suitable case for illustrating the conversion of time-resolved vessel movements into metrics such as distance, speed, propulsion power, fuel consumption, and WTW emissions within a specified port-boundary framework.

Additionally, the Port of Busan serves as a suitable context for illustrating the significance of time-resolved emissions assessment. Conventional port-emission inventories often depend on generalized assumptions about vessel activity, operational modes, or average fuel consumption. In contrast, the Port-LCA framework utilized in this chapter employs

AIS-derived vessel trajectories to depict vessel movement within a specified port boundary. This links vessel activity directly to traveled distance, speed variation, propulsion power, fuel consumption, and life cycle emissions. The Busan case study allows the proposed framework to move beyond static fuel comparisons and account for temporal variations in emissions within a port environment.

The case study analyzes container-vessel operations within a 20 NM radius of the Port of Busan. This boundary defines an area near the port where vessel emissions are significant for environmental exposure, regulatory oversight, and strategies for decarbonization of the port. However, the 20 NM boundary does not provide a comprehensive port-call inventory, as emissions from anchorage, waiting, hoteling, cargo handling, auxiliary engines, and boilers are not adequately represented unless they occur within the chosen AIS-derived operational tracks. Instead, the boundary establishes a consistent spatial framework for implementing the Port-LCA methodology and evaluating alternative marine fuel pathways under comparable operating conditions.

Additionally, the case study assesses seven anonymized trajectories of container vessels derived from AIS data. These vessels represent variations in size, engine power, service speed, and operational behavior within the Busan port boundary. To maintain commercial and operational confidentiality, the vessels are designated as Vessel 1 through Vessel 7. The chosen vessel sample enables the case study to analyze variations in fuel pathways and vessel heterogeneity. This analysis is important, as emissions within the same port boundary can differ markedly based on factors such as installed engine power, speed profile, and duration spent within the boundary.

While the analysis centers on the Port of Busan, the case study does not aim to deliver a complete official emissions inventory for the port. Busan serves as a representative and data-rich context for demonstrating the applicability, scalability, and transferability of the AIS-based Port-LCA framework. The results should be interpreted as estimates derived from the model, demonstrating the integration of vessel activity, vessel-specific technical characteristics, life cycle emission factors, and port-demand forecasting within a decision-support framework for port decarbonization. Together with the definitions of scope and system boundaries provided in the subsequent section, this case study description delineates the implementation of Step 1 of the methodology outlined in Chapter 4.

6.3 Application of the AIS-Based Port-LCA Framework

This section outlines the application of the six-step methodology introduced in Chapter 4 to the case study of the Port of Busan. The AIS-based Port-LCA framework employs a sequential modeling chain that transforms vessel-position data into time-resolved life cycle emission estimates. It further extrapolates these results to future port-activity scenarios and translates the outputs into comparative and decision-support information. Unlike a traditional static LCA, which relies on fixed assumptions for vessel operation, the Port-LCA framework directly associates emissions with vessel movements derived from AIS data within the defined port boundary. The comprehensive application of the framework is depicted in Figure 6-1.

Step 1: Goal, Scope, and System Boundary Definition. The initial step defines the analytical framework of the case study. The Port of Busan is defined by the maritime system, a 20 NM port-proximate spatial boundary, the selected vessel category and fuel

pathways, the assessment period, the functional unit, and the WTT, TTW, and WTW life cycle boundary. It introduces the seven anonymized container vessels along with the key case-specific modeling assumptions. The application of Step 1 is outlined in Section 6.4.

Step 2: AIS-Based Trajectory Reconstruction and Activity Profiling. The second step involves the conversion of raw AIS records into cleaned and time-resolved profiles of vessel activity. Relevant vessel trajectories are selected and organized in chronological order, while invalid coordinates, duplicate observations, inconsistent timestamps, Global Positioning System (GPS) anomalies, and physically implausible movements are filtered out. Consecutive AIS positions are utilized to compute elapsed time, Haversine distance, and vessel speed at the segment level. This converts the vessel-position data into time-resolved operational profiles within the boundaries of Busan port. The application of Step 2 is detailed in Section 6.5.

Step 3: Propulsion Power and Fuel-Consumption Modelling. The third step connects AIS-derived vessel movement to propulsion demand and fuel consumption. Segment-level speed is translated into propulsion power through the application of vessel-specific speed–power relationships, the installed main-engine power, and the service speed. Engine load is estimated and integrated with elapsed time and fuel consumption assumptions that depend on the load. Fuel-specific adjustments are implemented for MDO, methanol, and ammonia to address variations in engine performance, lower heating value, brake efficiency, and pilot-fuel requirements. The application of Step 3 is outlined in Section 6.6.

Step 4: Time-Resolved Life Cycle Emissions Inventory. The fourth step involves the application of fuel-specific emission factors to the computed fuel consumption for each valid AIS interval. TTW emissions denote greenhouse gas emissions linked to onboard fuel consumption, whereas WTT emissions encompass emissions from upstream fuel production and supply. These components are integrated to compute WTW emissions for each AIS segment, vessel, and fuel pathway. Non-CO₂ GHGs are transformed into CO₂-eq. emissions by applying the chosen GWP100 factors. The application of Step 4 is outlined in Section 6.7.

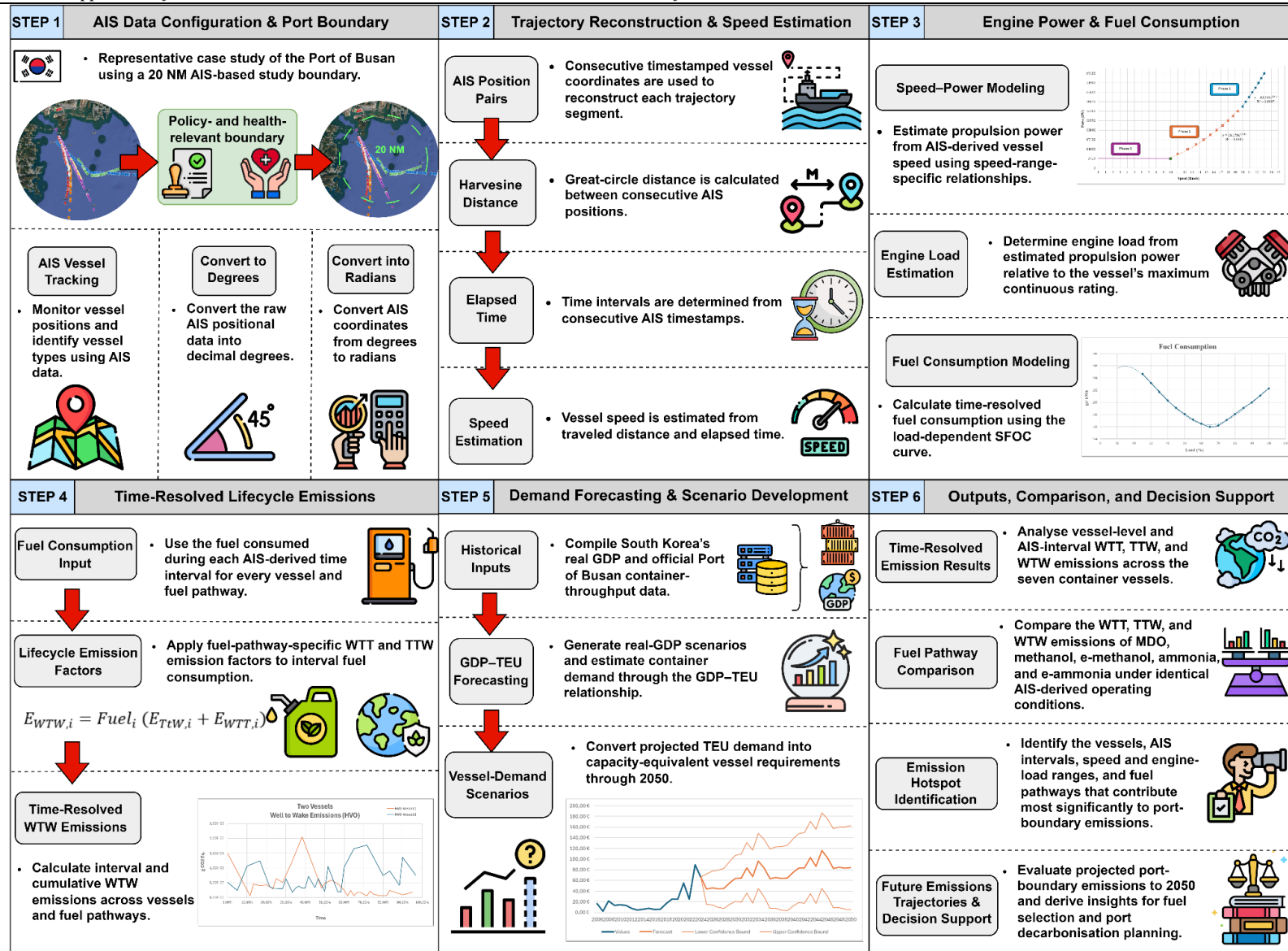


Figure 6-1. AIS-based Port-LCA framework for time-resolved port-boundary emissions assessment.

Step 5: Forecast-Based Activity and Emissions Projection. The fifth step expands the vessel-level Port-LCA findings to prospective port-boundary scenarios. Real GDP of South Korea and container throughput in Busan are utilized to analyze the correlation between macroeconomic activity and port demand. Holt–Winters exponential smoothing produces lower-confidence, central, and upper-confidence trajectories that extend to the year 2050. Future container throughput and capacity-equivalent vessel requirements are derived from these projections, which are subsequently integrated with vessel-level emission intensities to estimate future port-boundary emissions. The application of Step 5 is outlined in Section 6.8.

Step 6: Outputs, Comparison, and Decision Support. The sixth step analyzes and contrasts the outputs produced by the earlier stages. Time-resolved emissions are analyzed across the seven anonymized vessels and their AIS-derived operational intervals. The performance of MDO, methanol, e-methanol, ammonia, and e-ammonia is compared in terms of WTT, TTW, and WTW under equivalent operating conditions. Additionally, the analysis identifies emission hotspots linked to specific vessels, operational intervals, speed and engine load ranges, as well as upstream fuel pathways. Future port-boundary emissions trajectories, macroeconomic uncertainty, and sensitivity results are analyzed to inform fuel-pathway selection, infrastructure planning, emissions management, and long-term port decarbonization. The results related to Step 6 are detailed in Section 6.9.

Figure 6-1 serves as a guide for the subsequent sections of the chapter. Step 1 is defined by the goal, scope, system boundary, vessel sample, fuel pathways, and modeling assumptions outlined in Section 6.4. Step 2 is executed via the AIS data processing and

trajectory reconstruction methods outlined in Section 6.5. Step 3 addresses propulsion power and fuel consumption modeling in Section 6.6, whereas Step 4 outlines the time-resolved life cycle emissions inventory in Section 6.7. Step 5 includes the activity and emissions projections based on forecasts as detailed in Section 6.8. Step 6 is illustrated through time-resolved results, comparisons of vessels and fuel pathways, identification of emission hotspots, projections of future emissions trajectories, uncertainty analysis, and decision-support interpretation as detailed in Section 6.9.

6.4 Step 1: Goal, Scope, Functional Unit, and System Boundary

Step 1 delineates the analytical framework for the Port of Busan case study. It delineates the maritime system, spatial boundary, vessel category, fuel pathways, temporal scope, functional unit, life cycle boundary, and key case-specific assumptions. These definitions establish a uniform foundation for the application of AIS-based trajectory reconstruction, propulsion and fuel-consumption modeling, time-resolved life cycle emissions calculation, forecasting, and output-comparison procedures outlined in the following steps.

6.4.1 Sub-step 1.1: Maritime System and Boundary Definition

The case study aims to utilize the Port-LCA framework to evaluate time-resolved life cycle GHG emissions from specific container vessels operating within the Port of Busan boundary. The analysis applies the methodology outlined in Chapter 4 to a port-boundary context and serves as a complement to the forecast-oriented corridor case study discussed in Chapter 5.

The Port of Busan serves as the maritime system evaluated in this case study. High container-vessel traffic density, complex vessel movements, and its role as an East Asian transshipment hub render it a suitable context for illustrating the application of AIS-based, time-resolved LCA.

The spatial boundary is delineated as a 20 NM radius encompassing the Port of Busan. This boundary defines a consistent area near the port for the calculation of vessel activity, fuel consumption, and life cycle emissions. It captures near-port transit, maneuvering, and other vessel movements as represented by the selected AIS trajectories.

The 20 NM boundary was chosen to delineate the region where vessel emissions significantly impact environmental exposure and port emissions management. Ship-related pollutants, such as PM_{2.5}, NO_x, and SO_x, significantly impact air quality and public health in communities near ports. Consequently, port-decarbonization strategies necessitate spatially explicit evaluations of emissions produced in proximity to port areas (Mueller et al., 2023; Sun et al., 2025; Toscano, 2023). The chosen boundary thus establishes a suitable spatial domain for the application of the Port-LCA framework.

The chosen boundary should not be construed as a universal definition of emissions related to ports. Port limits, pilotage areas, anchorage locations, traffic separation schemes, and emissions control zones vary among different ports. Therefore, the spatial boundary must be modified when implementing the Port-LCA framework in a different location.

Moreover, the Busan assessment does not represent a comprehensive inventory of port-call emissions. Anchorage, waiting, berth occupancy, hoteling, cargo handling, auxiliary-engine operation, boiler use, and shore-side activities are inadequately represented unless

they take place within the chosen AIS-derived vessel tracks. The results are interpreted as estimates of life cycle emissions generated within the defined port boundary, rather than as a comprehensive inventory of all emissions associated with the Port of Busan.

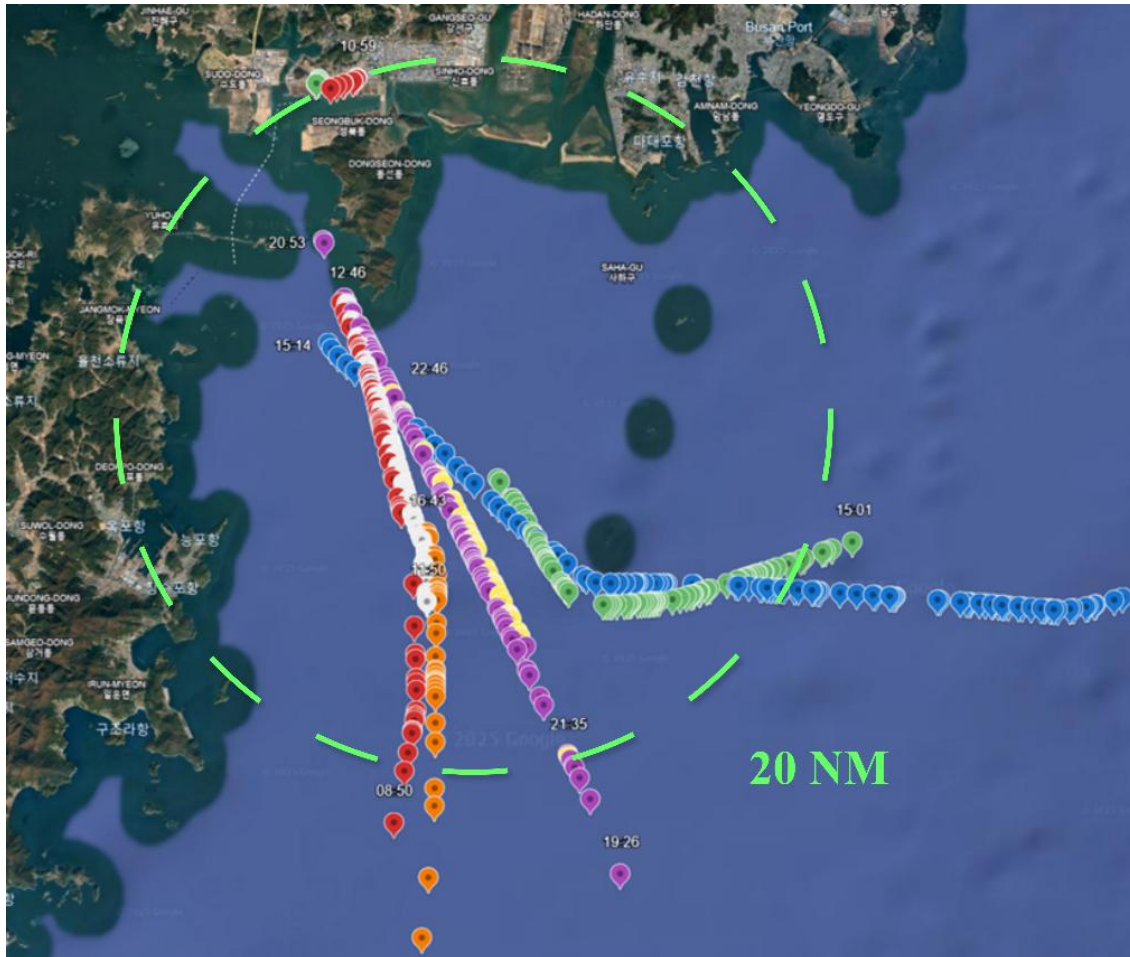


Figure 6-2. AIS-derived vessel trajectories within the 20 NM Port of Busan boundary. AIS trajectories and operational boundary developed by the author; underlying imagery from Google Maps/Google Earth. © Google.

6.4.2 Sub-step 1.2: Vessel Categories, Fuel Pathways, and Temporal Scope

The assessment emphasizes container vessels due to their significance in the operational activities and throughput of the Port of Busan. Seven anonymized container vessel trajectories are selected from the available AIS dataset. The vessels vary in container capacity, installed engine power, service speed, and operational behavior, allowing the framework to accommodate vessel diversity within a unified ship category.

Five marine fuel pathways are evaluated: MDO, methanol, e-methanol, ammonia, and e-ammonia. MDO serves as the standard baseline for conventional fossil fuels. Methanol and ammonia are alternative fuel pathways that can be generated through established fossil-based or transitional industrial processes (Brynnolf et al., 2014; European Union, 2023). Conversely, e-methanol and e-ammonia are characterized as lower-carbon synthetic pathways linked to renewable or RFNBO-type production routes (European Union, 2018; International Energy Agency (IEA), 2023).

The inclusion of both conventional and alternative pathways allows for an analysis that differentiates between the impact of the fuel utilized onboard and the effects of its upstream production process. It also prevents the evaluation of alternative fuels from being based exclusively on their onboard combustion characteristics.

The temporal scope integrates observed AIS-derived vessel activity with the development of long-term scenarios. The operational assessment utilizes AIS records gathered in the Busan port area from March 1 to 2, 2019. These data are utilized to compute vessel-level emission intensities based on the observed operating conditions.

Subsequently, the forecasting component broadens the evaluation to the year 2050. South Korea's real GDP serves as the macroeconomic scenario variable for Busan container throughput, with the projected throughput converted into capacity-equivalent vessel demand (Ministry of Oceans and Fisheries, 2026; UNCTAD, 2025; World Bank, 2026). This combination enables the case study to link current vessel-level activities with potential future developments in port-boundary emissions.

6.4.3 Sub-step 1.3: Life Cycle Boundary and Functional Unit

The functional unit is defined as one vessel-hour of operation within the specified port boundary. This functional unit is suitable because the case study focuses on AIS-derived, time-resolved vessel activity rather than cargo transport throughout an entire voyage. It allows for the comparison of vessels and fuel pathways through a standardized measure of operational exposure within the port boundary.

The primary result indicator is quantified as kg CO₂-eq per vessel-hour. This indicator facilitates the comparison of selected fuel pathways under equivalent operational conditions and serves as the foundation for aggregating vessel-level emissions within future port-boundary scenarios.

The life cycle system boundary adheres to a WTW framework. TTW emissions refer to GHG emissions linked to the use of fuel onboard, while WTT emissions encompass the upstream processes involved in fuel production and supply (IMO, 2024). These components are integrated to compute WTW emissions for each AIS interval, vessel, and fuel pathway.

This distinction is crucial as an alternative marine fuel may lower onboard emissions while generating significant upstream emissions if its production relies on carbon-intensive energy or feedstock sources (G. N. Lee et al., 2024; Lindstad et al., 2021). The WTW boundary facilitates the comparison of selected pathways based on their comprehensive life cycle GHG performance, rather than solely on their onboard emissions.

6.4.4 Case Study-Specific Extension: Vessel Sample and Technical Characteristics

The Port-LCA application analyzes seven anonymized container vessels operating within the designated boundary of the Port of Busan. To maintain commercial and operational confidentiality, the original vessel names and identifiers are withheld, and the vessels are referred to as Vessel 1 through Vessel 7. The framework's technical diversity allows for the assessment of vessel size, installed power, service speed, and operational behavior impact on time-resolved emissions.

The chosen vessels exhibit container capacities between 7,024 and 13,296 TEU, with main-engine powers varying from 47,430 to 72,240 kW. Their service speeds vary between 22.0 and 25.3 knots. These differences are important as propulsion demand, fuel consumption, and emissions are affected by the technical characteristics of a vessel and its activities observed within the port boundary.

Table 6-1. Principal characteristics of selected container vessels used in the Port-LCA case study.

Parameter	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6	Vessel 7	Unit
Ship Type	Container	Container	Container	Container	Container	Container	Container	-
Deadweight	108,804	109,021	115,993	145,149	112,580	78,716	131,831	tons
Capacity	8,814	8,465	11,008	13,296	9,365	7,024	11,040	TEU
Service Speed	23.0	25.2	25.0	24.1	22.0	25.3	24.3	knots
Main Engine Power	57,100	72,240	68,640	71,770	47,430	54,942	72,240	kW
Engine Type (Diesel)	10G95ME-C10.7-LPSCR LS	12G95ME-C10.7-LPSCR LS	12G95ME-C10.7-LPSCR LS	12G95ME-C10.7-LPSCR LS	10G95ME-C10.7-LPSCR LS	10G95ME-C10.7-LPSCR LS	12G95ME-C10.7-LPSCR LS	-
Engine Type (Methanol & Ammonia)	10G95ME-C10.7-LGIM-EGRTC LS	12G95ME-C10.7-LGIM-EGRTC LS	12G95ME-C10.7-LGIM-EGRTC LS	12G95ME-C10.7-LGIM-EGRTC LS	10G95ME-C10.7-LGIM-EGRTC LS	10G95ME-C10.7-LGIM-EGRTC LS	12G95ME-C10.7-LGIM-EGRTC LS	-

Source: The vessels' characteristics are extracted from the AIS data provided by the Busan Port Authority for 1–2 March 2019. The engine types are modeled by the author in CEAS software.

The vessel sample supports the application of vessel-specific speed–power relationships instead of a singular generic container-vessel profile. It also allows for the examination of whether vessels within the same general category display varying emission intensities due to factors such as installed power, service speed, trajectory, and operating conditions.

6.4.5 Case Study-Specific Extension: Key Modelling and Scenario Assumptions

The assumptions of the case study are established to guarantee transparency and reproducibility in the application of Port-LCA. Vessel activity is obtained from AIS trajectories, whereas propulsion demand is calculated based on the installed main-engine power, service speed, and the speed profile derived from AIS data for each vessel. Fuel consumption is calculated based on propulsion power, engine load, elapsed time, and load-dependent fuel consumption assumptions. This activity-based approach directly associates emissions with the technical characteristics of specific vessels and their observed operational behavior.

In the long-term projections of port boundaries, vessel exposure is considered a scenario parameter. Alternative exposure-time assumptions are evaluated, with an annual exposure of 24 hours per capacity-equivalent vessel serving as the primary projection case (IMO, 2021a; Stopford, 2009). This assumption establishes a reliable framework for extrapolating vessel-level emission intensities to future port-boundary estimates. It does not aim to accurately depict the actual duration of each vessel call at Busan.

Future port activity is modeled through a demand-scaling approach. South Korea's real GDP serves as the macroeconomic scenario variable, whereas Busan container throughput

indicates port activity. Projected throughput is transformed into capacity-equivalent vessel requirements by applying assumptions related to representative vessel capacity, load factor, and annual voyages (Ministry of Oceans and Fisheries, 2026; UNCTAD, 2025). The forecasting and scaling calculations are outlined in Step 5.

The calculations of life cycle emissions utilize a hybrid set of emission factors. The IMO life cycle GHG guidelines establish the primary framework for WTT, TTW, and WTW accounting (IMO, 2024). In the absence of default values for a selected pathway, supplementary factors from FuelEU Maritime and pertinent literature are utilized (European Union, 2023). The specific factors and their application are outlined in Step 4.

Finally, the case study configuration includes assumptions regarding uncertainty and sensitivity. Lower-confidence, central forecast, and upper-confidence GDP trajectories are utilized to propagate macroeconomic uncertainty through projected container throughput, vessel demand, and emissions. Mean emission intensity serves as the baseline aggregation measure, whereas median intensity offers a comparative robustness check (Hyndman & Athanasopoulos, 2021a). Sensitivity assessments evaluate the impact of AIS sampling gaps, engine power class, fleet composition, and other modeling assumptions on the derived results.

Together, these definitions and assumptions fulfill Step 1 of the methodology. They provide the analytical foundation for the AIS-based trajectory reconstruction and activity profiling conducted in Step 2.

6.5 Step 2: AIS-Based Trajectory Reconstruction and Activity Profiling

Step 2 utilizes the AIS-based trajectory-reconstruction method outlined in Chapter 4, applied to the Port of Busan dataset. The procedure transforms raw vessel-position records into organized, chronological, and time-resolved activity profiles. It encompasses the acquisition of AIS data and the processing of coordinates, subsequently leading to the calculation of elapsed time, distance traveled, and vessel speed at the segment level. These outputs serve as the operational foundation for the calculations of propulsion power, fuel consumption, and life cycle emissions conducted in the following steps.

6.5.1 Sub-step 2.1: AIS Data Acquisition and Coordinate Processing

The AIS dataset utilized in this case study was provided by the Busan Port Authority for research purposes. It includes vessel-position records gathered in the Busan port area over two days, specifically from March 1 to March 2, 2019. The two original daily files comprised 302,619 and 288,935 records, yielding approximately 591,554 raw observations prior to vessel selection and trajectory cleaning. Each AIS record contained the observation timestamp, Maritime Mobile Service Identity (MMSI), navigational status, speed over ground, latitude, longitude, vessel dimensions, and vessel type information.

While this case study utilizes AIS, the Port-LCA framework is not exclusively limited to AIS as the only source of vessel-activity information. Equivalent time-resolved activity data can be sourced from vessel traffic service (VTS) or radar records, port-call and terminal operational records, onboard GPS or voyage-data systems, as well as engine or fuel-monitoring data. Such sources may supplement or, when adequate spatial, temporal, and technical information is available, replace AIS inputs. The data must enable the

reconstruction of vessel activity, elapsed time, operational conditions, and pertinent vessel characteristics with adequate resolution for subsequent calculations of power, fuel consumption, and emissions.

Seven container-vessel trajectories were extracted from the raw dataset and utilized as the operational foundation for the Port-LCA calculations. To maintain commercial and operational confidentiality, the original vessel names and identifiers were omitted, and the chosen trajectories were labeled as Vessel 1 through Vessel 7. The records for each vessel were segregated and arranged in chronological order before additional processing.

Table 6-2 presents a summary of the cleaned AIS trajectories utilized in the case study. It provides the count of valid AIS points retained post-cleaning, the initiation and conclusion times of each trajectory, the observed duration, the median and mean sampling intervals, and the maximum time gap recorded for each anonymized vessel.

The cleaning procedure was performed before the calculation of distance, speed, propulsion power, fuel consumption, and emissions. Records were eliminated due to missing or unreadable timestamps, absent or invalid coordinates, latitude or longitude values exceeding physically valid ranges, exact duplicate observations, or zero or negative elapsed time in relation to the preceding record.

After the initial screening, preliminary Haversine distances and segment speeds were computed to detect physically implausible movement patterns. Segments with calculated speeds surpassing 30 knots or 120% of the vessel-specific service speed were flagged for inspection regarding movement consistency. Observations related to GPS jumps, abrupt spatial discontinuities, or trajectories that were inconsistent with physically plausible

vessel movement were excluded. In contrast, stationary and low-speed observations were preserved when they aligned spatially with near-port operations, as they could signify legitimate maneuvering, waiting, or low-speed transit.

The AIS data were primarily accessible at minute-scale resolution, though the sampling intervals differed among observations. A 10-minute threshold was employed to differentiate continuous trajectory segments from prolonged gaps. Intervals of 10 minutes or less were categorized as continuous observations, while intervals surpassing 10 minutes were designated as long gaps. Long gaps were not interpolated due to the necessity of unsupported assumptions about the vessel's route, speed, and engine load during the unobserved period.

Table 6-3 summarizes the cleaning criteria and sampling-gap treatments implemented prior to the Port-LCA calculations. It encompasses vessel separation, timestamp and coordinate validation, duplicate removal, time-consistency checks, preliminary distance calculation, speed screening, GPS-jump treatment, retention of valid low-speed records, long-gap identification, time normalization, and sensitivity treatment for irregular sampling.

Table 6-2. Summary of cleaned AIS trajectories used in the Port-LCA case study.

Track / Vessel	Vessel type	Valid AIS/GPS points after cleaning	Start time	End time	Observed duration (min)	Median sampling interval (min)	Mean sampling interval (min)	Maximum time gap (min)
Vessel 1	Container vessel	44	08:50	10:59	129	1	3.00	45
Vessel 2	Container vessel	50	15:14	17:35	141	1	2.88	33
Vessel 3	Container vessel	26	21:35	22:46	71	2	2.84	20
Vessel 4	Container vessel	55	15:01	17:40	159	1	2.94	89
Vessel 5	Container vessel	50	19:26	20:53	87	1	1.78	14
Vessel 6	Container vessel	50	11:50	12:46	56	1	1.14	4
Vessel 7	Container vessel	26	16:43	17:47	64	2	2.56	8
Total	Container vessel	301	-	-	-	-	-	-

Source: Author's processing of AIS data provided by the Busan Port Authority for 1–2 March 2019.

In the baseline calculation, the original elapsed time between consecutive valid observations was preserved. Thus, the calculated segment speed denotes the average movement of the vessel between two recorded AIS positions. To conduct a sensitivity test, the calculations were repeated with the exclusion of intervals exceeding 10 minutes. This allowed for the assessment of the impact of irregular AIS sampling on estimated speed, propulsion power, fuel consumption, WTW emissions, and time-normalized emission intensity.

Following the cleaning process, the latitude and longitude values were standardized into a uniform numerical format. The coordinates initially expressed in degrees were converted into radians to facilitate the Haversine-based distance calculations discussed in Chapter 4. The processed coordinate records were subsequently organized into consecutive observation pairs for each vessel.

Table 6-3. Objective AIS data-cleaning and sampling-gap treatment applied in the Port-LCA case study.

Processing item	Criterion and treatment
Vessel separation	Each anonymized vessel trajectory was processed independently and ordered chronologically.
Missing timestamps	Records with missing or non-readable timestamps were removed.
Invalid coordinates	Records with missing coordinates or latitude/longitude values outside physically valid ranges were removed.
Duplicate records	Exact duplicate observations were removed.
Time consistency	Records producing zero or negative elapsed time were removed.
Preliminary distance	The distance between consecutive valid positions was calculated using the Haversine formulation.
Speed screening	Segments exceeding 30 knots or 120% of the vessel-specific service speed were flagged for movement-consistency inspection.
GPS-jump treatment	Points responsible for abrupt spatial discontinuities and physically implausible segment speeds were removed.
Low-speed records	Stationary and low-speed records were retained when spatially consistent with port operation.
Continuous-segment threshold	Intervals of 10 minutes or less were classified as continuous minute-scale observations.
Long-gap treatment	Intervals exceeding 10 minutes were identified as long gaps and were not interpolated.
Baseline calculations	Original elapsed intervals were retained; calculated speed represents the average movement between consecutive observed positions.
Gap sensitivity	Calculations were repeated after excluding intervals longer than 10 minutes.
Time normalization	The 0–100% normalized time scale was used only for graphical comparison.
Model outputs	Cleaned records were used to calculate distance, speed, propulsion power, fuel consumption, TTW emissions, and WTW emissions.

Note: Data-cleaning and sampling-gap criteria were developed and applied by the author as described in Section 6.5. The 10-minute threshold distinguishes continuous observations from long sampling gaps.

6.5.2 Sub-step 2.2: Time Interval, Distance, and Speed Calculation

After the cleaning of AIS data and processing of coordinates, the trajectory-reconstruction procedure outlined in Chapter 4 was implemented for each anonymized vessel. Consecutive valid AIS observations were utilized to compute elapsed time, traveled distance, and segment-level speed for each reconstructed trajectory.

The elapsed time for each segment was determined by calculating the difference between consecutive observation timestamps. The distance traveled between each pair of valid vessel positions was calculated using the Haversine formula as presented in Equations 4.1–4.5. This formulation considers the Earth's curvature and translates the angular separation between successive latitude and longitude coordinates into the corresponding distance traveled.

Segment-level vessel speed was determined by dividing the Haversine distance by the associated elapsed time. The relevant unit conversions were subsequently implemented to represent speed in both km per hour and knots. Each valid AIS interval yielded an estimate of elapsed time, traveled distance, and average vessel speed.

These calculations converted the cleaned AIS records into time-resolved vessel activity profiles within the specified boundaries of the Port of Busan. The resulting profiles maintain the operational variation noted along each vessel trajectory and supply the necessary inputs for estimating propulsion power, engine load, fuel consumption, and segment-level life cycle emissions.

To facilitate graphical comparison, the duration of each vessel trajectory was normalized to a common scale of 0% to 100%. This normalized time scale was utilized solely to compare the shapes and temporal variations of the seven vessel-emission

profiles. It was not utilized for the calculation of distance, speed, propulsion power, fuel consumption, or emissions. All quantitative calculations were derived from the original elapsed time between consecutive valid AIS observations.

Sub-steps 2.1 and 2.2 transform the raw AIS dataset into cleaned and time-resolved operational profiles. These outputs finalize Step 2 and serve as the direct input for the propulsion-power and fuel-consumption calculations conducted in Step 3.

6.6 Step 3: Propulsion Power and Fuel-Consumption Modelling

Step 3 converts the time-resolved vessel-activity profiles developed in Step 2 into estimates of propulsion power, engine load, and fuel consumption. The general equations governing propulsion power, engine load, and segment-level fuel consumption were presented in Chapter 4 and are therefore not repeated in this section. Instead, the following subsections explain how these equations were applied using the vessel-specific characteristics, AIS-derived operating profiles, and fuel-specific assumptions of the Port of Busan case study.

6.6.1 Sub-step 3.1: Propulsion Power and Engine Load Estimation

After reconstructing the AIS-derived distance, elapsed time, and speed profiles, the movement of each vessel was translated into propulsion power demand and engine load. Propulsion power was estimated for each anonymized vessel based on its AIS-derived segment-level speed, installed main-engine power, and service speed. This vessel-specific treatment ensured that the estimated power demand accurately represented the technical characteristics of the seven selected vessels, rather than depending on a single generic container-vessel profile.

The propulsion power calculation was derived from the established cubic speed–power relationship, indicating that the required propulsion power increases roughly with the cube of vessel speed. This relationship is typically relevant near a vessel's design or service speed. Port-boundary operations often entail low-speed transit, maneuvering, acceleration, deceleration, and various non-steady operating conditions. Applying the cubic law uniformly at low speeds may underestimate the propulsion power requirement (Berthelsen & Nielsen, 2021).

Thus, a segmented speed–power approach was utilized to illustrate the various operational ranges identified in the AIS data. The speed range derived from AIS was segmented into operational categories to more accurately represent low-speed and port-transit behavior. In the low-speed range, a minimum main-engine load of approximately 10% of maximum continuous rating (MCR) was utilized as a correction to the propulsion-load estimate.

This minimum-load assumption is applicable solely to the main-engine propulsion model. It does not account for the total onboard energy demand and excludes hotel loads, auxiliary-engine demand, boiler operation, cargo-handling energy, and other non-propulsion loads.

Engine load was calculated by comparing the estimated propulsion power to the installed main-engine power of each vessel. The engine-load profile derived from AIS data linked operational behavior to fuel consumption calculations. As a result, variations in observed speed, installed power, and service speed persisted throughout the modeling process and affected the estimated fuel consumption and emissions of each vessel.

6.6.2 Sub-step 3.2: Modelling Fuel Consumption

Fuel consumption was estimated for each valid AIS interval by integrating the calculated propulsion power demand, engine load, elapsed time, and the relevant specific fuel consumption value. The segment-level fuel-consumption equation from Chapter 4 was directly applied and is not reiterated here. Each valid AIS interval generated a corresponding estimate of propulsion power, engine load, and fuel consumption.

Fuel consumption for the MDO pathway was determined using engine-load-dependent SFOC values. Engine performance data acquired from MAN CEAS under ISO reference conditions were utilized to develop the relevant SFOC curve. A fourth-degree polynomial interpolation was applied to estimate SFOC at intermediate engine load points.

This treatment facilitated the calculation of MDO consumption over a continuous spectrum of estimated engine loads, rather than relying on a singular fixed fuel-consumption rate. Consequently, the time-resolved MDO profile indicated variations in vessel speed, propulsion demand, engine load, and elapsed time across each reconstructed AIS trajectory.

The segment-level MDO consumption estimates served as the conventional-fuel reference for modeling the methanol and ammonia pathways. However, these alternative fuels were not considered direct mass-based substitutes for MDO due to differences in lower heating value, energy density, engine characteristics, and pilot-fuel requirements.

6.6.3 Sub-step 3.3: Adjustment Specific to Fuel Type and Time-Resolved Fuel Profile

Fuel consumption for the methanol and ammonia pathways was determined using a fuel-specific thermodynamic approach, rather than through direct conversion of the calculated MDO mass. This distinction is essential, as identical propulsion power requirements do not equate to identical fuel mass requirements when considering fuels with varying lower heating values and engine performance characteristics.

In the case of methanol, brake efficiency was calculated using main-fuel consumption and retained pilot-fuel contribution.

$$\eta_b = \frac{3.6}{(SFC_{fuel} \times LHV_{fuel}) + (SFC_{pilot} \times LHV_{pilot})} \quad \text{Eq. (6-1)}$$

where η_b is the brake efficiency, SFC_{fuel} is the main fuel specific fuel consumption in kg/kWh, LHV_{fuel} is the lower heating value of the main fuel in MJ/kg, SFC_{pilot} is the pilot fuel consumption in kg/kWh, and LHV_{pilot} is the lower heating value of the pilot fuel in MJ/kg. The value 3.6 represents the energy equivalent of 1 kWh in MJ.

For the ammonia case, the ammonia-specific fuel consumption was calculated using the load-dependent brake-efficiency framework and the lower heating value of ammonia:

$$SFC_{NH3} = \frac{\frac{3.6}{\eta_b} - (SFC_{pilot} \times LHV_{pilot})}{LHV_{NH3}} \quad \text{Eq. (6-2)}$$

where $SFC_{ammonia}$ is the ammonia-specific fuel consumption in kg/kWh and $LHV_{ammonia}$ is the lower heating value of ammonia in MJ/kg.

The total specific fuel consumption for the ammonia case was then calculated by adding the retained pilot-fuel contribution:

$$SFC_{total,NH_3} = SFC_{total,NH_3} + SFC_{pilot} \quad \text{Eq. (6-3)}$$

Table 6-4 summarizes the load-dependent fuel consumption assumptions utilized for the methanol and ammonia scenarios. It presents the pilot-fuel contribution for methanol, methanol consumption, brake efficiency, pilot-energy share, and ammonia consumption at various engine-load points.

Table 6-4. Load-dependent fuel-consumption assumptions used for methanol and ammonia cases.

Engine load (% SMCR)	Pilot fuel (Methanol)(g/kWh)	Methanol consumption (g/kWh)	Brake efficiency (%)	Pilot energy share (%)	Ammonia consumption (g/kWh)
100	8.0	325.0	52.31	5.00	347.7
95	8.2	321.9	52.69	5.19	344.4
90	8.5	319.2	52.97	5.42	341.5
85	8.8	316.6	53.24	5.67	338.7
80	9.1	314.2	53.49	5.91	336.2
75	9.5	311.7	53.71	6.19	333.5
70	9.9	307.6	54.16	6.56	329.1
65	10.3	305.1	54.36	6.91	326.4
60	10.8	303.8	54.33	7.28	325.0
55	11.4	302.7	54.23	7.69	323.9
50	12.1	301.7	54.04	8.20	322.8
45	12.9	301.6	53.68	8.73	322.7
40	13.8	301.4	53.27	9.34	322.5
35	15.0	300.6	52.83	10.15	321.6
30	16.4	299.2	52.35	11.14	320.1
25	18.1	296.7	51.83	12.46	317.4

Source: Author's calculations using the fuel-specific methodology and assumptions described in Section 6.6.3 and Eqs. (6-1)–(6-3).

The load-dependent values obtained were correlated with the propulsion power and engine load estimates determined for each AIS interval. As a result, each valid interval generated a fuel-specific estimate of MDO, methanol, or ammonia consumption. This

produced a time-resolved fuel profile that maintained the operational variation noted along each vessel trajectory.

The adopted approach allows the Port-LCA framework to systematically compare MDO, methanol, and ammonia by utilizing consistent propulsion-energy requirements and considering variations in fuel properties and engine performance. However, the fuel-consumption model does not explicitly account for storage-system effects, additional auxiliary-energy demand, ammonia slip, N₂O formation, exhaust after-treatment requirements, or detailed fuel-pathway certification constraints. The results regarding alternative fuels should be viewed as comparisons of pathways grounded in the specified technical assumptions, rather than as comprehensive representations of all effects related to the onboard fuel system.

Sub-steps 3.1–3.3 transform the AIS-derived vessel activity profiles into estimates of fuel consumption that are segmented and time-resolved. These outputs finalize Step 3 and serve as the direct inputs for the WTT, TTW, and WTW emissions calculations conducted in Step 4.

6.7 Step 4: Time-Resolved Life Cycle Emissions Inventory

Step 4 converts the segment-level fuel-consumption profiles developed in Step 3 into time-resolved life cycle GHG emissions. Fuel-specific TTW and WTT emission factors are applied to each valid AIS interval, after which the two life cycle stages are combined to calculate WTW emissions. The resulting inventory preserves the temporal variation of vessel activity and enables emissions to be examined by AIS interval, vessel, and fuel pathway.

6.7.1 Sub-step 4.1: Emission Factor and Impact Indicator Selection

The main environmental indicator utilized in the Busan case study is the impact of climate change, quantified in CO₂-eq emissions. The assessment incorporates CO₂, CH₄, and N₂O, which are standardized on a common CO₂-eq basis utilizing 100-year global warming potential factors. The GWP100 factors chosen are displayed in the table below.

Table 6-5. CML 2001 (GWP100) factors used for CO₂-eq conversion.

Impact Factor	CO₂	CH₄	N₂O	Reference
GWP 100	1	28	273	(IMO, 2024)

The TTW component denotes greenhouse gas emissions linked to fuel consumption onboard. Fuel-specific TTW emission factors are utilized based on the mass of fuel consumed during each valid AIS interval.

Table 6-6 displays the chosen factors for CO₂, CH₄, and N₂O, along with the lower calorific value associated with each fuel.

Table 6-6. Tank-to-Wake emission factors for selected marine fuels.

Fuel	CO₂ (gr/g fuel)	CH₄ (gr/g fuel)	N₂O (gr/g fuel)	LCV (MJ/g fuel)	Reference
MDO	3.206	0.00005	0.00018	0.0427	(European Union, 2023)
Methanol (Natural gas)	1.375	0	0	0.0199	
e-Methanol (RFNBO)	1.375	0	0	0.0199	
Ammonia (Natural gas)	0	0.00001	0	0.0186	(Brynnolf et al., 2014)
e-Ammonia (RFNBO)	0	0.00001	0	0.0186	

Note: E-methanol and e-ammonia use the same TTW emission factors as their corresponding methanol and ammonia fuel molecules; differentiation between fossil-derived and renewable pathways is applied in the WTT stage.

WTT emissions were determined by utilizing energy-based upstream GHG intensity values. Table 6-7 displays the WTT intensities for MDO, methanol derived from natural gas, ammonia produced from natural gas, e-methanol, and e-ammonia. The fossil-derived pathways denote traditional production routes, whereas the e-fuel pathways signify renewable or RFNBO-type production routes that utilize green hydrogen and, in the case of e-methanol, captured CO₂.

Table 6-7. Well-to-Tank GHG intensity of selected marine fuels.

Fuel	WTT intensity (g CO₂-eq/MJ)	Description	Reference
MDO	14.40	Conventional fossil marine fuel supply chain	(European Union, 2023)
Methanol (Natural gas)	31.30	Natural gas-based methanol production	
Ammonia (Natural gas)	121	Natural gas-based ammonia (Haber–Bosch)	
e-Methanol (RFNBO)	8.11	Renewable methanol from green hydrogen and CO ₂	(European Union, 2018)
e-Ammonia (RFNBO)	10.10	Renewable ammonia from green hydrogen	

The total WTW emissions were calculated by integrating the TTW and WTT components for each AIS segment and fuel pathway. This combined lifecycle result serves as the primary foundation for comparing MDO, methanol, e-methanol, ammonia, and e-ammonia in the Busan case study. The distinction between TTW and WTT emissions is crucial, as a fuel exhibiting low onboard emissions may still possess high upstream emissions if its production pathway depends on carbon-intensive energy sources. In contrast, e-fuel pathways can attain reduced lifecycle emissions if the upstream production relies on renewable energy sources.

6.7.2 Sub-step 4.2: Segment-Level Life Cycle Emissions Calculation

After estimating fuel consumption, life cycle GHG emissions were calculated for each valid AIS interval. The equations for TTW, WTT, WTW, and CO₂-eq calculations outlined in Chapter 4 were utilized directly and are not reiterated in this section. For each AIS interval, TTW emissions were determined by multiplying the fuel consumption by the relevant onboard emission factors for CO₂, CH₄, and N₂O. The non-CO₂ emissions were converted into CO₂-eq values utilizing the chosen GWP100 factors. This generated a segment-level TTW outcome for each vessel and fuel pathway.

WTT emissions were determined by integrating the energy content of the fuel utilized during each AIS interval with the associated upstream GHG intensity, expressed in grams of CO₂-eq /MJ. This treatment links the operational fuel requirements of each vessel segment to the upstream environmental characteristics of the chosen production pathway.

The TTW and WTT components were combined to calculate WTW emissions for each AIS interval. Each valid segment of the reconstructed trajectory produced estimates for fuel consumption, TTW emissions, WTT emissions, and total WTW emissions.

This segment-level treatment preserves the temporal variation evident in the AIS data. Changes in vessel speed, propulsion power, engine load, elapsed time, and fuel consumption are directly reflected in the emissions profile. Consequently, emissions are not characterized by a singular constant operating-mode assumption but fluctuate across the observed vessel trajectory.

The differentiation between TTW and WTT emissions is crucial for the chosen alternative fuels. A pathway characterized by low onboard emissions may still result in significant WTW emissions if upstream production relies on carbon-intensive energy sources. Renewable synthetic pathways can result in reduced WTW emissions when fuel production utilizes lower-carbon electricity and hydrogen.

6.7.3 Sub-step 4.3: Aggregation, Scenario, and Fuel Comparison

Upon completion of the segment-level calculations, the emissions results were aggregated for each anonymized vessel and fuel pathway. The emissions for WTT, TTW, and WTW were aggregated across all valid AIS intervals to derive trajectory-level totals, while preserving the original observed duration of each vessel track.

The aggregated results were normalized by vessel operating time and expressed as kg CO₂-eq per vessel-hour. This establishes a standardized framework for comparing vessels with varying trajectory durations and allows for the assessment of all five fuel pathways under consistent AIS-derived operating conditions.

Mean WTW emission intensity serves as the primary aggregation metric for fuel-pathway and future port-boundary calculations. The median emission intensity is calculated as a robustness measure to assess whether the results are unduly affected by vessels with exceptionally high or low emission profiles.

The aggregation procedure yields multiple complementary outputs: interval-level time-resolved emissions, vessel-level trajectory totals, vessel-hour emission intensities, and fleet-level summary measures. These outputs facilitate the analysis necessary to compare vessels, identify operational and fuel-pathway emission hotspots, and scale vessel-level emission intensities to future port-boundary scenarios.

Sub-steps 4.1–4.3 finalize the time-resolved life cycle emissions inventory. The WTT, TTW, and WTW outputs yield the environmental input necessary for the forecast-based activity and emissions projections formulated in Step 5, as well as the comparative analysis outlined in Step 6.

6.8 Step 5: Forecast-Based Activity and Emissions Projection

Step 5 extends the vessel-level results developed in Steps 2–4 to future port-activity and emissions scenarios. The forecasting procedure connects South Korea’s real GDP with container throughput at the Port of Busan, projects the selected macroeconomic indicator to 2050, converts the resulting throughput scenarios into capacity-equivalent vessel demand, and combines projected activity with the vessel-level WTW emission intensities calculated in Step 4.

The forecasting component aims to facilitate scenario analysis instead of delivering a definitive prediction of future port activity. Lower-confidence, central forecast, and upper-confidence trajectories are utilized to analyze the impact of macroeconomic uncertainty on container throughput, vessel demand, and future port-boundary emissions.

6.8.1 Sub-step 5.1: Historical Data Collection

The forecasting component employs annual South Korean real GDP as the macroeconomic indicator and annual container throughput at the Port of Busan as the port-activity indicator. Real GDP was chosen as it offers a measure of economic activity that mitigates the inflation and exchange-rate distortions linked to current-price or current-US-dollar GDP values (World Bank, 2026).

Historical container throughput data for the Port of Busan were collected and expressed in TEU. The GDP and TEU series were analyzed over the shared historical period from 2011 to 2024. These data serve as the empirical foundation for evaluating the correlation between national economic activity and container demand at the port.

The Port-LCA framework does not directly project future emissions based on historical emissions data. It initially predicts the activity variables that affect port-related vessel demand. The resulting port-activity scenarios are combined with the vessel-level emission intensities derived from AIS, as calculated in Step 4.

This separation maintains the distinction between the operational and forecasting components of the framework. AIS data delineate vessel activity and emission intensity within the specified port boundary, while historical GDP and TEU series serve as the foundation for future port-demand scenarios.

6.8.2 Sub-step 5.2: Indicator Screening and Forecast Input Development

Before utilizing real GDP for forecasting future container throughput scenarios, an assessment of its historical correlation with Busan container throughput was conducted. Pearson correlation was initially employed to evaluate the strength and direction of the association between the two-level series.

$$r(x, y) = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \quad \text{Eq. (6-4)}$$

where x_i and y_i are data points, $\bar{x}$ is the mean of the x -values, and $\bar{y}$ is the mean of the y -values (Newcastle University, 2024). The resulting coefficient was approximately 0.984, indicating a strong positive correlation between the two historical level series. However, due to the presence of long-term trends in both variables, the correlation is

regarded as a descriptive measure rather than as evidence of causality or independent predictive ability.

The long-term elasticity relationship between real GDP and container throughput was then estimated using a log–log regression specification:

$$\ln(TEU_t) = \alpha + \beta \cdot \ln(GDP_t) + \varepsilon_t \quad \text{Eq. (6-5)}$$

where TEU_t represents container throughput at a time t , GDP_t denotes the real Gross Domestic Product of South Korea, β is the elasticity of TEU with respect to GDP, ε_t is the regression error term, and α is the intercept term. The estimated model yields:

$$\ln(TEU_t) = -21.7977 + 1.0970 \cdot \ln(GDP_t) \quad \text{Eq. (6-6)}$$

The estimated coefficient indicates that, within the historical level relationship, a 1% increase in South Korea's real GDP is associated with an approximately 1.10% increase in Busan container throughput. This relationship was used as a transparent scenario-generation link between macroeconomic activity and port throughput.

Because a strong regression between trending level series may partly reflect their common time trend, a first-difference specification was also evaluated as a robustness check:

$$\Delta \ln(TEU_t) = \alpha + \beta \cdot \Delta \ln(GDP_t) + \varepsilon_t \quad \text{Eq. (6-7)}$$

The estimated first-difference equation was:

$$\Delta \ln(TEU_t) = 0.0108 + 0.7988 \cdot \Delta \ln(GDP_t) \quad \text{Eq. (6-8)}$$

The coefficient was positive but not statistically significant. Therefore, the first-difference model was used as a robustness check, while the log-level specification was retained for long-term scenario generation.

The relationship between real GDP and container throughput (TEU) was assessed before utilizing the forecasting results for scaling port-level emissions. This step is crucial as the Port-LCA model does not directly predict emissions based on historical emissions data. It initially estimates future container activity and vessel demand, subsequently integrating this activity projection with the vessel-level emission intensities obtained from the AIS-based analysis.

The empirical relationship between South Korea's real GDP and Busan container throughput was evaluated using log-level and first-difference models. The log-level specification delineates the enduring relationship between economic activity and port throughput, whereas the first-difference specification offers a more cautious assessment grounded in annual variations. This distinction is significant as high correlations in level data may partially indicate shared time trends, whereas first-difference relationships assess whether annual changes are correlated.

The residual diagnostics for the log-level real GDP–TEU regression are provided in the thesis appendix, as they support the transparency of the econometric specification without being central to the main Port-LCA results.

Table 6-8 summarizes the relationship between GDP and TEU, which is utilized to support the demand-scaling approach. The findings demonstrate a significant long-term relationship between South Korea's real GDP and Busan container throughput,

reinforcing the applicability of GDP as a clear macroeconomic factor for scenario development.

The estimated log-level relationship facilitated the conversion of the lower-confidence, central, and upper-confidence real-GDP trajectories into scenario-based TEU demand:

$$TEU_t = \exp [\alpha + \beta \ln(GDP_t)] \quad \text{Eq. (6-9)}$$

The residual diagnostics for the log-level real GDP–TEU regression are provided in the thesis appendix, as they support the transparency of the econometric specification without being central to the main Port-LCA results.

Table 6-8. Log-level and first-difference GDP–TEU relationship used for Busan demand scaling.

Statistic	Log-level model	First-difference model
Sample period	2011–2024	2012–2024
Observations	14	13
GDP coefficient	1.09	0.79
Standard error	0.058	0.64
t-statistic	18.95	1.25
p-value	2.61E-10	0.23
Lower 95% CI	0.97	–0.60
Upper 95% CI	1.22	2.20
R^2	0.96	0.12
Adjusted R^2	0.96	0.044

Durbin–Watson	1.31	Not evaluated
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Source: Author’s regression analysis using South Korea real-GDP and Port of Busan container-throughput data for 2011–2024. The chapter identifies those as the two historical datasets used.

6.8.3 Sub-step 5.3: Holt-Winters Exponential Smoothing Method

After establishing the GDP–TEU relationship, South Korea's annual real-GDP series was forecasted to 2050 utilizing the Holt–Winters exponential-smoothing method. The formulation and equations of the Holt–Winters method have been previously presented in Chapter 4 and will not be reiterated here.

In the Busan case study, the method was utilized to produce a central real-GDP forecast alongside lower-confidence and upper-confidence trajectories. Due to the nature of the input dataset comprising annual observations, an intra-annual seasonal cycle was not implemented. The model represents the fundamental level and trend of the annual macroeconomic series.

The resulting trajectories are not viewed as deterministic forecasts of the future South Korean economy. They offer a consistent array of macroeconomic scenarios that can be integrated into the GDP–TEU relationship and the subsequent Port-LCA modeling framework.

Thus, the lower-confidence, central forecast, and upper-confidence GDP trajectories serve as a foundation for analyzing the impact of varying economic growth conditions on Busan container throughput, capacity-equivalent vessel demand, and prospective port-boundary emissions.

6.8.4 Sub-step 5.4: Parameter Optimization and Forecast Error Minimization

The Holt–Winters parameters were optimized utilizing the historical real GDP series. The chosen parameters govern the updating of the model level, trend, and related

smoothing components. The values and forecast-error indicators are displayed in Table 6-9.

Table 6-9. Statistical values and errors used for the Holt-Winters exponential smoothing.

Statistic	Value
α	0.126
β	0.125
γ	2.22E-16
MASE	0.295
SMAPE	0.00783
MAE	1.67E+13
RMSE	2.46E+13

Source: Author's calculations from the Holt-Winters model applied to the South Korea real-GDP series.

The forecasting model's performance was assessed through Mean Absolute Scaled Error (MASE), Symmetric Mean Absolute Percentage Error (SMAPE), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) metrics. These indicators offer additional metrics for assessing forecast errors and facilitate the comparison of fitted values with the observed historical series before employing the model for long-term scenario generation.

The calculated MASE value of 0.295 indicates that the fitted model outperforms the corresponding naïve benchmark. The low SMAPE value indicates a strong proportional fit between the observed and modeled values. MAE and RMSE maintain the units of the original GDP series and offer assessments of the absolute magnitude of forecast errors.

These indicators serve as verification measures for the forecasting component, rather than as definitive evidence that future trajectories will align precisely with projections. The uncertainty linked to long-term economic development is illustrated by the lower-confidence and upper-confidence scenarios, which are then integrated into the port-activity and emissions calculations.

6.8.5 Sub-step 5.5: Future Emissions Projection and Forecast Outputs

The projected real-GDP trajectories were transformed into future container-throughput scenarios utilizing the GDP–TEU relationship established in Sub-step 5.2. The throughput projections were subsequently converted into capacity-equivalent vessel demand. This allows for the scaling of vessel-level Port-LCA results from the seven AIS-derived trajectories to future port-boundary activity scenarios.

The scaling procedure employs a representative-vessel methodology. The effective annual transport capacity of a representative vessel is determined by its nominal container capacity, the assumed load factor, and the annual number of voyages.

$$C_{\text{eff}} = C \cdot U \cdot V \quad \text{Eq. (6-10)}$$

where C represents the representative vessel capacity (TEU), U denotes the load factor (utilization rate), and V corresponds to the number of voyages per vessel per year. The number of vessels required to meet the forecasted demand is then calculated as:

$$N_t = \frac{TEU_t}{C_{\text{eff}}} \quad \text{Eq. (6-11)}$$

This is suitable for scenario analysis, as it aims to connect future activity growth with lifecycle emissions rather than recreating a detailed shipping schedule. Table 6-10

summarizes the assumptions utilized for estimating capacity-equivalent vessel requirements.

Table 6-10. Assumptions used for estimating capacity-equivalent vessel requirements.

Parameter	Value	Description / Rationale	Reference
Representative vessel capacity (TEU)	9,365	Median capacity of the seven sampled container vessels	(UNCTAD, 2025)
Load factor (utilization)	0.80	Typical global container fleet utilization (80%)	(Notteboom, 2004; UNCTAD, 2025)
Voyages per representative vessel per year	6	Based on ~60-day round-trip cycle ($365/60 \approx 6$ voyages/year)	(Stopford, 2009; Rodrigue, 2024)

The representative vessel capacity is established at 9,365 TEU, reflecting the median capacity among the seven selected vessels. A load factor of 0.80 and six voyages per representative vessel annually are utilized. These assumptions establish a clear capacity-based scaling mechanism and do not aim to replicate a comprehensive future shipping schedule.

Subsequently, the anticipated capacity-equivalent vessel demand is integrated with the vessel-level WTW emission intensities established in Step 4. The vessel-hour intensities are transformed into emissions per capacity-equivalent vessel based on the chosen annual port-boundary exposure assumption. An annual exposure of 24 hours per capacity-equivalent vessel is utilized for the primary projection scenario.

Total future port-boundary emissions are calculated by integrating projected vessel demand with the associated emissions per vessel within the specified boundary.

Total port-boundary emissions were calculated by combining projected vessel demand with the estimated emissions per vessel within the port boundary:

$$E_t^{\text{port}} = N_t \cdot E^{\text{vessel}} \quad \text{Eq. (6-12)}$$

where E_t^{port} represents the total port emissions at time t , N_t denotes the number of vessels, and E^{vessel} corresponds to emissions per vessel within the port boundary.

The scaling procedure preserves the differentiation between operational emission intensity and prospective activity. The AIS-based model quantifies emissions linked to vessel movement within the specified Busan port-boundary conditions, whereas the forecasting model projects future activity levels. Integrating these components allows for the analysis of WTW emissions projections for MDO, methanol, e-methanol, ammonia, and e-ammonia across various future demand scenarios.

The resulting projections are based on scenarios rather than being deterministic. The analysis relies on specified assumptions concerning real-GDP growth, container throughput, representative vessel capacity, load factor, annual voyage frequency, port-boundary exposure time, fleet-level emission intensity, and fuel-production pathway. The projected output should be regarded as internally consistent future Port-LCA scenarios rather than exact forecasts of future vessel calls or official port emissions.

Sub-steps 5.1–5.5 finalize the stage of forecasting activities and projecting emissions. The resulting vessel-demand and port-boundary emissions trajectories yield future-oriented outputs that are analyzed and interpreted in Step 6.

6.9 Step 6: Outputs, Comparison, and Decision Support

Step 6 presents and interprets the outputs generated from the previous stages of the Busan Port-LCA application. The results adhere to the modeling sequence outlined in Steps 1–5: future port activity is projected via the GDP–TEU–vessel-demand chain; AIS-derived trajectories are transformed into time-resolved propulsion demand, fuel consumption, and life cycle emissions; and vessel-level emission intensities are adjusted to future port-boundary scenarios.

The analysis evaluates current operational variability and potential future developments in port-boundary emissions. It assesses capacity-equivalent vessel demand, time-resolved emission behavior, vessel heterogeneity, fuel pathway performance, long-term emissions trajectories, macroeconomic uncertainty, and the sensitivity of key results to modeling assumptions.

These outputs indicate that the assessment of port decarbonization cannot rely exclusively on static fuel-emission factors. Vessel behavior, technical characteristics, port activity growth, upstream fuel production, operational exposure, and uncertainty are essential factors to consider. Step 6 connects the numerical results to their implications for fuel selection, operational management, infrastructure planning, and long-term port decarbonization.

6.9.1 Future Port-Activity Results

The initial output pertains to the anticipated capacity-equivalent vessel demand for the Port of Busan. The Holt–Winters real-GDP trajectories, GDP–TEU relationship, and capacity-equivalent vessel-demand assumptions established in Step 5 were utilized to estimate the representative vessel requirements linked to future container throughput.

In the central scenario, the number of capacity-equivalent vessels is projected to rise from 543 in 2030 to 819 by 2050. Figure 6-3 illustrates the anticipated demand across the lower-confidence, central, and upper-confidence scenarios.

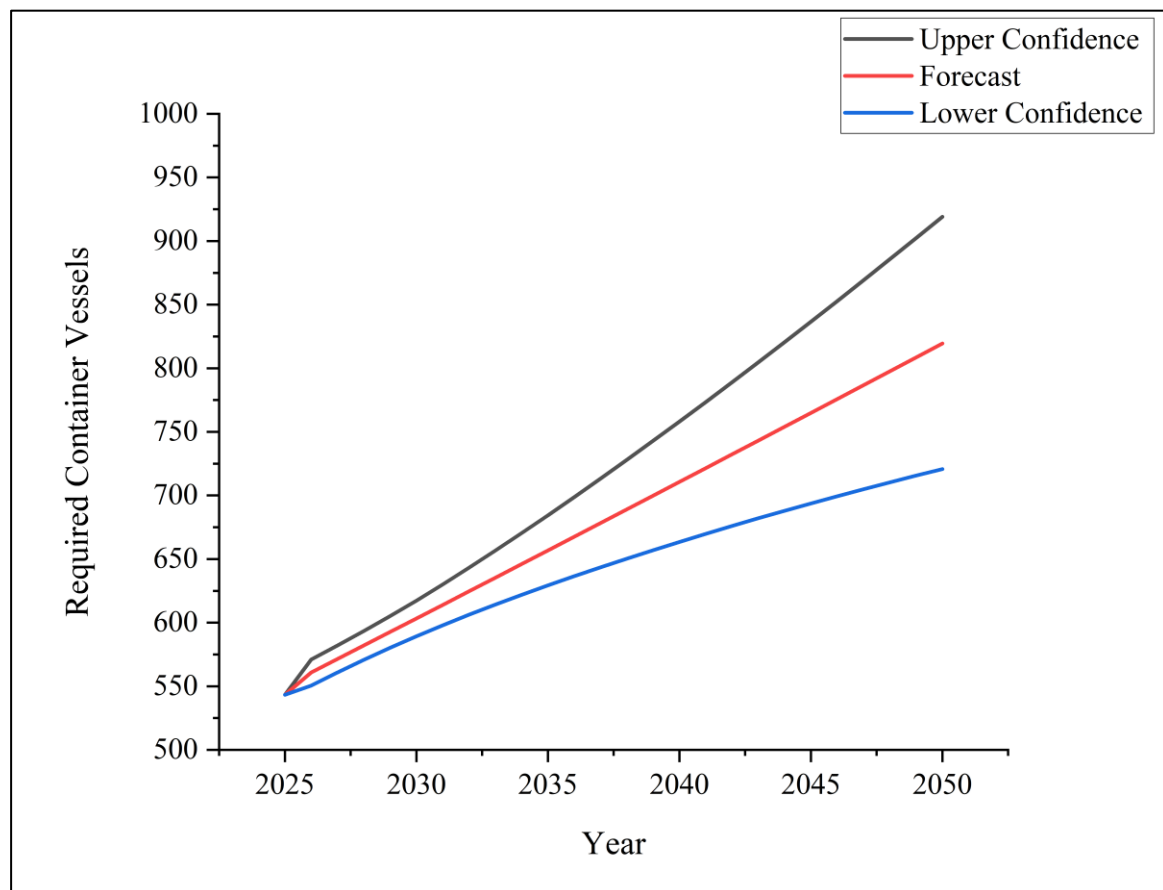


Figure 6-3. Projected container-vessel requirements for the Port of Busan from 2025 to 2050 under lower-confidence, central forecast, and upper-confidence GDP-driven demand scenarios, highlighting how macroeconomic uncertainty influences future vessel activity.

The projected vessel requirement rises across all three scenarios, indicating the expected growth in container throughput during the forecast period. Moreover, the gap between the lower-confidence and upper-confidence trajectories widens over time, indicating that uncertainty increasingly impacts the latter stages of the projection horizon.

The anticipated rise in vessel demand has significant implications for emissions at port boundaries. Even when vessel-level emission intensity is stable, total emissions rise with the growth of port activity. Activity growth may therefore partially counterbalance reductions attained through fuel switching or enhancements in vessel efficiency.

The expanding range of uncertainty suggests that long-term port planning should not depend solely on the central trajectory. Decisions regarding alternative-fuel infrastructure, shore-power capacity, operational controls, and emissions management should be assessed under various future demand scenarios.

The results should be understood as capacity-equivalent vessel requirements rather than exact predictions of future vessel calls. The scaling method quantifies port activity using a standardized vessel equivalent but does not accurately reflect future fleet composition, vessel-size distribution, service frequency, routing patterns, or terminal operations in detail. Figure 6-3 provides a basis for activity scaling in the Port-LCA scenarios, rather than serving as a comprehensive operational forecast of future vessel calls at Busan.

6.9.2 Time-Resolved Emissions Results

The second output addresses the time-resolved emission behavior of the selected vessels within the 20 NM boundary of the Port of Busan. For each anonymized vessel, the cleaned AIS trajectory was transformed into elapsed time, distance, speed, propulsion power, fuel consumption, and well-to-wake emissions. The resulting profiles illustrate variations in emissions over the observed operating period, rather than condensing vessel activity into a singular average value.

The profiles indicate significant temporal variation in port-boundary emissions. Higher-emission intervals typically coincide with increased AIS-derived speed and estimated propulsion demand, whereas lower-emission intervals are linked to slower or less energy-intensive vessel movement. This underscores the significance of utilizing time-resolved AIS data instead of solely depending on average operating assumptions.

The figure illustrates that operational behavior affects emissions alongside vessel size and fuel type. Short intervals of increased speed or propulsion requirements can result in significant emission peaks. In contrast, sustained low-speed operations may demonstrate reduced instantaneous intensity; however, they can still significantly impact total emissions when the vessel remains within the port limits for an extended duration.

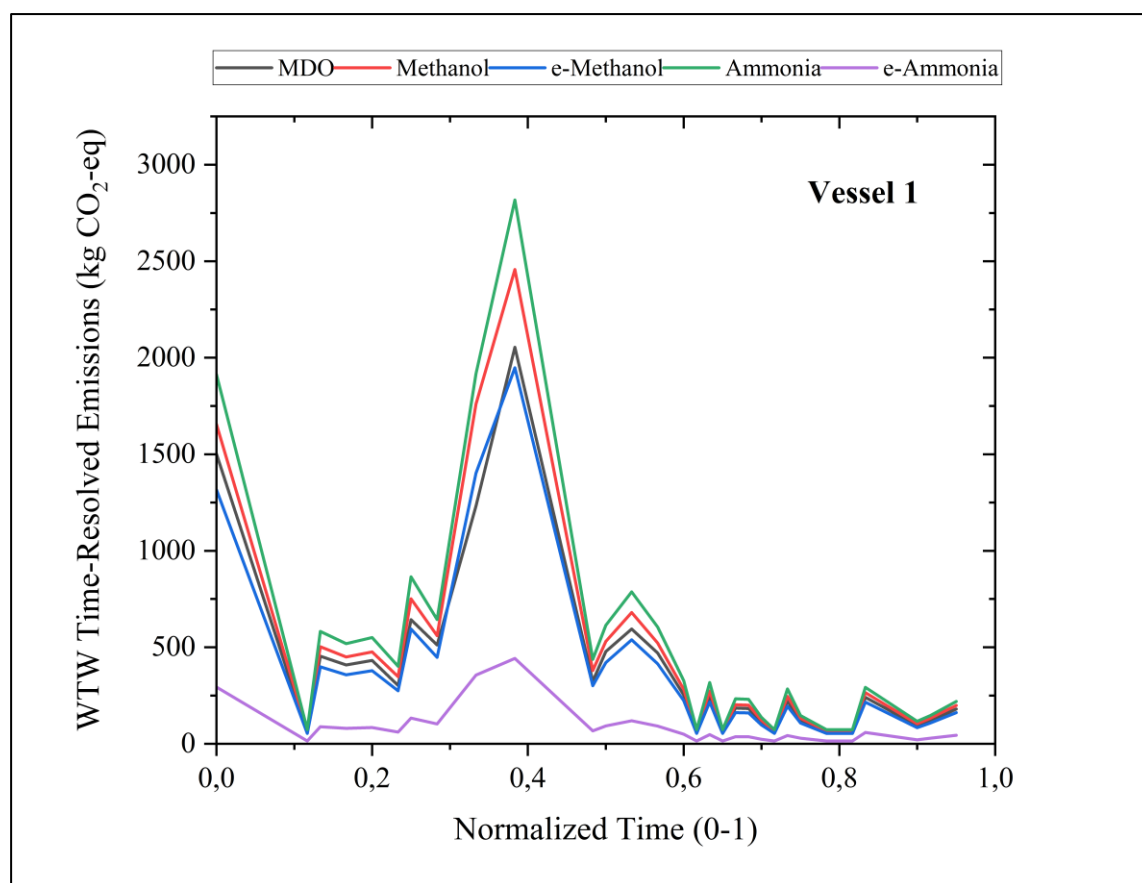


Figure 6-4. Time-resolved WTW emission profiles for alternative marine fuel pathways during a representative vessel-hour, showing how lifecycle emissions vary with AIS-derived operational changes and fuel-specific emission factors

The time axis is normalized from 0% to 100% to enable comparison among trajectories with varying observed durations. The figure should be interpreted as a comparison of emission-profile shapes rather than a direct comparison of absolute residence times. All quantitative calculations preserve the original elapsed time between successive AIS observations.

Overall, the time-resolved results illustrate a significant capability of the Port-LCA framework. Static average intensities provide insights into typical fuel or vessel performance; however, they fail to indicate the timing of operational emission peaks or their correlation with vessel movement. The integration of AIS activity, propulsion

demand, and fuel consumption offers a more operationally relevant framework for interpreting emissions within port boundaries.

6.9.3 Vessel Heterogeneity and Emission Hotspot Identification

The third output analyzes the variation in emissions across the seven selected container vessels. All vessels within the same general ship category exhibit variations in capacity, installed main-engine power, service speed, observed trajectory, and operating behavior. These differences influence propulsion requirements, engine load, fuel consumption, and WTW emissions.

Figure 6-5 presents a comparison of the vessel-level time-resolved emission profiles, highlighting the impact of vessel-specific propulsion characteristics.

The results indicate that port-boundary emissions are affected by factors beyond vessel category alone. Vessel size and installed power are significant factors; however, the observed speed profile, elapsed time, and duration of operation across various engine-load ranges also influence the final emissions profile. Two container vessels can produce varying emissions within the same port boundary, despite utilizing the same fuel pathway.

The time-resolved profiles facilitate the identification of operational emission hotspots. In this case study, hotspots refer to AIS intervals linked to elevated propulsion demand and WTW emissions. They may result from increased speed, acceleration, energy-demanding maneuvers, higher power requirements, or prolonged operational exposure within the specified limits.

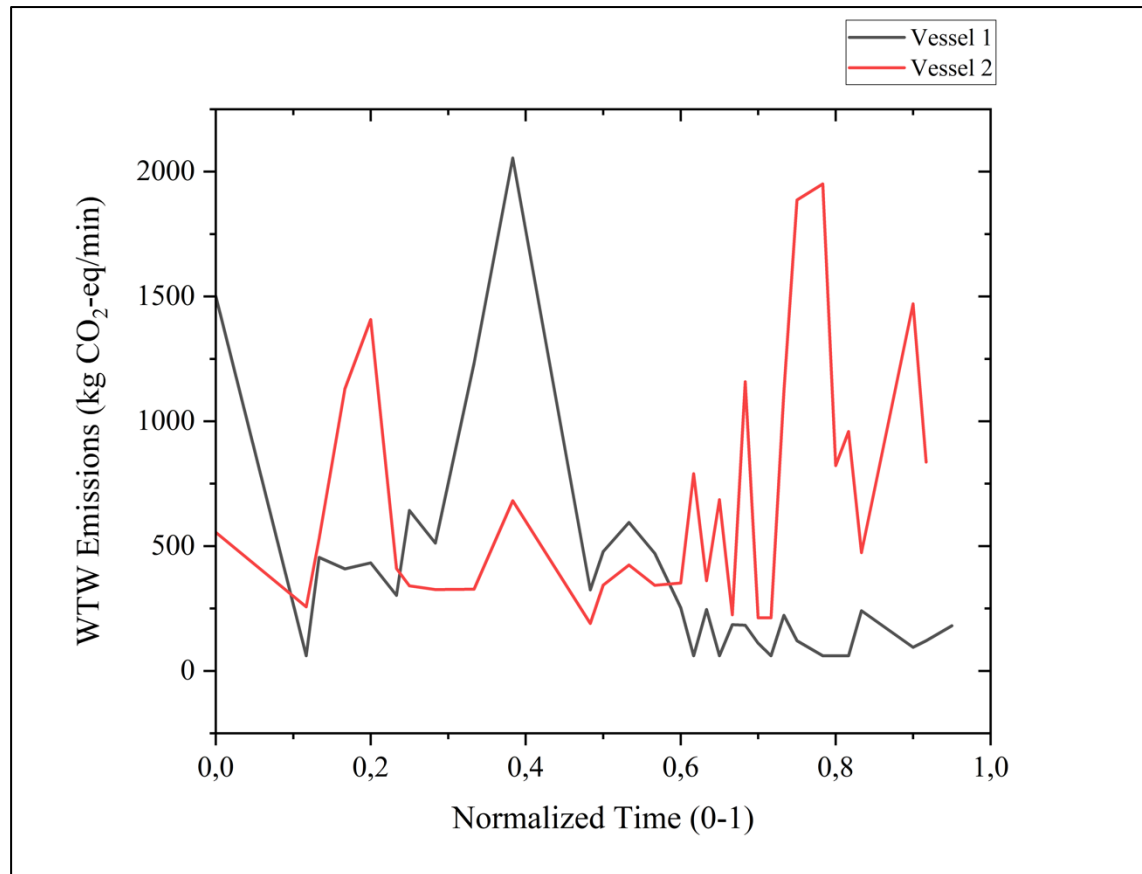


Figure 6-5. Comparison of time-resolved WTW emission profiles for vessels with different installed engine power, illustrating how vessel-specific propulsion demand influences emission intensity within the same port-boundary modeling framework.

These findings endorse the application of vessel-specific emissions modeling over generic approaches. Using a single average profile to represent all container vessels would obscure variations in propulsion demand, operational behavior, and residence time. The resulting estimate of port emissions may consequently neglect vessels or operational periods that disproportionately impact the overall emissions profile.

From a decision-support standpoint, vessels or operational periods characterized by sustained high emission intensity may be prioritized for speed management measures, operational optimization, alternative fuel deployment, or other targeted interventions. The analysis demonstrates that the Port-LCA framework can identify both fuel-related and operational emission hotspots.

6.9.4 Fuel Pathway Comparison

The fourth output compares the WTW performance of MDO, natural-gas-derived methanol, e-methanol, natural-gas-derived ammonia, and e-ammonia. The comparison uses the mean and median WTW emission intensities expressed in kg CO₂-eq per vessel-hour.

Table 6-11. Mean WTW emission intensity per vessel-hour across fuel pathways.

Fuel Pathway	Mean WTW Emissions (kg CO₂-eq/ vessel-hour)	Median WTW Emissions	Difference (%)
MDO	19,037	17,143	9.9
Methanol	21,153	18,891	10.6
e-Methanol	16,873	15,050	10.8
Ammonia	23,967	21,728	9.3
e-Ammonia	4,056	3,449	15.0

Source: Author's calculations based on the seven AIS-derived vessel trajectories and fuel-pathway assumptions described in Sections 6.5–6.7.

The results indicate significant disparities between fossil-derived and renewable synthetic fuel pathways. E-ammonia exhibits the lowest mean WTW intensity, estimated at approximately 4,056 kg CO₂-eq per vessel-hour. In contrast, ammonia produced from natural gas exhibits the highest mean intensity, approximately 23,967 kg CO₂-eq per vessel-hour.

The comparison indicates that alternative fuels cannot be evaluated exclusively based on their onboard emissions. While ammonia itself does not emit CO₂ directly during onboard use, the production of ammonia from natural gas involves significant upstream

emissions. As a result, its WTW performance is less favorable compared to the other assessed pathways.

In contrast, e-ammonia demonstrates the lowest WTW intensity due to its upstream pathway, which relies on lower-carbon energy and hydrogen production assumptions. The significant disparity between ammonia and e-ammonia illustrates that the environmental performance of an alternative fuel is heavily influenced by its production method, rather than solely by the fuel molecule utilized during operation.

A comparable distinction is observable between methanol and e-methanol. While their onboard emission factors are comparable, the upstream production pathways vary. E-methanol demonstrates superior performance compared to methanol derived from natural gas, based on the specified life cycle assumptions.

These findings demonstrate that a TTW-only comparison may yield incomplete or misleading conclusions. Fuel switching requires an assessment of fuel origin, electricity source, hydrogen production methods, and supply chain emissions. Port authorities and policymakers should evaluate future bunkering and fuel-infrastructure decisions using WTW analysis rather than relying solely on onboard criteria.

6.9.5 Future Port-Boundary Emissions Trajectories

The fifth output integrates the projected capacity-equivalent vessel demand with the average vessel-hour emission intensity associated with each fuel pathway. This generates annual WTW emissions trajectories for the Port of Busan based on the chosen exposure time, activity, and fuel pathway assumptions.

Figure 6-6 illustrates the anticipated port-boundary emissions for the five fuel pathways under various GDP-driven demand scenarios.

The projections indicate that future port-boundary emissions are affected by both activity growth and fuel-production pathways. As the demand for capacity-equivalent vessels rises, fuel pathways characterized by high WTW intensity led to a significant and rapid increase in annual emissions. Lower-intensity e-fuel pathways mitigate this growth; however, their overall emissions remain contingent on future activity levels.

The impact of fuel selection becomes more pronounced as the demand for vessels increases. Differences between high- and low-intensity pathways accumulate over the projection period, indicating that fuel-infrastructure decisions made in the near term may have significant long-term emissions implications.

The results indicate that alternative fuels are not intrinsically low carbon. Ammonia derived from natural gas exhibits the highest WTW intensity due to its carbon-intensive upstream production process. Transitioning to this pathway without ensuring lower-carbon production may result in a shift of emissions from onboard operations to upstream fuel production, rather than achieving a reduction in total life cycle emissions.

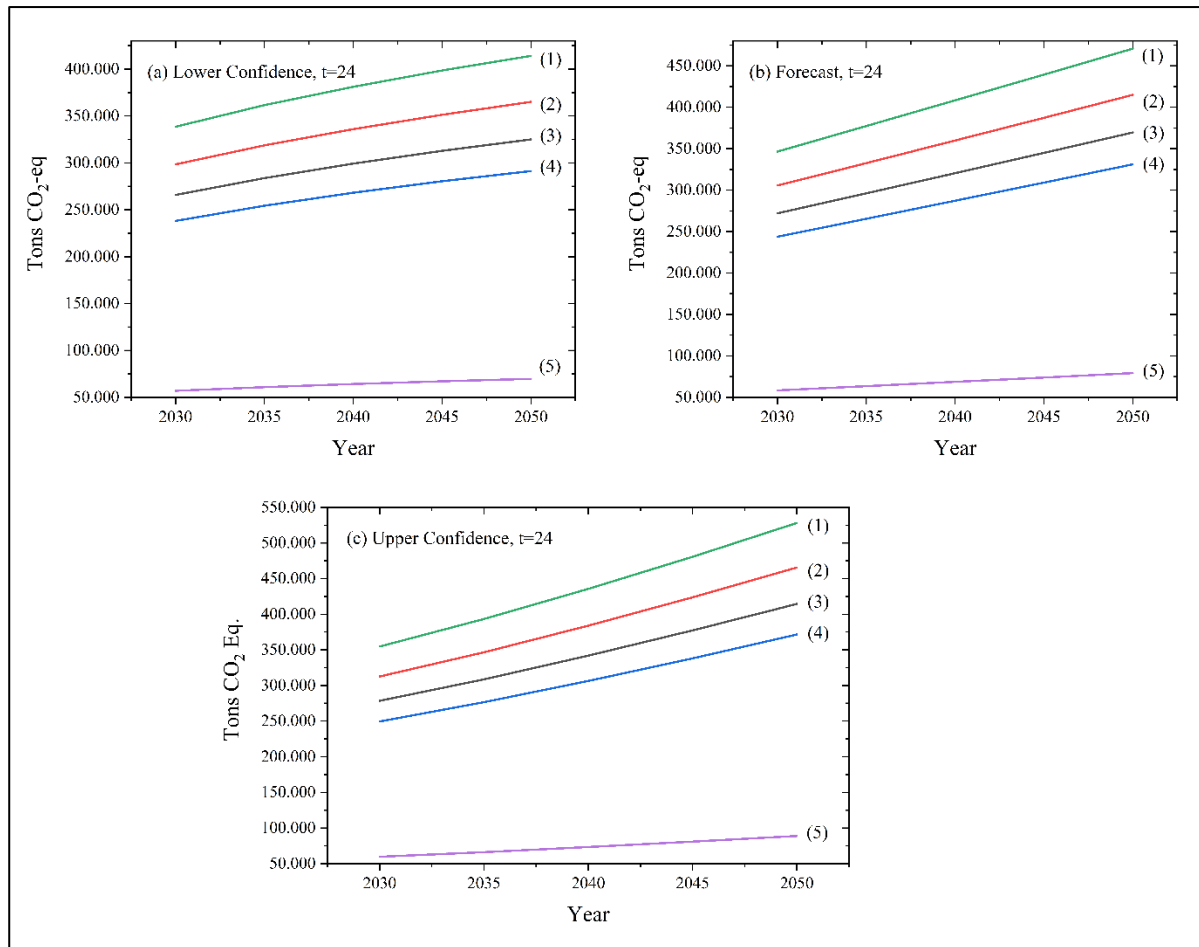


Figure 6-6. Projected port-boundary WTW emissions across fuel pathways under alternative GDP growth scenarios (t = 24 h), where (1) ammonia from natural gas, (2) methanol from natural gas, (3) MDO, (4) e-methanol, and (5) e-ammonia

In contrast, e-ammonia and e-methanol exhibit lower projected emissions due to their chosen production pathways, which utilize less carbon-intensive energy sources. The comparison confirms that the decarbonization benefit of an alternative fuel is contingent upon both onboard use and upstream production.

Figure 6-6 illustrates the importance of integrating LCA with prospective port-demand scenarios. A static comparison assesses the relative performance of fuels based on current assumptions, while the Port-LCA projections illustrate how these differences evolve with increasing future activity.

6.9.6 Macroeconomic Uncertainty and Decision-Support Insights

The sixth output evaluates the impact of macroeconomic uncertainty on projected emissions at port boundaries. The lower-confidence, central forecast, and upper-confidence real-GDP trajectories were analyzed through the GDP–TEU relationship, capacity-equivalent vessel-demand calculation, and emissions-scaling procedure.

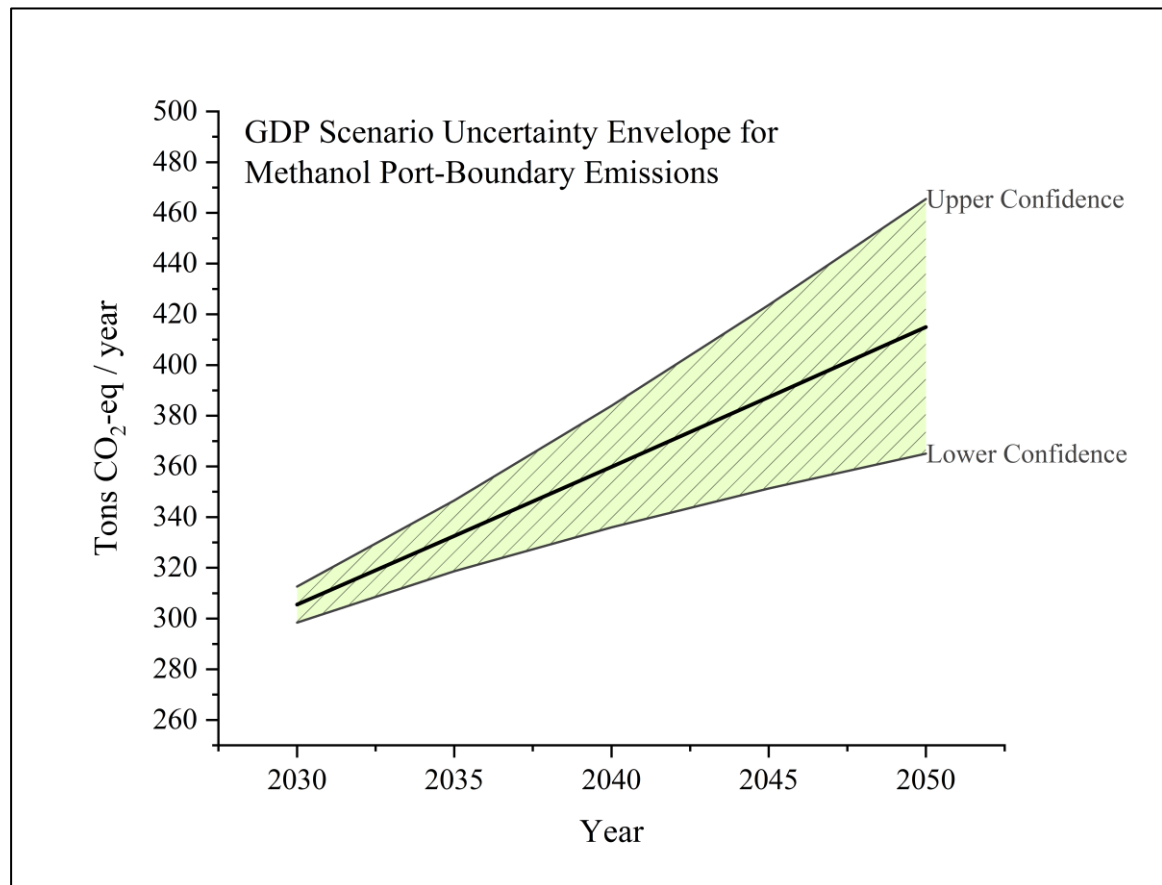


Figure 6-7. Macroeconomic uncertainty envelope for projected port-boundary WTW emissions under the methanol pathway, showing the lower-confidence, central, and upper-confidence real-GDP-driven demand scenarios at an annual port-boundary exposure of 24 hours per capacity-equivalent vessel.

Figure 6-7 illustrates the macroeconomic uncertainty envelope for projected port-boundary WTW emissions associated with the methanol pathway. It presents lower-confidence, central forecast, and upper-confidence GDP-driven demand scenarios, calculated based on an annual exposure of 24 hours per capacity-equivalent vessel.

The uncertainty range expands progressively towards 2050 as minor variations in long-term growth assumptions accumulate over time. The central trajectory should not be viewed as a singular expected future, but rather as one outcome among a wider array of plausible scenarios.

This finding is particularly pertinent to enduring port infrastructure and fuel-supply investments. Under an upper-confidence demand trajectory, the port may necessitate increased alternative-fuel capacity, enhanced operational controls, or expedited implementation of emissions-reduction measures. In a lower-confidence trajectory, analogous infrastructure may still be necessary but could be implemented at an alternative scale or schedule.

The analysis demonstrates the propagation of uncertainty within the Port-LCA framework. It commences with macroeconomic activity, progresses through the GDP–TEU relationship, influences capacity-equivalent vessel demand, and ultimately alters projected port-boundary emissions. Long-term uncertainty is influenced by technical and economic factors.

From a decision-support perspective, the primary value of scenario analysis extends beyond the central projection. The uncertainty envelope delineates the spectrum of activity and emissions conditions within which future fuel infrastructure, operational measures, and port decarbonization strategies must maintain effectiveness.

6.9.7 Sensitivity, Robustness, and Verification Results

The final output analyzes the sensitivity and robustness of the Port-LCA results. The framework relies on AIS-derived vessel trajectories, modeled propulsion demand, fuel consumption assumptions, life cycle emission factors, exposure time assumptions, fleet

composition, and scenario-based activity scaling. Variations in these inputs may influence emissions at both the vessel level and future port boundaries.

Figure 6-8 illustrates the sensitivity and robustness findings of the primary modeling assumptions.

The results demonstrate that various sources of uncertainty influence the model outputs in distinct manners. AIS sampling gaps impact trajectory duration, subsequently affecting absolute trajectory-level emissions. Excluding intervals exceeding 10 minutes diminishes the activity represented in the reconstructed trajectory. Nonetheless, the impact on time-normalized vessel-hour intensity and the relative fuel ranking is diminished, as the fuel pathways are assessed based on identical operational profiles.

The comparison between mean and median aggregation impacts the absolute fleet-level intensity; however, it does not alter the ranking of the five fuel pathways. This suggests that certain vessels exhibit emission intensities that deviate from the central fleet tendency, while the overarching conclusion regarding the significance of the production pathway remains consistent.

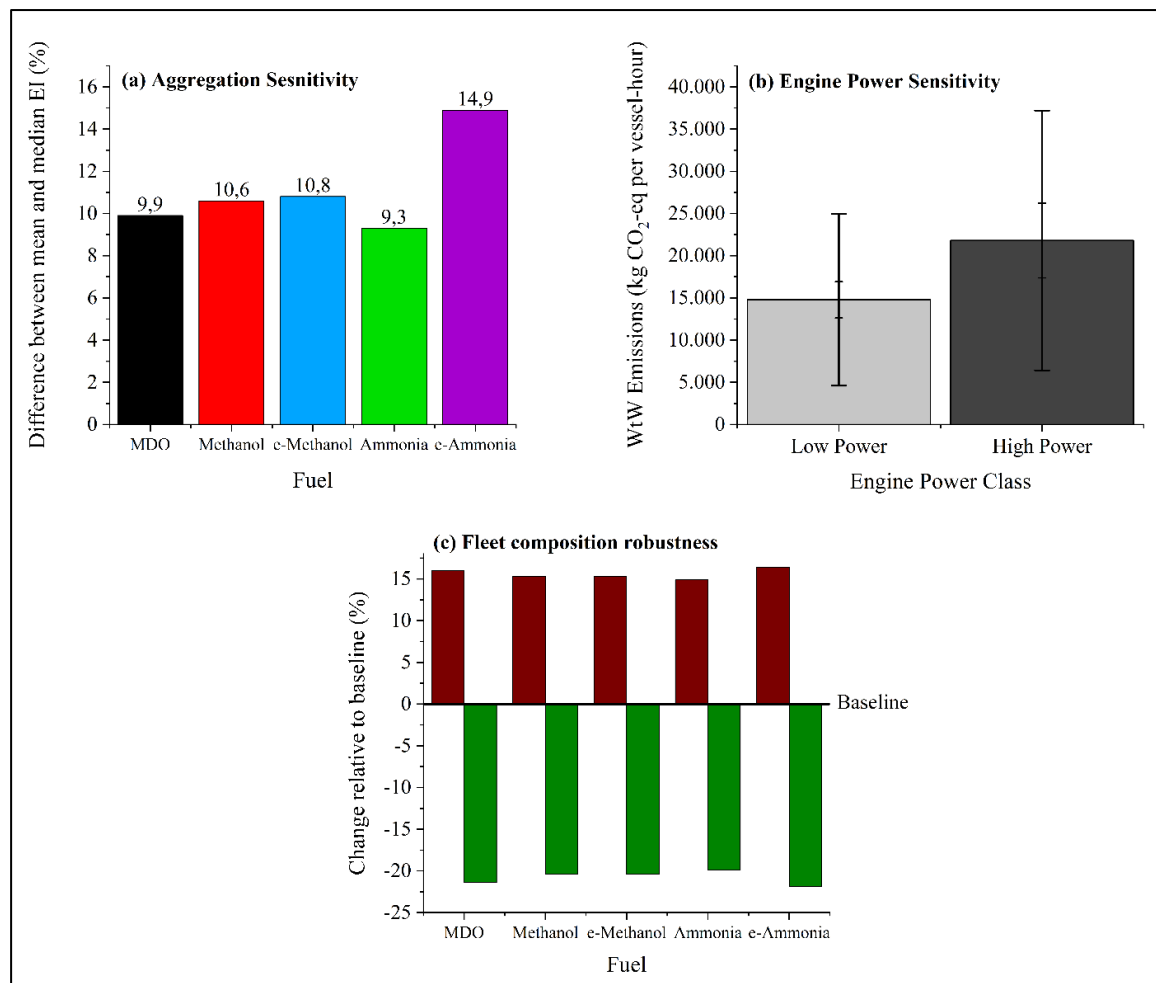


Figure 6-8. Sensitivity and robustness analysis of the Port-LCA framework, examining the influence of aggregation method, engine-power class, fleet composition, AIS sampling gaps, and GDP-driven demand uncertainty on projected WTW emissions.

Variations in engine power class and fleet composition directly influence the magnitude of projected emissions. The future scaling stage is contingent upon the representativeness of the seven selected vessels. A future fleet consisting of larger or more powerful vessels, or vessels with varying operating profiles, may yield different absolute emissions outcomes.

Nonetheless, the relative ranking of the chosen fuel pathways remains consistent across the key sensitivity analyses. This reinforces the central conclusion that WTW

performance is significantly influenced by upstream fuel production, and that nominally similar fuel molecules can yield markedly different life cycle emissions.

The sensitivity analysis does not serve as external validation for measured onboard fuel use or the official emissions inventory of the Port of Busan. It assesses the internal dynamics of the modeling chain and identifies the assumptions that have the greatest impact on the outputs. The results should be interpreted as a proof-of-concept application of the Port-LCA framework, rather than as a fully validated official inventory.

Subsections 6.9.1–6.9.7 collectively fulfill the requirements of Step 6. They illustrate the application of Port-LCA outputs for assessing future activities, analyzing time-resolved operational behavior, comparing fuel pathways, identifying emission hotspots, evaluating long-term emissions trajectories, propagating macroeconomic uncertainty, and informing port-decarbonization decisions.

6.10 Case Study Limitations and Validation Constraints

While the Busan Port-LCA case study illustrates the benefits of integrating AIS-derived vessel activity, lifecycle emission factors, and scenario development based on forecasts, the findings must be considered in light of several significant limitations. These limitations pertain to the AIS dataset, the vessel sample, the modeling assumptions, the fuel pathways, the forecasting approach, and the lack of direct validation against measured emissions or official port-level inventories.

The initial limitation pertains to the temporal scope of the AIS dataset. The case study utilizes AIS records spanning two days in March 2019. This dataset adequately illustrates the proposed Port-LCA workflow and demonstrates the conversion of vessel-

position data into time-resolved emissions. However, it fails to account for seasonal variation, annual traffic cycles, weather-related disruptions, berth congestion, alterations in service schedules, or long-term operational variability. Consequently, the findings should not be regarded as a comprehensive annual emissions inventory for the Port of Busan.

The second limitation pertains to the vessel sample. The analysis employs seven anonymized container vessels chosen from the available AIS dataset. These vessels exhibit notable differences in capacity, installed power, service speed, trajectory, and operational behavior; however, they do not encompass the complete range of vessels arriving at Busan. The Port of Busan accommodates various ship sizes, routes, terminal operations, and operational profiles. Consequently, the vessel-level emission intensities obtained in this case study should be regarded as representative scenario inputs rather than conclusive emission factors for the entire Busan container fleet.

The third limitation pertains to the definition of the port boundary. The case study employs a 20 NM boundary to delineate the spatial domain of the Port-LCA assessment. This boundary effectively captures vessel activity near ports and facilitates the application of a consistent AIS-based calculation framework. However, it does not necessarily align with all operational areas related to a comprehensive port call. Anchorage zones, waiting areas, pilotage operations, berth occupancy, cargo handling, auxiliary engines, boilers, and shore-side activities are not fully represented unless included in the selected AIS-derived vessel tracks. Thus, the findings reflect emissions from vessel movements at the port boundary, rather than encompassing total emissions from all activities related to the Port of Busan.

The fourth limitation pertains to the modelling of propulsion and fuel consumption. Propulsion power was estimated from AIS-derived speed utilizing a speed–power relationship and vessel-specific technical parameters. While this approach is transparent and appropriate for a time-resolved modeling framework, it oversimplifies various real operational effects. Factors include acceleration and deceleration, shallow-water effects, wind and current resistance, hull and propeller condition, tug assistance, maneuvering loads, and engine transient behavior. The low-speed correction implemented in the model mitigates the risk of underestimating propulsion demand at low speeds; however, it does not substitute for comprehensive engine or voyage-performance data.

The fifth limitation pertains to the assumptions regarding alternative fuels. Methanol and ammonia were modeled utilizing fuel-specific assumptions regarding lower heating value, load-dependent consumption, brake efficiency, and pilot-fuel contribution. Nevertheless, the model does not explicitly account for storage-system effects, additional auxiliary-energy demand, ammonia slip, N₂O formation, after-treatment requirements, safety-related design modifications, or comprehensive fuel-certification constraints. These factors may have an impact on the practical performance of methanol and ammonia pathways and warrant investigation in future research.

The sixth limitation pertains to the lifecycle emission factors. The WTT and TTW emission factors enable the case study to evaluate fuel pathways from a WTW perspective. However, the results are highly contingent upon the assumed production route, electricity source, upstream energy input, and emission-factor source. This is especially significant for e-methanol and e-ammonia, as their lifecycle performance is contingent upon the availability of low-carbon electricity and low-emission hydrogen

production. Consequently, the fuel rankings must be understood as results specific to each pathway rather than as universal conclusions applicable to all fuel molecules.

The seventh limitation pertains to the forecasting and demand-scaling methodology. South Korea's real GDP served as the macroeconomic driver for Busan container throughput, which was subsequently converted into capacity-equivalent vessel demand. This method offers a transparent approach to scenario generation; however, it fails to encompass all factors influencing future port activity. Future throughput may be influenced by alterations in shipping networks, restructuring of trade routes, competition among ports, terminal capacity, geopolitical disruptions, logistics policies, trends in vessel size, and shifts in supply chain geography. The forecast should be viewed as a scenario-based projection of activity rather than a definitive prediction of future traffic in Busan.

The eighth limitation pertains to validation. Direct validation against measured vessel fuel consumption, engine-load records, or official port-emission inventories was unfeasible due to the absence of comparable public datasets for the selected vessels and operating periods. Consequently, the case study employs internal consistency checks, sensitivity analysis, literature-derived emission factors, and clear modelling assumptions. This indicates that the results offer proof-of-concept evidence for the Port-LCA framework; however, they should not be regarded as a fully validated official emissions inventory for the Port of Busan.

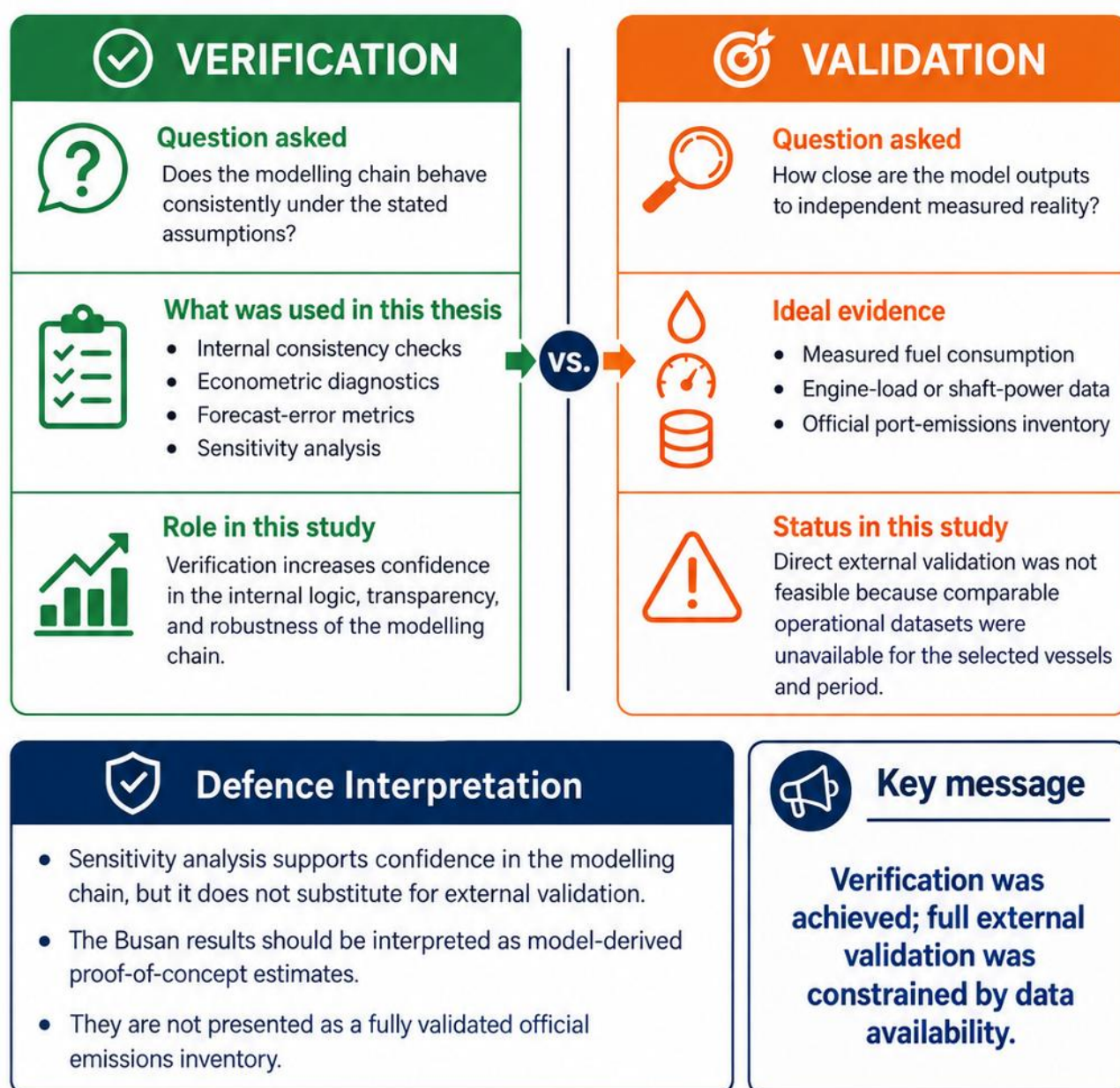


Figure 6-9. Distinction between model verification and external validation in the Busan Port-LCA application.

Table 6-12 summarizes the main verification checks, sensitivity tests, and validation constraints associated with the Busan Port-LCA case study. The table helps distinguish between aspects of the model that are directly calculated from available data, aspects

that are tested through sensitivity analysis, and aspects that remain constrained by data availability.

Table 6-12. Verification checks, sensitivity tests, and validation constraints for the Busan Port-LCA case study.

Assessment category	Indicator or test	Result	Interpretation
Case-study output	Mean WTW emission intensity	MDO: 19,037; methanol: 21,153; e-methanol: 16,873; ammonia: 23,967; e-ammonia: 4,056 kg CO ₂ -eq/vessel-hour	Provides an internally consistent comparison of the five pathways under common AIS-derived activity and the selected model assumptions.
GDP–TEU relationship	Log-level regression, 2011–2024	(n=14); coefficient = 1.0970; 95% CI = 0.9709–1.2231; (p=2.61E-10); (R ² =0.96)	Indicates a strong historical long-term association used for scenario generation, not proof of causality.
Time-series robustness	First-difference regression, 2012–2024	(n=13); coefficient = 0.7988; 95% CI = -0.6079–2.2055; (p=0.2373); (R ² =0.1244)	The relationship is not statistically significant after differencing and does not demonstrate short-term predictive capability.
Forecasting-model fit	Holt–Winters in-sample metrics	MASE = 0.295; SMAPE = 0.00783; MAE = (1.67E+13); RMSE = (2.46E+13) constant-LCU units	Supports transparent scenario construction but does not validate projections to 2050.
Model sensitivity	Aggregation and fleet composition	Mean–median difference: 9–15%; high-power fleet: approximately +15%; low-power fleet: approximately -20%	Absolute emissions vary with aggregation and fleet assumptions, while the fuel ranking remains unchanged.
AIS-gap sensitivity	Exclusion of intervals longer than 10 minutes	Exposure duration: -32%; absolute WTW emissions: -31%; mean speed: 3.7% change; mean power: 1.9% change; vessel-hour intensity: 1.5–2.0% change	Irregular sampling has a stronger effect on absolute trajectory emissions than on time-normalized fuel comparisons.
Input-parameter uncertainty	SFOC curves and WTT/TTW emission factors	Qualitative assessment; no probability distributions assigned	These parameters influence fuel consumption and absolute WTW emissions, but defensible vessel- and pathway-specific uncertainty ranges were unavailable.
External validation	Official Busan inventory or onboard fuel-use measurements	Comparable data unavailable for the selected vessels and period	A model-versus-measurement percentage error could not be calculated; the results remain model-derived estimates.

System-boundary constraints	Alternative boundaries and complete port-call operations	10/20/30 NM sensitivity not performed; anchorage, waiting, hoteling, auxiliary engines, and boilers not comprehensively included	The framework represents a 20 NM port-boundary proof-of-concept and may underestimate complete port-call emissions under congested conditions.
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Source: Author's calculations and sensitivity analyses presented in Sections 6.8–6.10.

Overall, the limitations do not detract from the methodological contribution of the case study. They establish the correct interpretation of the results. The Busan application should be regarded as a proof-of-concept demonstration of AIS-based, time-resolved Port-LCA rather than a comprehensive operational inventory. The primary contribution is the demonstration of how vessel movement, fuel consumption, lifecycle emission factors, and future demand scenarios can be integrated into a transparent assessment framework within port boundaries.

6.11 Closing Remarks

This chapter applied the AIS-based Port-LCA framework to the Port of Busan and demonstrated its use for time-resolved vessel-level emissions assessment and future port-boundary scenario development. The principal findings and methodological implications can be summarised as follows:

- The case study implemented all six methodological steps developed in Chapter 4, linking AIS-derived vessel activity with propulsion-power estimation, fuel consumption, WTT, TTW and WTW emissions, future demand forecasting, sensitivity analysis and decision-support interpretation.
- The time-resolved analysis demonstrated that port-boundary emissions vary considerably across vessel trajectories. Differences in speed, engine load, installed power, trajectory duration and operational behaviour produced substantial vessel-to-vessel variability that would be obscured by a single generic operating profile.

- The WTW comparison demonstrated the importance of the upstream production pathway. E-ammonia produced the lowest mean WTW intensity among the assessed pathways, at approximately 4,056 kg CO₂-eq/vessel-hour, whereas natural-gas-derived ammonia produced the highest, at approximately 23,967 kg CO₂-eq/vessel-hour. MDO, natural-gas-derived methanol and e-methanol yielded approximately 19,037, 21,153 and 16,873 kg CO₂-eq/vessel-hour, respectively. These results demonstrate that low onboard emissions do not necessarily correspond to low lifecycle emissions.
- The forecasting component extended the operational assessment to future port activity. Under the central scenario, capacity-equivalent vessel demand increased from approximately 543 vessels in 2030 to 819 in 2050, demonstrating that growth in port activity can increase total port-boundary emissions even when vessel-level emission intensity remains unchanged.
- The uncertainty and sensitivity analyses showed that absolute emissions are affected by macroeconomic assumptions, fleet composition, engine-power class, AIS sampling gaps, exposure time, aggregation method and fuel-specific emission factors. Although the relative fuel ranking remained stable across the principal sensitivity analyses undertaken, the results remain conditional on the defined pathways and modelling assumptions.
- The Busan application represents a proof-of-concept rather than a complete port inventory. The operational assessment is based on seven anonymized container-vessel trajectories observed over two days and therefore does not represent annual traffic patterns, the full Busan vessel population or an official Port of Busan emissions inventory.

- The absolute emissions estimates are also affected by simplifications in vessel-operation modelling. Auxiliary-engine demand, hoteling and manoeuvring are not comprehensively represented, while weather, currents, shallow-water effects, hull and propeller condition, acceleration and engine transients may alter propulsion demand and fuel consumption. These factors may affect absolute results and, where fuel-specific low-load or auxiliary-energy requirements differ, could also influence relative fuel-pathway performance.
- The results are specific to the selected 20 NM port boundary. Alternative spatial boundaries would alter the vessel activity and exposure included in the assessment, while fuller representation of anchorage, waiting, berthing, hoteling and associated auxiliary-engine operation could increase estimated port-related emissions. A multi-boundary sensitivity analysis was not undertaken, and the results should therefore be interpreted within the adopted spatial boundary.
- Direct external validation against measured fuel consumption, engine-load or shaft-power records, or an official Busan emissions inventory was not possible. The results should consequently be interpreted as model-derived estimates, supported by internal consistency checks, forecast diagnostics and sensitivity analyses rather than as externally validated inventory values.

In summary, the Busan case study illustrates the use of the Port-LCA framework for the integration of time-resolved vessel activity, lifecycle fuel assessment, and future demand scenarios. Together with the Singapore–Rotterdam case study, it reinforces the application of the overarching framework at both corridor and port-boundary scales. Chapter 7 integrates the findings from the two case studies.

7 Discussion, Limitations, and Future Work

This chapter examines the key contributions of the thesis by analyzing the findings from the Singapore–Rotterdam green-corridor and Port of Busan case studies in relation to the broader framework of maritime decarbonization. It initially explores the methodological innovation of combining forecasting and time-resolved operational analysis with LCA. It subsequently examines the original contribution of the research to decision-making within the maritime industry and the shift towards net-zero shipping. Finally, the chapter delineates the primary methodological and data-related constraints of the study and highlights key priorities for subsequent research and the advancement of the proposed methodologies.

7.1 Methodological Advances in Maritime Life Cycle Assessment

The primary methodological innovation of this thesis resides in the expansion of maritime LCA to encompass dynamic evaluations of various marine fuels, moving beyond mere static comparisons. Current maritime LCA studies offer a significant foundation for the comparison of fuel pathways; however, they often depend on static activity levels, typical operating profiles, and evaluations that pertain to a specific moment in time. These methodologies serve as valuable tools for preliminary environmental assessments; however, they do not comprehensively capture the future and operational contexts in which decisions regarding maritime decarbonization are undertaken.

This thesis tackles this limitation by combining LCA with forecasting, scenario analysis, regulatory interpretation, and vessel activity derived from AIS data. The resulting framework establishes a connection between the environmental performance

of alternative fuel pathways and future transport demand, as well as actual operating conditions. Maritime LCA is thus utilized not merely as a method for emissions accounting, but also as a framework for decision support in both strategic and operational planning.

The initial area of innovation pertains to the amalgamation of forecasting with LCA. Traditional LCA typically assesses a fuel based on current or predetermined conditions and does not explicitly consider potential alterations in future maritime operations. Nonetheless, decreases in GHG intensity do not automatically result in a decline in overall emissions, particularly when there is a persistent increase in transport demand. The forecasting component developed in this thesis establishes a connection between projected activity, fuel consumption, WTW emissions, and regulatory exposure.

The case study of Singapore- Rotterdam exemplified this methodology at the scale of green corridors. Historical economic and container-transport data were utilized to formulate future demand scenarios, which were subsequently linked to the projected number of vessels necessary to service the corridor. The resultant activity levels were integrated with the life cycle emissions associated with MDO, bio-methanol, and e-methanol. This allowed the evaluation to investigate the potential evolution of fuel performance in response to rising demand, rather than presuming that corridor activity remains unchanged.

The methodology establishes a connection between carbon emission assessment and the implications of FuelEU Maritime and the EU ETS. This holds significance as these mechanisms evaluate various dimensions of fuel performance. FuelEU Maritime emphasizes the GHG intensity from WTW, while the EU ETS primarily introduces

financial exposure through operational emissions. Their integration facilitates the evaluation of fuel pathways concerning environmental performance, adherence to regulations, and related cost implications.

The second area of innovation is the advancement of a time-resolved Port-LCA methodology based on AIS. Traditional evaluations of port emissions often rely on average operational modes, presumed engine loads, or consolidated vessel activities. While these methodologies are suitable for extensive inventories, they may obscure distinctions among vessels and fluctuations that take place over brief intervals.

The Busan application transforms AIS-derived vessel trajectories into calculations of distance, elapsed time, speed, propulsion power, fuel consumption, and WTW emissions. Emissions are thus characterized as outputs that vary over time in relation to vessel movement, rather than being fixed values attributed to a specific ship category. This facilitates the recognition of operational discrepancies and transient emission peaks that would remain undetected through average assumptions.

The methodology additionally considers the heterogeneity of vessels. The chosen vessels exhibited variations in capacity, installed power, service speed, trajectory, and duration within the port boundary. The observed differences influenced the projected fuel consumption and emissions, even though all vessels were categorized under the same general ship type. The findings thus illustrate the significance of vessel-specific operational data in enhancing the understanding of emissions at port boundaries.

A notable methodological contribution is the implementation of the framework across two complementary scales. The green-corridor case study facilitates a comprehensive evaluation of long-term fuel demand and regulatory factors, while the port-boundary

case study delivers an in-depth analysis of emissions from an operational perspective. These methods are not identical when applied to different locations. They embody both strategic and operational elements within a comprehensive framework for maritime decarbonization.

The thesis further delineates the distinction between a fuel and its corresponding production pathway. Methanol and ammonia cannot be ascribed a singular life cycle performance, as their emissions are contingent upon various factors including feedstocks, sources of electricity, production technologies, and upstream supply chains. A fuel characterized by low onboard carbon emissions may nonetheless generate elevated WTW emissions when produced via carbon-intensive methodologies.

The methodological contribution is thus not the identification of a universally preferable marine fuel. It involves the formulation of a clear methodology for evaluating specific fuel pathways within established production, demand, operational, and regulatory frameworks. Through the integration of forecasting, activity derived from AIS, and WTW accounting, this thesis offers a more thorough foundation for assessing maritime decarbonization compared to relying solely on static fuel comparisons.

7.2 Original Contribution to Industry

The primary contribution to the industry is found in the translation of LCA into evidence that aligns with practical maritime decision-making. Shipowners, port authorities, fuel suppliers, classification societies, and infrastructure developers are required to take into account extended investment horizons, unpredictable fuel availability, evolving regulatory frameworks, the preparedness of infrastructure, and fluctuations in vessel operations. The methodologies articulated in this thesis offer systematic frameworks for the analysis of these factors.

For shipowners and operators, the Singapore–Rotterdam framework facilitates the assessment of alternative fuel pathways within a long-term planning context. Decisions regarding vessels and retrofitting are likely to maintain their significance over an extended period, as regulatory requirements and emissions costs are anticipated to become increasingly stringent. Evaluating fuels solely within the context of present circumstances may consequently result in the development of technologies that subsequently encounter increased compliance risks or inadequate life cycle reductions.

The findings from the case study indicate that reduced emissions during operation do not automatically correlate with diminished overall climate impacts. Methanol demonstrated a reduction in TTW emissions when compared to MDO; however, its overall WTW performance was significantly influenced by the specific production pathway employed. E-methanol generated from renewable energy demonstrated the most significant decarbonization potential among the pathways analyzed, whereas the efficacy of bio-methanol fluctuated based on its feedstock and electricity source.

This finding suggests that decisions within the industry ought to prioritize certified fuel pathways over fuel labels. Shipowners ought to evaluate the production methods of fuel, the carbon intensity associated with the electricity utilized, the provenance of the feedstock, and the dependability of the future supply chain. These factors must be assessed in conjunction with engine compatibility, bunkering availability, regulatory performance, and projected operational demand.

The forecasting results further underscore the significance of assessing absolute emissions in conjunction with emissions intensity. A company may decrease emissions on a per voyage or per unit of energy basis, even as total emissions rise due to an expansion in fleet operations. Net-zero strategies should consequently assess both the environmental efficacy of specific fuel pathways and the overall magnitude of prospective operations.

For port authorities, the Port-LCA framework offers a methodology for associating emissions with vessel behavior within a specified port boundary. The time-resolved analysis facilitates the identification of specific periods and operational conditions linked to increased emissions. It is capable of differentiating between vessels that possess varying technical and operational characteristics, which may be obscured within fleet-average inventories.

This information may facilitate the implementation of operational measures including speed management, optimization of arrival times, reduction of waiting periods, enhancement of berth allocation, and improved coordination between vessels and ports. These measures have the potential to decrease energy demand, whereas alternative fuels can diminish the greenhouse gas intensity associated with the energy utilized. Effective

port decarbonization necessitates the integration of operational enhancements alongside the adoption of lower-carbon fuel alternatives.

The findings from Busan further illustrate that achieving zero-carbon operations onboard does not necessarily equate to reduced life cycle emissions. Based on the chosen assumptions, renewable e-ammonia exhibited the lowest WTW emissions, whereas ammonia derived from natural gas demonstrated the highest emissions. The decarbonization potential of ammonia is contingent upon the origin of hydrogen and the energy utilized in its production.

For fuel suppliers and infrastructure developers, this underscores the necessity of establishing comprehensive low-carbon supply chains. The environmental significance of e-methanol and e-ammonia is contingent upon factors such as renewable electricity, low-emission hydrogen, production capacity, as well as the availability of storage, transport, and bunkering facilities. Investment decisions should thus consider the entire process rather than solely focusing on the provision of the final fuel to the vessel.

The forecasting methodology can also aid in estimating the future scale of fuel and infrastructure requirements. Linking demand scenarios with vessel operations can enhance decision-making related to production capacity, storage facilities, and bunkering systems. This mitigates the potential for creating infrastructure that may be inadequate for future demand or underutilized due to the slower-than-anticipated adoption of fuel technologies.

Classification societies and technical organizations may employ analogous methodologies to facilitate fuel-readiness assessments, conduct green-corridor studies, verify life cycle claims, and evaluate port-decarbonization strategies. The clear

delineation of fuel pathways, system boundaries, vessel assumptions, and activity scenarios can enhance the consistency and comparability of these assessments.

For policymakers, the findings advocate for the ongoing advancement of WTW regulation and the certification of fuels specific to various pathways. Policies that focus exclusively on emissions produced during operation may inadvertently promote fuels that transfer emissions to the upstream production phase. It is essential to provide clear and comprehensive reporting on feedstocks, electricity sources, hydrogen production, and life cycle emission factors to guarantee that regulatory incentives yield authentic climate advantages.

In summary, the thesis presents a well-organized framework designed for context-specific decision-making within the industrial sector. The corridor methodology facilitates comprehensive planning for fuel, regulatory frameworks, and infrastructure over an extended period, whereas the port methodology is focused on evaluating operational emissions. Together, they can assist maritime stakeholders in formulating net-zero strategies that take into account both the carbon intensity of fuels and the scale and manner of their utilization.

7.3 Limitations and Future Research Directions

The results of this thesis must be understood in the context of the chosen case studies, the defined system boundaries, the availability of data, and the assumptions made during the modeling process. The findings offer a comparative and scenario-based framework for decision support, as opposed to deterministic predictions or formal emissions inventories. While the methodological framework can be adapted for various applications, the numerical outcomes necessitate recalibration for each specific corridor, port, and vessel population.

The initial limitation pertains to the breadth of the case studies. The forecasting methodology was illustrated through a specific containership corridor utilizing a representative vessel and chosen methanol pathways. The Port-LCA methodology was employed to analyze seven anonymized container vessels within a specified boundary of Busan port. The findings, consequently, do not encompass all categories of vessels, engine technologies, port configurations, or operational conditions.

Future research should extend the methodologies to encompass additional corridors, ports, and categories of vessels. Research focused on tankers, bulk carriers, ferries, and short-sea vessels would enhance comprehension of the broader applicability of the framework. Comparisons across multiple ports and corridors would facilitate the differentiation of transferable methodological findings from those that are specific to individual cases.

The second limitation pertains to the challenges associated with long-term forecasting. The Holt–Winters method offers a clear approach for projecting historical demand trends; however, it falls short in capturing the structural changes induced by geopolitical

events, trade policy shifts, technological advancements, or competition among ports. The forecasts should consequently be regarded as scenarios rather than exact predictions.

Future research ought to conduct a comparative analysis of the Holt–Winters method alongside Autoregressive Integrated Moving Average (ARIMA), econometric models, machine-learning techniques, and simulation approaches. The integration of combined forecasts alongside alternative scenario narratives has the potential to enhance the depiction of uncertainty and the likelihood of structural changes within maritime activity.

The third limitation pertains to life cycle inventory data. Several assumptions regarding fuel production were formulated based on existing literature, regulatory documents, and publicly accessible data concerning proposed projects. The resultant emissions from well to tank are contingent upon various assumptions related to feedstocks, sources of electricity, methods of hydrogen production, carbon capture technologies, and overall process efficiency.

Future applications ought to utilize verified data that is specific to plants whenever such information is accessible. Information regarding fuel certification, guarantees of origin, and regionally differentiated electricity scenarios would enhance the precision of pathway comparisons. Probabilistic analysis may serve to quantify the impact of uncertainty in production assumptions and emission factors.

Another limitation pertains to the operational model based on AIS. AIS records may encompass absent observations, inconsistent intervals, and ambiguous operating conditions. Estimates of propulsion power and fuel consumption were derived from

vessel speed and technical specifications instead of being measured directly. The calculations are insufficient to comprehensively account for weather conditions, currents, shallow-water effects, hull integrity, maneuvering loads, or engine transients.

The Busan boundary does not constitute a comprehensive port call. Anchorage, waiting, hoteling, cargo handling, auxiliary-engine use, and shore-side activities were not thoroughly addressed. The results should consequently be regarded as emissions associated with port boundaries rather than a comprehensive inventory of operations at the Port of Busan.

Future research should integrate AIS data with berth records, port-call information, meteorological data, auxiliary-engine profiles, and quantified fuel consumption metrics. It is essential to evaluate alternative boundary definitions to assess the impact of spatial assumptions on the estimated emissions.

A notable limitation is the absence of direct external validation. Comparable measurements of onboard fuel usage and official emissions inventories were not accessible for the chosen vessels and timeframes. Sensitivity testing reinforces the comparative findings; however, it cannot substitute for validation against actual performance measurements.

Future collaboration with shipowners, ports, engine manufacturers, and classification societies may facilitate access to onboard monitoring data, bunker records, and vessel performance reports. These datasets would facilitate the calibration of the operational model and allow for the evaluation of the accuracy of absolute emissions estimates.

Ultimately, the study centers on the examination of GHG emissions. It fails to deliver a comprehensive evaluation of air pollution, resource consumption, toxicity, safety,

capital expenditure, fuel prices, or infrastructure costs. The calculations associated with the EU ETS and FuelEU Maritime illustrate specific regulatory implications, rather than providing a comprehensive techno-economic assessment.

Future research ought to incorporate life cycle emissions alongside analyses of economic, technical, safety, and infrastructure factors. Furthermore, the integration of supplementary environmental indicators and probabilistic uncertainty methodologies may be considered. These advancements would evolve the framework from a clear proof-of-concept methodology into a more extensive decision-support platform for maritime decarbonization.

In summary, the primary objectives for forthcoming endeavors include the expansion of case-study applications, enhancement of forecasting methods, acquisition of higher-quality fuel-production data, development of more intricate operational modeling, and validation through comparison with measured data. Enhancing these aspects would bolster the practical implementation of forecasting and time-resolved LCA in facilitating the maritime shift towards achieving net-zero emissions.

7.4 Closing Remarks

The principal points arising from the discussion can be summarized as follows:

- The thesis demonstrates the value of integrating established LCA, forecasting, scenario-analysis, and AIS-based techniques within a common maritime assessment framework, providing complementary strategic and operational perspectives.
- The two case studies show that marine-fuel performance is strongly dependent on production pathway, future activity, operational conditions, regulatory context, and

defined system boundaries; therefore, the numerical results remain case- and assumption-specific.

- The framework provides a basis for comparative and scenario-based decision support, but the applications should not be interpreted as comprehensive investment assessments or validated official emissions inventories.
- Future research should extend the framework to additional vessels, ports and corridors, improve forecasting and operational data, undertake external validation, and incorporate wider environmental, economic, safety, infrastructure, and fuel-availability considerations.

Chapter 8 concludes the thesis by aligning the principal findings with the research questions and objectives and summarizing the overall contribution to knowledge.

8 Conclusions

This chapter concludes the thesis by synthesizing the principal findings and illustrating how the research addressed the methodological gaps identified in the LCA literature. Instead of reiterating the detailed results and discussion from the previous chapters, the conclusion aligns with the progression of the research. This section first summarizes the limitations identified in the literature review and the methodological response formulated in this thesis. It subsequently outlines the principal findings derived from the case studies of the Singapore–Rotterdam green corridor and the Port of Busan. It delineates the key implications of the research for academia, the maritime industry, policymakers, port authorities, and future studies on maritime decarbonization.

The chapter provides an account of how forecasting and time-resolved LCA can enhance the evaluation of alternative marine fuel pathways across strategic and operational decision-making scales.

8.1 Research Gap and Methodological Response

The literature review in Chapter 2 identified multiple limitations in the current application of life cycle assessment to maritime decarbonization. Previous studies have highlighted the significance of assessing alternative marine fuels from a WTW perspective; however, numerous evaluations continue to rely on static operating assumptions, aggregated activity profiles, and fixed representations of transport demand. Future alterations in maritime activity, fuel production pathways, regulatory mandates, and operational conditions are not consistently well represented. The literature indicates a lack of integration between long-term forecasting and detailed emissions assessment, especially within port boundaries, where factors such as vessel

speed, engine load, operating duration, and movement patterns exhibit significant variability.

These limitations establish a disparity between traditional fuel-comparison studies and the evidence necessary for strategic and operational decision-making. At the scale of green corridors, decision-makers need to comprehend the interactions between future transport demand, fuel pathways, WTW emissions, and regulatory exposure over time. At the port-boundary scale, emissions assessment necessitates detailed vessel-activity data to accurately reflect variations in movement and operating conditions. Evaluating these two scales independently may overlook the interrelationship among the life cycle performance of marine fuels, future activity growth, and actual vessel operations.

Chapter 4 addressed these gaps by developing an integrated methodological framework that combines LCA, forecasting, scenario analysis, regulatory interpretation, and operational data derived from AIS. The forecasting component links various marine fuel pathways with anticipated transport demand and future regulatory conditions, allowing for a prospective examination of emissions and compliance implications. The time-resolved component translates AIS-derived vessel trajectories into operational parameters such as distance, speed, propulsion power, fuel consumption, and emissions within a specified port boundary.

The resulting framework enhances maritime LCA by integrating complementary strategic and operational perspectives, moving beyond static fuel comparisons. Instead of attempting to identify a single universally preferable fuel, this approach allows for the evaluation of alternative fuel pathways within specific production, demand, regulatory, and operational contexts. The applicability was subsequently demonstrated

through the Singapore–Rotterdam green-corridor case study and the Port of Busan case study, as detailed in Chapters 5 and 6.

8.2 Conclusions Aligned with the Research Questions and Objectives

Objective 1 – Integrated methodological framework

Objective 1 was accomplished by creating an integrated maritime LCA framework that incorporates lifecycle assessment, forecasting, scenario analysis, regulatory interpretation, and time-resolved operational data. This signifies a clear methodological contribution of the thesis.

Objective 2 / RQ1 – Singapore–Rotterdam green corridor

The Singapore–Rotterdam application illustrated the capability of forecasting-oriented LCA to evaluate specific fuel pathways in the context of future demand and regulatory scenarios. The case study calculations highlighted the significance of the entire fuel production pathway, with results extending to 2050 representing model-based projections contingent upon specified demand, regulatory, and lifecycle assumptions.

Objective 3 / RQ2 – Port of Busan

The Busan application served as a proof-of-concept, illustrating the integration of AIS-derived vessel activity with LCA to generate time-resolved WTW emissions estimates within a specified port boundary. These outputs represent model results for the chosen seven vessel trajectories and should not be considered an annual or operationally validated emissions inventory for the Port of Busan.

Objective 4 / RQ3 – Integrated interpretation

The two applications demonstrate that forecasting-oriented and time-resolved LCA offer complementary strategic and operational insights. This interpretation is based on the two case studies, and its application to other maritime contexts presents future methodological potential, necessitating recalibration and further validation.

Answer to the Fundamental Research Question

Forecasting and time-resolved LCA can improve the evaluation of alternative marine fuel pathways by connecting lifecycle performance with future activities, regulatory conditions, and vessel-specific operational behaviors. The two case studies illustrate this integration at both corridor and port-boundary scales. However, the numerical findings and future projections are contingent upon the assumptions and boundaries of the respective applications.

8.3 Implications and Final Conclusions

In academic contexts, the findings illustrate the importance of broadening maritime LCA to encompass more than just static fuel comparisons. Future research should enhance the integration of life cycle inventories with transport-demand forecasting, vessel-specific operational data, regulatory scenarios, and uncertainty analysis. The developed approaches can be further enhanced by incorporating measured fuel-consumption data, expanding to additional vessel and port applications, considering broader impact categories, and utilizing more advanced forecasting techniques. These developments would enhance external validation and increase the transferability of forecasting and time-resolved LCA across maritime contexts.

In the maritime industry, findings suggest that decisions regarding alternative fuels should consider comprehensive fuel pathways instead of relying solely on fuel labels or TTW emissions. Shipowners, fuel suppliers, classification societies, and infrastructure developers should collectively evaluate production methods, energy sources, projected demand, regulatory exposure, operational profiles, and fuel availability. The framework facilitates initial comparative and scenario-based evaluations of alternative fuel pathways, regulatory exposure, and operational emission patterns under specified assumptions. This should not be viewed as an investment-readiness or comprehensive techno-economic assessment, as factors such as capital expenditure, infrastructure readiness, safety, fuel availability, technology maturity, and broader market conditions are beyond the scope of this thesis.

Findings indicate that policymakers and port authorities should utilize WTW accounting and activity-sensitive assessment in the formulation of maritime decarbonization strategies. Regulatory mechanisms must promote fuels that provide authentic life cycle reductions while preventing the transfer of emissions from onboard usage to upstream production. Green-corridor strategies must consider future demand growth, as a decrease in emissions alone may not adequately lower absolute emissions. At the port scale, assessments derived from AIS data can enhance the understanding of the timing and location of vessel emissions. However, these estimates should be regarded as comparative decision-support tools rather than official emissions inventories.

The broader public interest is advanced through transparent and evidence-based evaluations of maritime fuel transitions. Decisions characterized as environmentally

beneficial must encompass the entire emissions pathway and should not depend exclusively on the lack of carbon emissions during onboard combustion.

In conclusion, this thesis demonstrates that forecasting and time-resolved LCA improve the evaluation of alternative marine fuel pathways by linking environmental performance with future demand, regulatory conditions, and actual vessel activity. The two approaches offer complementary evidence at both strategic green-corridor and operational port-boundary levels. No single fuel pathway can be deemed universally superior; its appropriateness is contingent upon production conditions, operational applications, regulatory frameworks, and the scale of evaluation. Maritime decarbonization necessitates integrated, context-specific, and life cycle-based decision-making, as opposed to isolated or static fuel comparisons. The findings are derived from two case-study applications and should therefore be interpreted as case-specific and model-derived evidence rather than operationally validated outcomes directly transferable to the wider maritime sector.

8.4 Closing Remarks

The principal conclusions of this thesis can be summarized as follows:

- The research objectives were addressed through the development and application of an integrated maritime LCA framework combining WTW assessment, forecasting, scenario analysis, regulatory interpretation, and time-resolved operational data.
- The Singapore–Rotterdam and Busan case studies demonstrated that the environmental performance of alternative marine fuels depends on the complete

fuel pathway, future activity, regulatory conditions, operational characteristics, and defined system boundaries, rather than on onboard emissions alone.

- Future demand, emissions, and regulatory outcomes presented in the thesis are model-based and scenario-dependent projections, while the Busan application represents a proof-of-concept rather than an operationally validated or complete port emissions inventory.
- The framework can support comparative and scenario-based assessment, but it should not be interpreted as a complete investment-readiness or techno-economic tool. Further assessment of safety, infrastructure, capital expenditure, fuel availability, technology maturity, and wider environmental impacts is required.
- The principal contribution to knowledge is the integration of established LCA, forecasting, scenario-analysis, regulatory, and time-resolved vessel-activity methods within a common maritime framework spanning complementary corridor and port-boundary scales. Its methodological structure is transferable, while its numerical outputs remain case-specific and require recalibration for different maritime contexts.

Overall, the thesis demonstrates the value of integrating lifecycle, future-oriented, and operational perspectives when assessing maritime decarbonization pathways.

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Research Outputs and Selected Doctoral Achievements

The following peer-reviewed publications, manuscripts under review, conference contributions, technical report, scholarship, academic appointment, and selected professional achievements were completed during the doctoral period. These outputs either arose directly from the research presented in this thesis or formed part of the broader academic and professional development undertaken throughout the doctoral journey.

Peer-Reviewed Journal Articles

J1: Chalaris, I., Jeong, B. and Jang, H., 2022. ‘Application of parametric trend life cycle assessment for investigating the carbon footprint of ammonia as marine fuel’. *The International Journal of Life Cycle Assessment*, vol. 27, pp. 1145–1163. doi: 10.1007/s11367-022-02091-4.

J2: Chalaris, I., Jeong, B. and Jee, J., 2025. ‘Strategic forecasting of GHG intensity: Econometrically enhanced LCA for the Singapore–Rotterdam containership green corridor’. *Results in Engineering*, vol. 28, article 107437. doi: 10.1016/j.rineng.2025.107437.

Manuscript Under Review

M1: Chalaris, I., Jeong, B., Gunbeyaz, S.A. and Jee, J., 2026. ‘Port-LCA for Maritime Decarbonization: AIS-Based Time-Resolved Analysis of Alternative Marine Fuels’. Manuscript submitted to *Ocean Engineering* and currently under peer review (Revision 3).

Conference Papers and Presentations

C1: Chalaris, I., 2023. ‘Development of a Dynamic LCA Methodology: Comparison between Conventional Life Cycle Assessment and IMO Draft Life Cycle Proposal’. Research presented at the Conference on Ocean Energy and Marine Transport Research 2023 (OEMT 2023), Glasgow, United Kingdom, 7–8 June 2023.

C2: Chalaris, I., 2024. ‘Econometrically Enhanced Lifecycle Analysis for the Singapore–Rotterdam Containership Green Corridor’. Research presented at the Conference on Ocean Energy and Marine Transport Research 2024 (OEMT 2024), Glasgow, United Kingdom, 16–17 September 2024.

C3: Chalaris, I., Jeong, B. and Jee, J., 2024. ‘Strategic Forecasting of GHG Intensity: Econometrically Enhanced LCA for the Singapore–Rotterdam Containership Green Corridor’. Research presented at the 2nd Global Conference on Naval Architecture and Ocean Engineering (G-NAOE 2024), Southampton, United Kingdom, 5–9 November 2024.

C4: Chalaris, I. and Jeong, B., 2025. ‘Port-LCA: A Real-Time Life Cycle Assessment Framework for Vessel GHG Emissions in Ports’. Peer-reviewed paper presented at the SNAME Maritime Convention 2025, Norfolk, Virginia, United States, 29–31 October 2025. doi: 10.5957/SMC-2025-055.

C5: Chalaris, I., 2025. ‘Port-LCA: A Dynamic Framework for Quantifying Vessel Greenhouse Gas Emissions Within Port Boundaries’. Research presented at the Conference on Ocean Energy and Marine Transport Research 2025 (OEMT 2025), Glasgow, United Kingdom, 10–11 December 2025.

Accepted Conference Contribution

C3: Hemmen, R.K.F. and Chalaris, I., 2026. ‘System-Level Evaluation of Sustainable Energy Pathways for Marine Propulsion’. Accepted for presentation at the *SNAME Maritime Convention 2026*, Houston, Texas, United States, 28–30 October 2026.

Technical Reports and Research Notes

R1: Chalaris, I., Papathanasiou, M.-A., Chalaris, M., Petrakakos, H. and Jeong, B., 2025. ‘Navigating the Future: A Review of Nuclear Power in Decarbonising Commercial Shipping’. *IENE Research Note No. 5*. Institute of Energy for South-East Europe, Athens, Greece.

Scholarships and Awards

S1: Awarded a scholarship by the Greek Section of the SNAME in 2023, in support of advanced doctoral studies in life cycle assessment and maritime decarbonization at the University of Strathclyde.

Academic and Research Appointments

A1: Appointed Research Affiliate at the MIT Climate & Sustainability Consortium, Massachusetts Institute of Technology, for the period March 2026–March 2027. The appointment supports collaborative research in maritime decarbonization, life cycle assessment, alternative marine fuels, fleet evolution, and the Singapore–Rotterdam green shipping corridor.

Research Leadership and Professional Service

A2: Appointed Chair of the M-50 ‘Alternative Fuels’ Panel within the Ship’s Machinery Committee of the SNAME Technical and Research Program in September 2024.

A3: Co-founded the Hellenic Young Generation in Nuclear in March 2025 and serves as its National Representative within the International Youth Nuclear Congress.

A4: Served as Student Paper Chair for the SNAME Maritime Convention 2022, contributing to the coordination and evaluation of student research submissions.

International Workshops and Professional Engagement

A5: Participated as the Hellenic National Representative in the International Youth Nuclear Congress Board Consultative Workshop held in Vienna, Austria, in November 2025. The programme included international working sessions, strategic discussions regarding the development of national young-generation nuclear networks, and a technical visit to the nuclear research reactor at TU Wien.

APPENDIX A

Supplementary Material for the Singapore–Rotterdam Green Corridor Case Study

A.1 Purpose and Scope of Appendix A

This appendix provides additional data, assumptions, and diagnostic materials that support the case study of the Singapore–Rotterdam green corridor presented in Chapter 5. The primary chapter outlines the forecasting-oriented LCA framework and presents the key findings. In contrast, the material provided here details the necessary inputs for tracing the WTT calculations, interpreting the annual operating profile of the case vessel, and replicating the supporting econometric analysis.

The data were sourced from international institutions, port authorities, industry reports, and peer-reviewed scientific literature. Historical GDP, population, and container throughput data were verified against multiple sources. Additionally, historical trend analysis and sensitivity testing were employed to assess the robustness of the forecasting assumptions. Regulatory inputs were synchronized with FuelEU Maritime and the European Union Emissions Trading System. Due to the inherent uncertainties surrounding future economic development, fuel availability, and infrastructure deployment, the resulting values should be regarded as scenario-based estimates rather than deterministic predictions.

A.2 Alternative-Fuel Production and Transportation Assumptions

This section documents the project-level methanol production assumptions and the detailed upstream inputs used in the WTT calculations. It includes production capacities, feedstocks, energy requirements, carbon-capture assumptions, and road-transport parameters for the pathways assessed in Chapter 5.

A.2.1 Methanol Production Projects in Rotterdam and Singapore

Table A.1 summarises the methanol projects used to define the production pathways considered in the Singapore–Rotterdam case study.

Table A.1. Methanol production projects and investment assumptions considered for Rotterdam and Singapore.

Company or consortium	Start-up year	Capacity (t/year)	Feedstock	Product	Location	Reference
Consortium Nouryon/Gasunie/BioMCN and three other partners	2026	15,000	CO ₂ and electrolytic H ₂	E-methanol	Delfzijl	(Lloyd's Register, 2023)
PTTEP, Air Liquide, YTL PowerSeraya, Oiltanking, Kenoil Marine Services, and Maersk	2024	50,000	Biogenic CO ₂ and electrolytic H ₂	E-methanol	Jurong Island	
OCI/BioMCN	2020	60,000	Biogas	Bio-methanol	Delfzijl	
Gidara and Lowlands	2024	90,000	Municipal solid waste	Bio-methanol	Delfzijl	

A.2.2 Transportation of Municipal Solid Waste to the AMR Facility

The assumptions in Table A.2 describe the road transport of municipal solid waste from the collection points to the Amsterdam Metropolitan Region facility associated with the Gidara and Lowlands pathway.

Table A.2. Data and assumptions for transporting municipal solid waste to the AMR facility.

Parameter	Value	Unit	Reference
Municipal solid waste	185,384.09	t/year	—
Truck carrying capacity	25	t	—
Trips per year	7,200	trips/year	—
Transport mode	Road transport by truck	—	—
Total distance	720,000	km/year	—
Fuel-consumption rate	251	g/km	(European Environment Agency, 2023)
Total fuel consumption	180,720	kg/year	—
CO ₂ emission factor	0.486	g/km	(European Environment Agency, 2023)
CH ₄ emission factor	0.0203	g/km	
N ₂ O emission factor	0.032	g/km	
CO ₂ emissions	349,920	g	—
CH ₄ emissions	14,616	g	—
N ₂ O emissions	23,040	g	—
CH ₄ emissions	365,400	g CO ₂ -eq	—
N ₂ O emissions	6.29E+06	g CO ₂ -eq	—
Total GHG emissions	7,005.24	kg CO ₂ -eq/year	—

A.2.3 E-Methanol Production Assumptions for Rotterdam

Table A.3 provides the stoichiometric, energy and carbon-capture inputs used to estimate the upstream emissions of the Rotterdam e-methanol pathway associated with the Nouryon/Gasunie/BioMCN consortium.

Table A.3. Data and assumptions for the Well-to-Tank production calculations of e-methanol in Rotterdam.

Parameter	Value	Unit	Reference
Molar mass of CO ₂	44.01	g/mol	—
Molar mass of H ₂	2.02	g/mol	—
Molar mass of CH ₃ OH	32.04	g/mol	—
Moles of methanol	1.40E+09	mol	—
Mass of CO ₂ required	40,399.9	t	—
Mass of H ₂ required	5,562.9	t	—
Total production energy required	3.1E+08	MJ	—
Electrolysis electricity requirement	53.4	kWh/kg H ₂	(Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022)
Electricity emissions from solar PV for H ₂ production	4.33E+06	kg CO ₂ -eq	—
Electricity emissions from wind for H ₂ production	1.92E+06	kg CO ₂ -eq	—
Methanol conversion parameter	20.97	MJ/kg CH ₃ OH	(Kajaste et al., 2018)
Hydrogen conversion efficiency	0.51	—	—
Electrolyser capacity	20	MW	—
Hydrogen production	3,000	t/year	—

Annual electricity requirement for hydrogen production	1.60E+08	kWh/year	—
Direct air capture energy consumption	3	MWh/t CO ₂	(Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022)
Direct air capture energy requirement	1.21E+05	MWh	—
Carbon-capture factor (DAC and point-source capture)	−1.38	t CO ₂ -eq/t methanol	(Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022)
Carbon-capture contribution	−2.07E+07	kg CO ₂ -eq	—
Electricity emissions from wind for DAC	1.45E+06	kg CO ₂ -eq	—
Electricity emissions from solar PV for DAC	3.27E+06	kg CO ₂ -eq	—
Total production GHG emissions using wind electricity	−1.73E+07	kg CO ₂ -eq	—
Total production GHG emissions using solar PV electricity	−1.31E+07	kg CO ₂ -eq	—

A.2.4 Transportation of E-Methanol in Rotterdam

Table A.4 records the road-transport assumptions used to estimate emissions from moving e-methanol from the production location to the relevant supply point in Rotterdam.

Table A.4. Data and assumptions for the transportation calculations of e-methanol in Rotterdam.

Parameter	Value	Unit	Reference
E-methanol produced	15,000	t/year	—
Truck carrying capacity	25	t	—
Distance	312	km	—
Transport mode	Road transport by truck	—	—
Total distance	374,400	km/year	—
Fuel-consumption rate	251	g/km	(European Environment Agency, 2023)
CO ₂ emission factor	0.486	g/km	
CH ₄ emission factor	0.0203	g/km	
N ₂ O emission factor	0.032	g/km	
CO ₂ emissions	181,958.4	g	—
CH ₄ emissions	7,600.3	g	—
N ₂ O emissions	11,980.8	g	—
CH ₄ emissions	190,008	g CO ₂ -eq	—
N ₂ O emissions	3.27E+06	g CO ₂ -eq	—
Total GHG emissions	3,642.7	kg CO ₂ -eq/year	—

A.2.5 Transportation of Bio-Methanol in Rotterdam

Table A.5 provides the corresponding road-transport inputs for the OCI/BioMCN bio-methanol pathway.

Table A.5. Data and assumptions for the transportation calculations of bio-methanol in Rotterdam.

Parameter	Value	Unit	Reference
Bio-methanol produced	45,799.77	t/year	—
Trips per year	1,832	trips/year	—
Distance	312	km	—
Transport mode	Road transport by truck	—	—
Total distance	1.14E+06	km/year	—
Fuel-consumption rate	251	g/km	(European Environment Agency, 2023)
CO ₂ emission factor	0.486	g/km	
CH ₄ emission factor	0.0203	g/km	
N ₂ O emission factor	0.032	g/km	
CO ₂ emissions	555,576.90	g	—
CH ₄ emissions	23,206.20	g	—
N ₂ O emissions	36,581.20	g	—
CH ₄ emissions	580,154.90	g CO ₂ -eq	—
N ₂ O emissions	9.99E+06	g CO ₂ -eq	—
Total GHG emissions	11,122.40	kg CO ₂ -eq/year	—

A.3 Annual Operational Profile of the Case Vessel

The annual operating profile in Table A.6 defines the sailing and port-residence assumptions applied to the 8,000 TEU containership considered in Chapter 5. Port time is disaggregated into berthing, anchoring, and maneuvering periods for Rotterdam and Singapore.

Table A.6. Annual operational profile assumed for the case vessel on the Singapore–Rotterdam green corridor.

Location	Parameter	Value	Reference
—	Sailing days	347.40	—
—	Sailing hours	8,336.80	—
Rotterdam	Total port days	8.62	(UNCTAD, 2024)
	Total port hours	206.90	
	Days at berth	0.86	(IMO, 2021)
	Days anchored	0.86	
	Days manoeuvring	0.43	
	Hours at berth	20.69	
	Hours anchored	20.69	
	Hours of manoeuvring	10.35	
Singapore	Total port days	9.01	(UNCTAD, 2024)
	Total port hours	216.31	
	Days at berth	0.90	(IMO, 2021)
	Days anchored	0.90	
	Days manoeuvring	0.45	
	Hours at berth	21.63	
	Hours anchored	21.63	
	Hours of manoeuvring	10.82	

A.4 Supplementary Econometric Analysis

The econometric analysis supports the relationship between socioeconomic development and container demand used in the forecasting stage of Chapter 5. Pearson correlation was first applied to assess the strength of association between the selected variables, after which multiple linear regression equations were used to represent the central, lower-confidence, and upper-confidence demand scenarios.

A.4.1 Pearson Correlation Analysis

The Pearson correlation coefficient, shown in Equation (A.1), measures the linear association between paired observations of two variables.

$$r(x, y) = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \quad \text{Eq. (A.1)}$$

where x_i and y_i are paired observations, $\bar{x}$ and $\bar{y}$ are the corresponding sample means, and $r_{x,y}$ is the Pearson correlation coefficient. The resulting correlation matrix is presented in Table A.7.

Table A.7. Pearson correlation matrix for the TEU-demand, GDP, and population variables.

	SGP	NLD	GDP (current US\$)	Population (total)
SGP	1	—	—	—
NLD	0.972	1	—	—
GDP (current US\$)	0.989	0.963	1	—
Population (total)	0.989	0.951	0.992	1

Note: SGP and NLD denote the Singapore and Netherlands data series, respectively.

A.4.2 Regression Equations for the Demand Scenarios

Multiple linear regression was used to estimate container demand, Y , as a function of GDP and population. The estimated equations corresponding to the central forecast, lower-confidence, and upper-confidence scenarios are given in Equations (A.2)–(A.4), respectively.

Central forecast scenario

$$Y = -20609677.43 + (1.62263E - 07 * GDP) + (0.005398955 * Population) \quad \text{Eq. (A.2)}$$

Lower-confidence scenario

$$Y = 32312349.14 + (3.9946E - 07 * GDP) - (0.004394066 * Population) \quad \text{Eq. (A.3)}$$

Upper-confidence scenario

$$Y = -47830675.06 + (1.74086E - 08 * GDP) + (0.009184468 * Population) \quad \text{Eq. (A.4)}$$

A.5 Role of Appendix A in Supporting Chapter 5

The supporting material presented in Appendix A strengthens the transparency and reproducibility of the Singapore–Rotterdam case study. The production and transport tables provide the numerical basis for the upstream fuel assessment, the operational profile documents the assumed annual activity of the case vessel, and the econometric results support the demand-forecasting component. The appendix should therefore be read in conjunction with the system boundary, equations, scenario definitions, and principal findings reported in Chapter 5.

APPENDIX B

Supplementary Material for the Busan Port-LCA Case Study

B.1 Purpose and Scope of the Appendix

This appendix presents supplementary material for Chapter 6, which utilizes the Port-LCA framework in the context of the Port of Busan. The primary chapter outlines the methodological framework, case-study assumptions, equations, key figures, and main findings. The appendix aims to present supplementary data, diagnostic outputs, and comprehensive numerical projection tables that enhance the transparency and reproducibility of the case study.

The appendix does not reiterate the primary equations outlined in Chapter 6. It does not replicate the tables incorporated into the main chapter, including vessel characteristics, cleaned AIS trajectory summary, AIS cleaning procedure, methanol and ammonia fuel-consumption assumptions, GDP–TEU statistical comparison, vessel-demand assumptions, mean WTW emission intensities, and validation-constraint table. Instead, this appendix contains supplementary material that aids in verification and detailed interpretation, though it is not critical to the primary narrative of Chapter 6.

The appendix is divided into three sections. Section B.2 presents additional information regarding AIS data fields. Section B.3 provides the econometric diagnostic figure along with the historical and forecasted GDP input data utilized for the demand scenarios. Section B.4 provides comprehensive annual projections of WTW port-boundary emissions,

categorized by fuel pathways, macroeconomic scenarios, and vessel residence-time assumptions.

B.2 Supplementary AIS Data Fields

Chapter 6 provided a summary of the AIS data source, the cleaning procedures, the trajectory reconstruction process, and the definition of port boundaries utilized in the Busan case study. The primary chapter encompassed the cleaned trajectory summary along with the AIS cleaning and sampling-gap treatment, as these elements are directly pertinent to the interpretation of the Port-LCA results. This appendix includes a supplementary table detailing the AIS fields utilized in the calculations.

Appendix Table 6A.1 enumerates the AIS data fields utilized in the Port-LCA calculations and elucidates the role of each field in facilitating the modelling workflow. The timestamp field facilitates the calculation of elapsed time between consecutive vessel positions. The latitude and longitude fields are employed for spatial calculations. The derived elapsed-time and coordinate fields enable calculations related to distance, speed, fuel consumption, and emissions. The normalized time field serves exclusively for graphical comparisons of vessel profiles and is not utilized in quantitative emissions calculations.

Table B.1. AIS data fields used in the Port-LCA calculations.

Field	Description	Use in the Port-LCA framework
Date / Time	Timestamp of each AIS/GPS position record	Used to calculate elapsed time between consecutive points
AP_LAT	Original latitude coordinate in AIS/GPS format	Converted into decimal degrees before spatial calculations
AP_LONG	Original longitude coordinate in AIS/GPS format	Converted into decimal degrees before spatial calculations
Latitude (Deg)	Latitude converted into decimal degrees	Used for distance, speed, and trajectory calculations
Longitude (Deg)	Longitude converted into decimal degrees	Used for distance, speed, and trajectory calculations
Elapsed time	Time difference between consecutive AIS/GPS points	Used in speed, fuel-consumption, and emissions calculations
Normalized time (%)	Relative time scale from 0% to 100%	Used only for comparing vessel emission profiles graphically

B.3 Econometric Diagnostics and GDP Forecast Input Data

Chapter 6 utilized South Korea's real GDP as the macroeconomic driver for future scenarios of container throughput in Busan. The primary chapter detailed the relationship between GDP and TEU, including the regression equations, first-difference robustness check, and a statistical comparison table. This appendix presents the diagnostic figure and the comprehensive historical and forecasted GDP input data utilized in the scenario-development process.

Figure B.1 displays the residuals from the log-level real GDP–TEU regression for the Port of Busan during the period 2011–2024. This figure demonstrates the transparency of the econometric specification by illustrating the behavior of the residuals throughout the

historical sample. It is in the appendix instead of the main chapter due to its nature as a diagnostic output, whereas the main chapter emphasizes equations, statistical comparisons, and scenario implications.

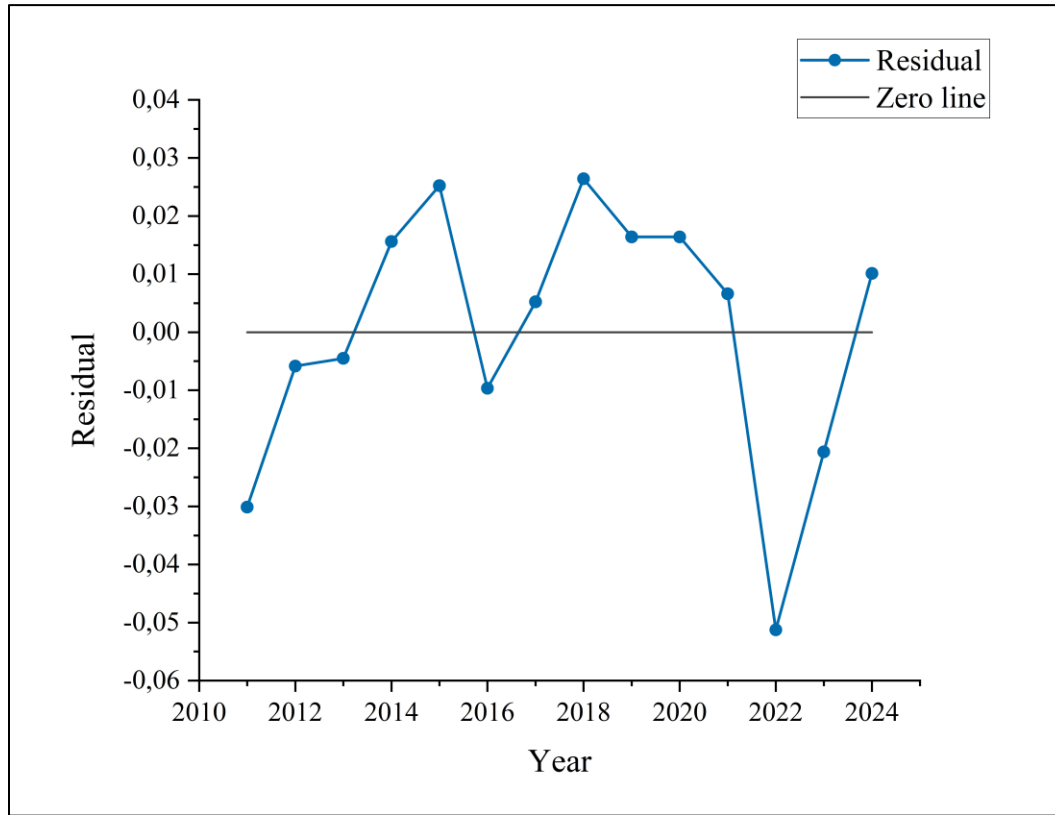


Figure B-1. Residuals of the log-level real-GDP–TEU regression for the Port of Busan, 2011–2024.

Table B.2 provides the historical South Korean real-GDP data and the Holt–Winters forecast trajectories used in the Busan demand scenarios. The table includes the historical GDP series, the central forecast, and the lower-confidence and upper-confidence bounds. These trajectories form the macroeconomic basis for estimating future Busan container throughput and capacity-equivalent vessel demand.

Table B.2. Historical and forecasted South Korean real-GDP data used in the Holt–Winters demand scenarios.

Year	GDP (constant LCU)	Forecast (GDP (constant LCU))	Lower Confidence Bound (GDP (constant LCU))	Upper Confidence Bound (GDP (constant LCU))
2000	1.04E+15	-	-	-
2001	1.12E+15	-	-	-
2002	1.16E+15	-	-	-
2003	1.22E+15	-	-	-
2004	1.27E+15	-	-	-
2005	1.34E+15	-	-	-
2006	1.41E+15	-	-	-
2007	1.46E+15	-	-	-
2008	1.47E+15	-	-	-
2009	1.57E+15	-	-	-
2010	1.63E+15	-	-	-
2011	1.67E+15	-	-	-

2012	1.73E+15	-	-	-
2013	1.78E+15	-	-	-
2014	1.84E+15	-	-	-
2015	1.89E+15	-	-	-
2016	1.89E+15	-	-	-
2017	1.96E+15	-	-	-
2018	2.02E+15	-	-	-
2019	2.07E+15	-	-	-
2020	2.05E+15	-	-	-
2021	2.15E+15	-	-	-
2022	2.21E+15	-	-	-
2023	2.24E+15	-	-	-
2024	2.29E+15	-	-	-
2025	2.31E+15	2.31E+15	2.31E+15	2.31E+15
2026	-	2.38E+15	2.34E+15	2.42E+15

2027	-	2.42E+15	2.38E+15	2.47E+15
2028	-	2.46E+15	2.42E+15	2.51E+15
2029	-	2.50E+15	2.46E+15	2.55E+15
2030	-	2,54E+15	2.49E+15	2.60E+15
2031	-	2.58E+15	2.53E+15	2.65E+15
2032	-	2.62E+15	2.56E+15	2.70E+15
2033	-	2.67E+15	2.59E+15	2.75E+15
2034	-	2.71E+15	2.62E+15	2.80E+15
2035	-	2.75E+15	2.65E+15	2.86E+15
2036	-	2.79E+15	2.67E+15	2,91E+15
2037	-	2.83E+15	2.70E+15	2.97E+15
2038	-	2.87E+15	2.73E+15	3.02E+15
2039	-	2.91E+15	2.75E+15	3.08E+15
2040	-	2.95E+15	2.78E+15	3.14E+15
2041	-	2.99E+15	2.80E+15	3.19E+15

2042	-	3.03E+15	2.83E+15	3.25E+15
2043	-	3.08E+15	2.85E+15	3.31E+15
2044	-	3.12E+15	2.87E+15	3.37E+15
2045	-	3.16E+15	2.89E+15	3.43E+15
2046	-	3.20E+15	2.91E+15	3.49E+15
2047	-	3.24E+15	2.94E+15	3.55E+15
2048	-	3.28E+15	2.96E+15	3.61E+15
2049	-	3.32E+15	2.98E+15	3.68E+15
2050	-	3.36E+15	3.00E+15	3.74E+15

B.4 Detailed Port-Boundary WTW Emissions Projection Tables

Chapter 6 presents the primary results both graphically and analytically, emphasizing the comparison of fuel pathways, long-term port-boundary emissions, macroeconomic uncertainty, and sensitivity analysis. The annual numerical projections are presented in this appendix to prevent excessive detail in the main results section.

The tables in this section present projected annual WTW CO₂-eq emissions within the Busan port boundary for the years 2030 to 2050. The results are categorized according to fuel pathway, macroeconomic scenario, and vessel residence-time assumption. The residence-time scenarios are labeled as (t1) to (t7), representing durations of 6, 12, 18, 24, 30, 36, and 42 hours per vessel within the port boundary. These tables present the numerical foundation for the long-term emissions trends analyzed in Section 6.9.

Table B.3. Forecasted annual CO₂-eq emissions within the port boundary under the MDO scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	6.80E+04	1.36E+05	2.04E+05	2.72E+05	3.40E+05	4.08E+05	6.04E+05	tons CO ₂ -eq/year
2035	7.40E+04	1.48E+05	2.22E+05	2.96E+05	3.70E+05	4.44E+05	5.18E+05	tons CO ₂ -eq/year
2040	8.01E+04	1.60E+05	2.40E+05	3.20E+05	4.01E+05	4.81E+05	5.61E+05	tons CO ₂ -eq/year
2045	8.62E+04	1.72E+05	2.59E+05	3.45E+05	4.31E+05	5.17E+05	6.04E+05	tons CO ₂ -eq/year
2050	9.24E+04	1.85E+05	2.77E+05	3.70E+05	4.62E+05	5.54E+05	6.47E+05	tons CO ₂ -eq/year

Table B.4. Forecasted annual CO₂-eq emissions within the port boundary under the methanol from natural gas scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	7.64E+04	1.53E+05	2.29E+05	3.06E+05	3.82E+05	4.58E+05	5.35E+05	tons CO ₂ -eq/year
2035	8.31E+04	1.66E+05	2.49E+05	3.33E+05	4.16E+05	4.99E+05	5.82E+05	tons CO ₂ -eq/year
2040	9.00E+04	1.80E+05	2.70E+05	3.60E+05	4.50E+05	5.40E+05	6.30E+05	tons CO ₂ -eq/year
2045	9.68E+04	1.94E+05	2.90E+05	3.87E+05	4.84E+05	5.81E+05	6.78E+05	tons CO ₂ -eq/year
2050	1.04E+05	2.07E+05	3.11E+05	4.15E+05	5.19E+05	6.22E+05	7.26E+05	tons CO ₂ -eq/year

Table B.5. Forecasted annual CO₂-eq emissions within the port boundary under the e-methanol scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	6.10E+04	1.22E+05	1.83E+05	2.44E+05	3.05E+05	3.66E+05	4.27E+05	tons CO ₂ -eq/year
2035	6.64E+04	1.33E+05	1.99E+05	2.65E+05	3.32E+05	3.98E+05	4.64E+05	tons CO ₂ -eq/year
2040	7.18E+04	1.44E+05	2.15E+05	2.87E+05	3.59E+05	4.31E+05	5.03E+05	tons CO ₂ -eq/year
2045	7.73E+04	1.55E+05	2.32E+05	3.09E+05	3.86E+05	4.64E+05	5.41E+05	tons CO ₂ -eq/year
2050	8.28E+04	1.66E+05	2.48E+05	3.31E+05	4.14E+05	4.97E+05	5.80E+05	tons CO ₂ -eq/year

Table B.6. Forecasted annual CO₂-eq emissions within the port boundary under the ammonia from natural gas scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	8.66E+04	1.73E+05	2.60E+05	3.47E+05	4.33E+05	5.20E+05	6.07E+05	tons CO ₂ -eq/year
2035	9.43E+04	1.89E+05	2.83E+05	3.77E+05	4.72E+05	5.66E+05	6.60E+05	tons CO ₂ -eq/year
2040	1.02E+05	2.04E+05	3.06E+05	4.08E+05	5.10E+05	6.12E+05	7.14E+05	tons CO ₂ -eq/year
2045	1.10E+05	2.20E+05	3.30E+05	4.39E+05	5.49E+05	6.59E+05	7.69E+05	tons CO ₂ -eq/year
2050	1.18E+05	2.35E+05	3.53E+05	4.71E+05	5.88E+05	7.06E+05	8.24E+05	tons CO ₂ -eq/year

Table B.7. Forecasted annual CO₂-eq emissions within the port boundary under the e-ammonia scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	1.46E+04	2.92E+04	4.37E+04	5.83E+04	7.29E+04	8.75E+04	1.02E+05	tons CO ₂ -eq/year
2035	1.59E+04	3.17E+04	4.76E+04	6.35E+04	7.93E+04	9.52E+04	1.11E+05	tons CO ₂ -eq/year
2040	1.72E+04	3.43E+04	5.15E+04	6.87E+04	8.58E+04	1.03E+05	1.20E+05	tons CO ₂ -eq/year
2045	1.85E+04	3.70E+04	5.54E+04	7.39E+04	9.24E+04	1.11E+05	1.29E+05	tons CO ₂ -eq/year
2050	1.98E+04	3.96E+04	5.94E+04	7.92E+04	9.90E+04	1.19E+05	1.39E+05	tons CO ₂ -eq/year

Table B.8. Lower confidence bound of forecasted annual CO₂-eq emissions within the port boundary under the MDO scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	6.64E+04	1.33E+05	1.99E+05	2.66E+05	3.32E+05	3.99E+05	4.65E+05	tons CO ₂ -eq/year
2035	7.09E+04	1.42E+05	2.13E+05	2.84E+05	3.55E+05	4.26E+05	4.97E+05	tons CO ₂ -eq/year
2040	7.48E+04	1.50E+05	2.24E+05	2.99E+05	3.74E+05	4.49E+05	5.24E+05	tons CO ₂ -eq/year
2045	7.82E+04	1.56E+05	2.35E+05	3.13E+05	3.91E+05	4.69E+05	5.47E+05	tons CO ₂ -eq/year
2050	8.13E+04	1.63E+05	2.44E+05	3.25E+05	4.06E+05	4.88E+05	5.69E+05	tons CO ₂ -eq/year

Table B.9. Lower confidence bound of forecasted annual CO₂-eq emissions within the port boundary under the methanol from natural gas scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	7.46E+04	1.49E+05	2.24E+05	2.98E+05	3.73E+05	4.48E+05	5.22E+05	tons CO ₂ -eq/year
2035	7.97E+04	1.59E+05	2.39E+05	3.19E+05	3.98E+05	4.78E+05	5.58E+05	tons CO ₂ -eq/year
2040	8.40E+04	1.68E+05	2.52E+05	3.36E+05	4.20E+05	5.04E+05	5.88E+05	tons CO ₂ -eq/year
2045	8.78E+04	1.76E+05	2.63E+05	3.51E+05	4.39E+05	5.27E+05	6.15E+05	tons CO ₂ -eq/year
2050	9.13E+04	1.83E+05	2.74E+05	3.65E+05	4.56E+05	5.48E+05	6.39E+05	tons CO ₂ -eq/year

Table B.10. Lower confidence bound of forecasted annual CO₂-eq emissions within the port boundary under the e-methanol scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	5.95E+04	1.19E+05	1.79E+05	2.38E+05	2.98E+05	3.57E+05	4.17E+05	tons CO ₂ -eq/year
2035	6.36E+04	1.27E+05	1.91E+05	2.54E+05	3.18E+05	3.81E+05	4.45E+05	tons CO ₂ -eq/year
2040	6.70E+04	1.34E+05	2.01E+05	2.68E+05	3.35E+05	4.02E+05	4.69E+05	tons CO ₂ -eq/year
2045	7.01E+04	1.40E+05	2.10E+05	2.80E+05	3.50E+05	4.21E+05	4.91E+05	tons CO ₂ -eq/year
2050	7.28E+04	1.46E+05	2.18E+05	2.91E+05	3.64E+05	4.37E+05	5.10E+05	tons CO ₂ -eq/year

Table B.11. Lower confidence bound of forecasted annual CO₂-eq emissions within the port boundary under the ammonia from natural gas scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	8.46E+04	1.69E+05	2.54E+05	3.39E+05	4.23E+05	5.08E+05	5.92E+05	tons CO ₂ -eq/year
2035	9.04E+04	1.81E+05	2.71E+05	3.62E+05	4.52E+05	5.42E+05	6.33E+05	tons CO ₂ -eq/year
2040	9.53E+04	1.91E+05	2.86E+05	3.81E+05	4.76E+05	5.72E+05	6.67E+05	tons CO ₂ -eq/year
2045	9.96E+04	1.99E+05	2.99E+05	3.99E+05	4.98E+05	5.98E+05	6.97E+05	tons CO ₂ -eq/year
2050	1.04E+05	2.07E+05	3.11E+05	4.14E+05	5.18E+05	6.21E+05	7.25E+05	tons CO ₂ -eq/year

Table B.12. Lower confidence bound of forecasted annual CO₂-eq emissions within the port boundary under the e-ammonia scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	1.42E+04	2.85E+04	4.27E+04	5.69E+04	7.12E+04	8.54E+04	9.97E+04	tons CO ₂ -eq/year
2035	1.52E+04	3.04E+04	4.56E+04	6.08E+04	7.60E+04	9.12E+04	1.06E+05	tons CO ₂ -eq/year
2040	1.60E+04	3.21E+04	4.81E+04	6.41E+04	8.01E+04	9.62E+04	1.12E+05	tons CO ₂ -eq/year
2045	1.68E+04	3.35E+04	5.03E+04	6.70E+04	8.38E+04	1.01E+05	1.17E+05	tons CO ₂ -eq/year
2050	1.74E+04	3.48E+04	5.22E+04	6.97E+04	8.71E+04	1.04E+05	1.22E+05	tons CO ₂ -eq/year

Table B.13. Upper confidence bound of forecasted annual CO₂-eq emissions within the port boundary under the MDO scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	6.96E+04	1.39E+05	2.09E+05	2.78E+05	3.48E+05	4.18E+05	4.87E+05	tons CO ₂ -eq/year
2035	7.72E+04	1.54E+05	2.31E+05	3.09E+05	3.86E+05	4.63E+05	5.40E+05	tons CO ₂ -eq/year
2040	8.55E+04	1.71E+05	2.56E+05	3.42E+05	4.27E+05	5.13E+05	5.98E+05	tons CO ₂ -eq/year
2045	9.43E+04	1.89E+05	2.83E+05	3.77E+05	4.72E+05	5.66E+05	6.60E+05	tons CO ₂ -eq/year
2050	1.04E+05	2.07E+05	3.11E+05	4.14E+05	5.18E+05	6.22E+05	7.25E+05	tons CO ₂ -eq/year

Table B.14. Upper confidence bound of forecasted annual CO₂-eq emissions within the port boundary under the methanol from natural gas scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	7.82E+04	1.56E+05	2.34E+05	3.13E+05	3.91E+05	4.69E+05	5.47E+05	tons CO ₂ -eq/year
2035	8.66E+04	1.73E+05	2.60E+05	3.47E+05	4.33E+05	5.20E+05	6.06E+05	tons CO ₂ -eq/year
2040	9.60E+04	1.92E+05	2.88E+05	3.84E+05	4.80E+05	5.76E+05	6.72E+05	tons CO ₂ -eq/year
2045	1.06E+05	2.12E+05	3.18E+05	4.24E+05	5.30E+05	6.35E+05	7.41E+05	tons CO ₂ -eq/year
2050	1.16E+05	2.33E+05	3.49E+05	4.65E+05	5.82E+05	6.98E+05	8.15E+05	tons CO ₂ -eq/year

Table B.15. Upper confidence bound of forecasted annual CO₂-eq emissions within the port boundary under the e-methanol scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	6.24E+04	1.25E+05	1.87E+05	2.49E+05	3.12E+05	3.74E+05	4.37E+05	tons CO ₂ -eq/year
2035	6.91E+04	1.38E+05	2.07E+05	2.77E+05	3.46E+05	4.15E+05	4.84E+05	tons CO ₂ -eq/year
2040	7.66E+04	1.53E+05	2.30E+05	3.06E+05	3.83E+05	4.60E+05	5.36E+05	tons CO ₂ -eq/year
2045	8.45E+04	1.69E+05	2.54E+05	3.38E+05	4.23E+05	5.07E+05	5.92E+05	tons CO ₂ -eq/year
2050	9.29E+04	1.86E+05	2.79E+05	3.71E+05	4.64E+05	5.57E+05	6.50E+05	tons CO ₂ -eq/year

Table B.16. Upper confidence bound of forecasted annual CO₂-eq emissions within the port boundary under the ammonia from natural gas scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	8.87E+04	1.77E+05	2.66E+05	3.55E+05	4.43E+05	5.32E+05	6.21E+05	tons CO ₂ -eq/year
2035	9.83E+04	1.97E+05	2.95E+05	3.93E+05	4.91E+05	5.90E+05	6.88E+05	tons CO ₂ -eq/year
2040	1.09E+05	2.18E+05	3.27E+05	4.36E+05	5.44E+05	6.53E+05	7.62E+05	tons CO ₂ -eq/year
2045	1.20E+05	2.40E+05	3.60E+05	4.81E+05	6.01E+05	7.21E+05	8.41E+05	tons CO ₂ -eq/year
2050	1.32E+05	2.64E+05	3.96E+05	5.28E+05	6.60E+05	7.92E+05	9.24E+05	tons CO ₂ -eq/year

Table B.17. Upper confidence bound of forecasted annual CO₂-eq emissions within the port boundary under the e-ammonia scenario as a function of annual vessel residence time inside the port boundary (t1–t7), where t1–t7 correspond to 6–42 hours per vessel.

Year	t1 (6 h)	t2 (12 h)	t3 (18 h)	t4 (24 h)	t5 (30 h)	t6 (36 h)	t7 (42 h)	Unit
2030	1.49E+04	2.98E+04	4.47E+04	5.97E+04	7.46E+04	8.95E+04	1.04E+05	tons CO ₂ -eq/year
2035	1.65E+04	3.31E+04	4.96E+04	6.61E+04	8.27E+04	9.92E+04	1.16E+05	tons CO ₂ -eq/year
2040	1.83E+04	3.66E+04	5.49E+04	7.33E+04	9.16E+04	1.10E+05	1.28E+05	tons CO ₂ -eq/year
2045	2.02E+04	4.04E+04	6.06E+04	8.08E+04	1.01E+05	1.21E+05	1.41E+05	tons CO ₂ -eq/year
2050	2.22E+04	4.44E+04	6.66E+04	8.88E+04	1.11E+05	1.33E+05	1.55E+05	tons CO ₂ -eq/year

B.5 Graphical Aids Supporting the Port-LCA Methodology

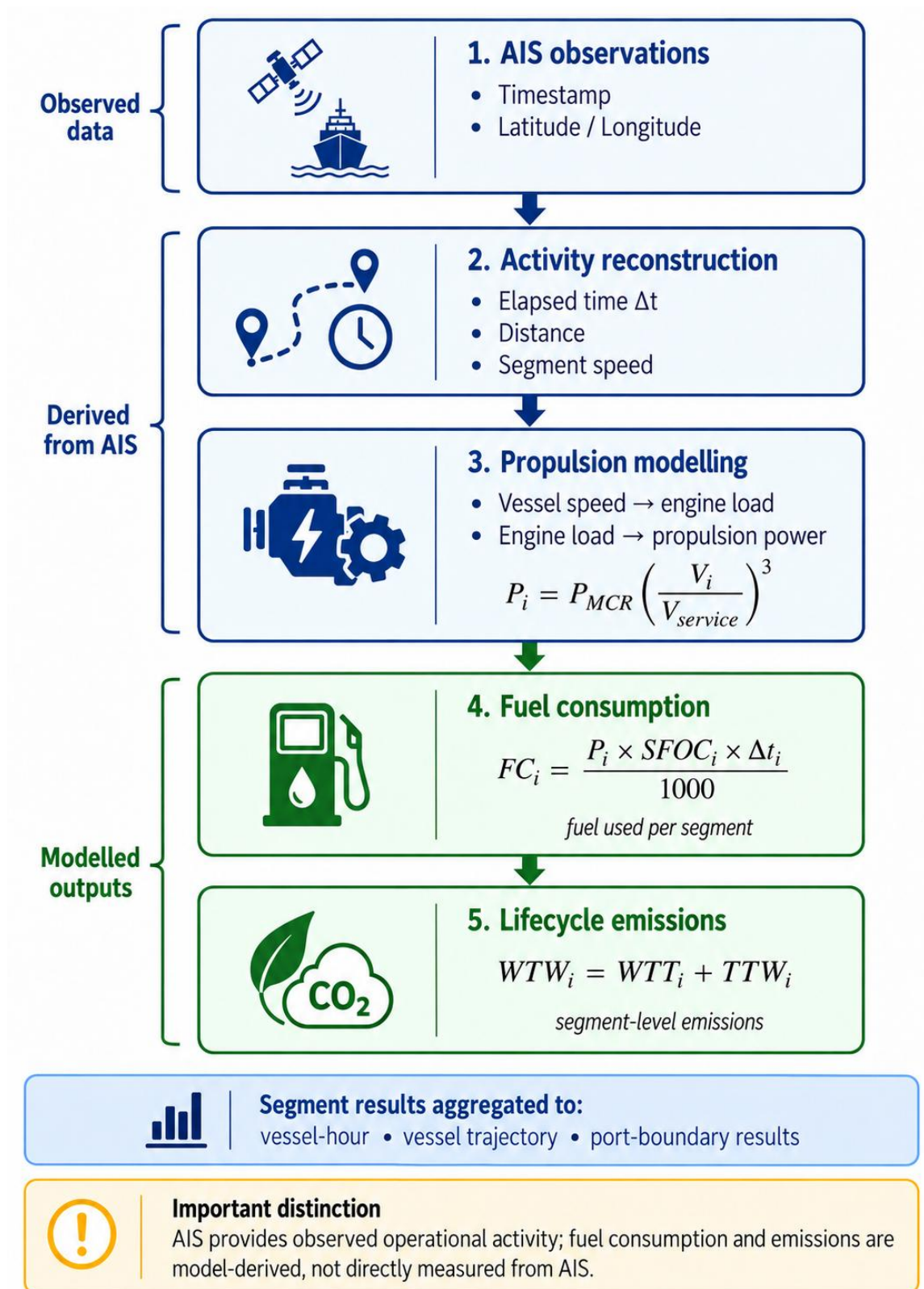
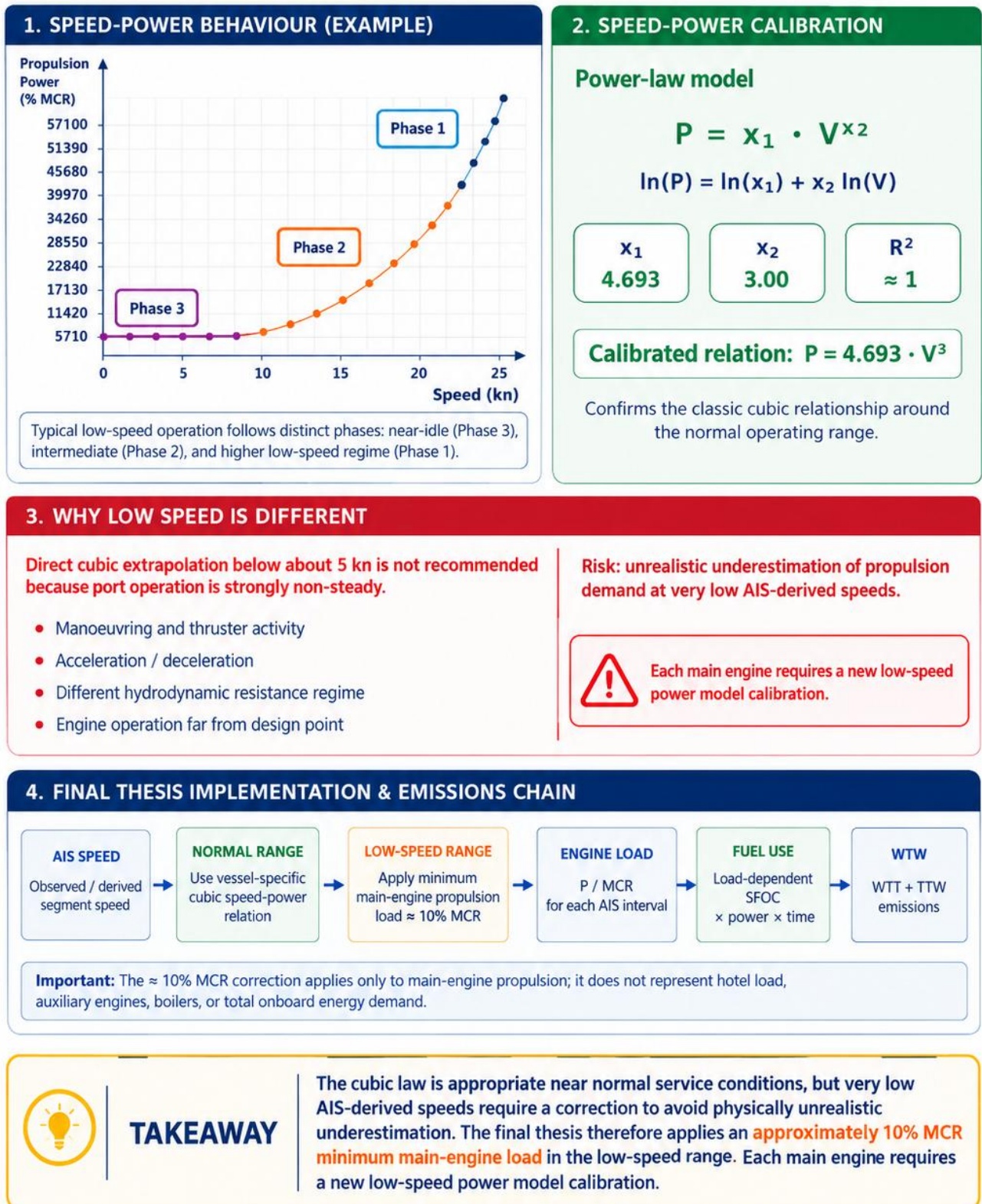


Figure B-2. Graphical representation of the AIS-to-WTW calculation chain.



Supporting note: explored a 7,000 kW floor below 5 kn; final thesis implementation uses $\approx 10\%$ MCR.

Figure B-3. Graphical explanation of the low-speed propulsion-power treatment applied in the Port-LCA model.

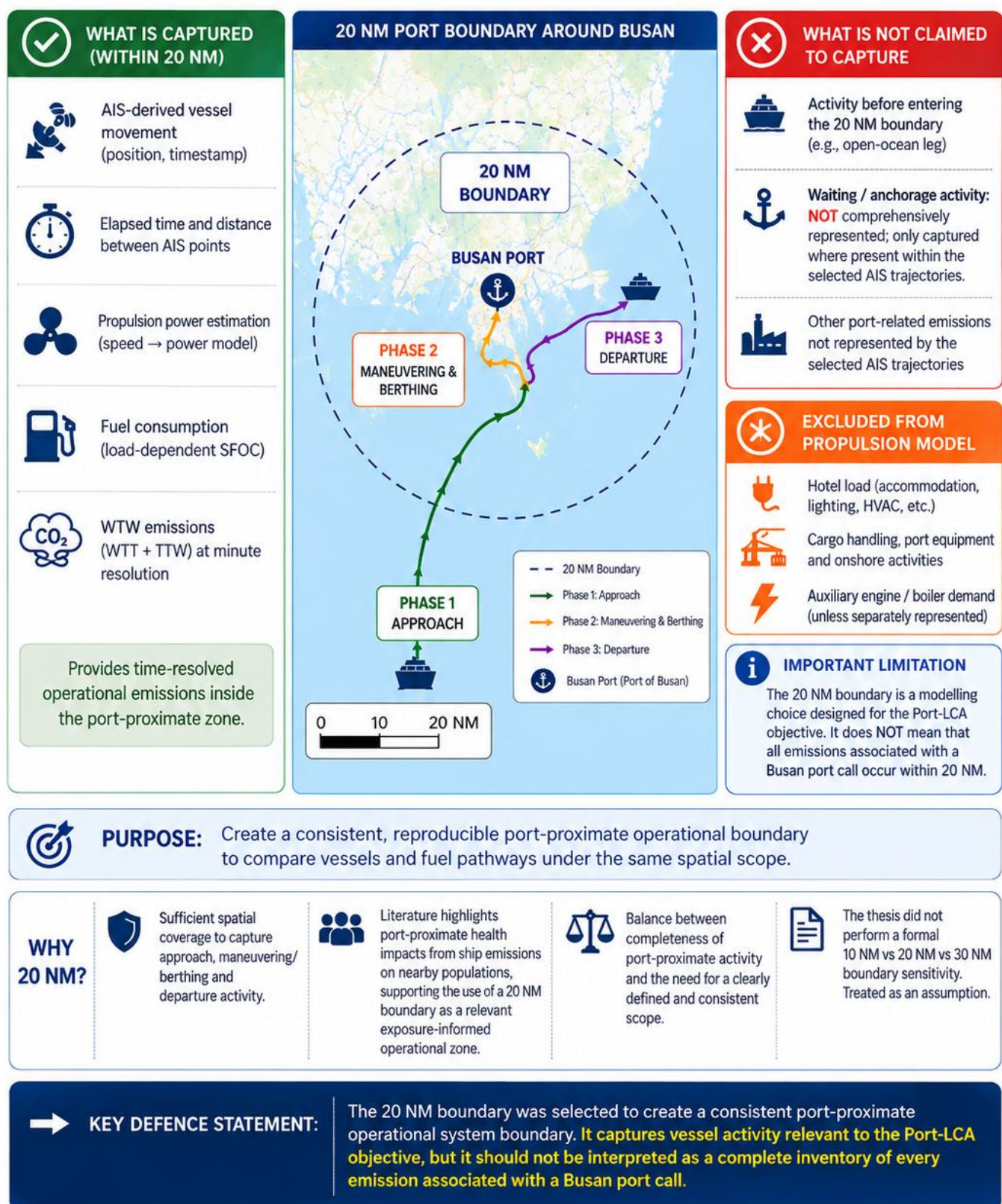


Figure B-4. Graphical representation of the 20 NM operational boundary adopted for the Busan Port-LCA case study.

B.6 Role of the Appendix in Supporting Chapter 6

The supporting material in this appendix enhances the transparency of the Busan Port-LCA case study. The AIS data-field table elucidates the application of both raw and derived AIS variables within the modeling workflow. The regression residual figure and GDP forecast table substantiate the demand-forecasting component of the case study. The emissions projection tables offer the numerical foundation for the graphical and analytical findings discussed in Section 6.9.

This appendix serves as supplementary evidence for the main chapter. The primary chapter outlines the methodological rationale, key calculations, and interpretation of findings, whereas the appendix offers supplementary diagnostic and numerical information to ensure reproducibility.

APPENDIX C

LITERATURE CRITICAL REVIEW MATRIX

C.1 Purpose and Scope of Appendix C

This appendix presents the structured critical review matrix used to support the literature review and the thesis' methodological positioning. The matrix documents the objective, methodological framework, key findings, contributions, innovations, limitations, publication source, and year of each reviewed item. It thus offers a clear account of the assessment process of the literature, extending beyond a mere descriptive summary of individual publications.

The review includes 71 sources published from 2006 to 2026, sourced from 28 journals and other reputable publications. To maintain readability in an A4 thesis format, the original ten-column spreadsheet matrix is displayed in two interconnected tables. Source numbers are consistently retained across both tables, facilitating examination of each source's methodological characteristics alongside its critical appraisal.

C.2 Overview of the Literature Corpus

Tables C.1 and C.2 summarize the temporal and publication-source composition of the reviewed literature. The distribution demonstrates that the evidence base is weighted towards recent research, while also retaining foundational methodological standards and earlier studies that established key applications of LCA.

Table C.1. Distribution of reviewed sources by publication period.

Publication period	Number of sources	Percentage of total
2020–2026	52	73.24%
2015–2019	11	15.49%
2010–2014	6	8.45%
Before 2010	2	2.82%
Total	71	100%

Table C.2. Distribution of reviewed sources by journal or publication source.

No.	Journal or source	Number of sources
1	Journal of Cleaner Production	13
2	Ocean Engineering	8
3	Science of the Total Environment	8
4	Results in Engineering	5
5	The International Journal of Life Cycle Assessment	5
6	Energies	3
7	Environmental Science & Technology	3
8	Transportation Research Part D	3
9	Applied Energy	2
10	British Standard / ISO Standard	2
11	Energy Conversion and Management	2
12	Advances in Climate Change Research	1
13	Chemical Engineering Journal	1
14	Cleaner Environmental Systems	1
15	Energy Conversion and Management: X	1
16	Environmental Impact Assessment Review	1
17	Fuel	1
18	Green Carbon	1
19	Journal of Industrial Ecology	1
20	Journal of International Maritime Safety, Environmental Affairs, and Shipping	1
21	Journal of Marine Engineering & Technology	1
22	Journal of Marine Science and Engineering	1
23	Procedia Manufacturing	1
24	Renewable and Sustainable Energy Reviews	1
25	Research in Engineering Design	1
26	Springer / Edited Book	1
27	Sustainability	1
28	Sustainable Production and Consumption	1
	Total	71

C.3 Literature Critical Review Matrix

The complete review matrix is divided into two complementary tables. Table C.3 records the scope and methods of each source, while Table C.4 presents its findings and critical appraisal. The numbering in the first column corresponds across both tables.

C.3.1 Study Scope and Methodological Characteristics

Table C.3. Study scope, methodological approach, and bibliographic details of the reviewed literature.

No.	Title	Aim	Methods	Journal or source	Year
1	LCA data quality: A management science perspective	To investigate the adequacy of current LCA data-quality assessment approaches from a management science perspective, focusing on the role of companies in the LCA data collection process.	Applied the ecoinvent Data Quality System to a primary LCA data collection project; used organizational immersion, participant observation, interviews, and management science theory.	Journal of Cleaner Production	2017
2	Life cycle comparison of marine fuels for IMO 2020 Sulphur Cap	To assess the life cycle environmental effects of marine fuels used in response to the IMO 2020 Sulphur Cap and examine whether low-Sulphur fuels deliver improved overall environmental performance.	Conducted LCA of four marine fuels, including HFO, LFO, VLSFO, and ULSFO, considering production, distribution, and operation processes across multiple environmental impact indicators.	Science of the Total Environment	2021
3	Life Cycle Assessment as a complementary utility to regulatory measures of shipping energy efficiency	To demonstrate that LCA can complement IMO energy-efficiency metrics such as EEDI and EEOI by providing broader environmental and lifecycle information for ships.	Summarized an LCA model formulation and applied it to a case study vessel; compared LCA-based environmental performance outputs with regulatory metrics such as EEDI and EEOI.	Ocean Engineering	2016
4	LCA as a tool to aid in the selection of retrofitting alternatives	To demonstrate the usefulness of LCA as a decision-support tool for selecting ship retrofitting alternatives, using ballast water treatment systems as the application case.	Compared three ballast water treatment technologies using a theoretical case vessel; applied ISO 14040 and ISO 14044 principles, GaBi-based LCA modelling, environmental impact assessment, and cost-benefit analysis.	Ocean Engineering	2014

No.	Title	Aim	Methods	Journal or source	Year
5	Life cycle assessment comparing electric and petrol-powered rigid inflatable boats for recreational and harbour-master applications	To conduct a cradle-to-grave comparative LCA of electric and petrol-powered rigid inflatable boats under recreational and harbor-master usage scenarios.	Used ISO-compliant process-based LCA in SimaPro; assessed production, operation, and end-of-life stages over a 20-year lifetime; analyzed ten environmental impact categories, two usage scenarios, electricity-grid sensitivity, and break-even operation.	Ocean Engineering	2025
6	Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol	To compare the life cycle environmental performance of LNG, LBG, methanol, and bio-methanol as alternative marine fuels.	Applied LCA to assess raw material acquisition, fuel production, distribution, storage, and combustion for a ro-ro vessel, using 1 ton-km of cargo transport as the functional unit.	Journal of Cleaner Production	2014
7	Energy-related GHG emissions balances: IPCC versus LCA	To compare IPCC and LCA approaches for estimating the GHG emissions balance of a small municipality and assessing how methodological choice affects climate strategy evaluation.	Estimated a local GHG balance using IPCC emission factors, LCA emission factors from ELCD, and site-specific LCA electricity emission factors; assessed renewable energy strategies for emission reduction.	Science of the Total Environment	2018
8	Strategic forecasting of GHG intensity: Econometrically enhanced LCA for the Singapore–Rotterdam containership green corridor	To assess and forecast the GHG intensity and regulatory cost implications of MDO, bio-methanol, and e-methanol for an 8000 TEU containership operating on the Singapore–Rotterdam Green Corridor until 2050.	Integrated LCA with the Holt–Winters additive forecasting method, econometric parameters, GDP, population, TEU demand, Pearson correlation, regression analysis, FuelEU Maritime, and EU ETS penalty calculations.	Results in Engineering	2025
9	Application of parametric trend life cycle assessment for investigating the carbon footprint of ammonia as marine fuel	To determine whether ammonia can reduce the carbon footprint of maritime activities from a WTW perspective.	Applied Parametric Trend LCA using data from over 2061 bulk carriers, eight ammonia production pathways, regression analysis, and an ME-LGI engine assumption.	The International Journal of Life Cycle Assessment	2022
10	Coordinated reduction of CO ₂ emissions and environmental impacts with integrated city-level LEAP and LCA method: A case study of Jinan, China	To evaluate the energy demand, CO ₂ reduction, and environmental co-benefits of urban decarbonization policies in Jinan, China, from 2016 to 2050.	Developed an integrated city-level LEAP–LCA framework; assessed low-carbon, pollution-control, and deep CO ₂ reduction scenarios using CML2001 and ReCiPe2008 impact assessment methods.	Advances in Climate Change Research	2021

No.	Title	Aim	Methods	Journal or source	Year
11	A systematic review of real-time data monitoring and its potential application to support dynamic life cycle inventories	To review how real-time data monitoring has been used in LCA studies and assess its potential to support dynamic life cycle inventories.	Conducted a systematic literature review following PRISMA-based screening; selected 34 peer-reviewed studies addressing real-time data, sensors, IoT, and dynamic LCI development.	Environmental Impact Assessment Review	2024
12	Consequential life cycle assessment: a review	To review the development of consequential LCA and its integration with economic modelling approaches.	Conducted a systematic literature review of CLCA studies, focusing on attributional versus consequential LCA, affected technologies, partial equilibrium models, computable general equilibrium models, rebound effects, and experience curves.	The International Journal of Life Cycle Assessment	2011
13	Life Cycle Assessment of Greenhouse Gas Emissions from Marine Fuels: A Case Study of Saudi Crude Oil versus Natural Gas in Different Global Regions	To compare the life cycle GHG emissions of HFO and MGO produced from Saudi crude oil with LNG in different global regions.	Applied LCA using a functional unit of 1 kWh delivered to the ship propeller; used bottom-up engineering models for oil and gas systems, regional supply-chain modelling, methane loss assessment, and 20-year/100-year GWP sensitivity analysis.	Journal of Industrial Ecology	2019
14	Life Cycle Assessment: Past, Present, and Future	To review the historical development of LCA and discuss its evolution towards Life Cycle Sustainability Analysis.	Narrative and conceptual review of LCA development from early energy analysis to ISO-standardized LCA, consequential LCA, social LCA, life cycle costing, and LCSA.	Environmental Science & Technology	2011
15	Life-cycle assessment and life-cycle cost assessment of lithium-ion batteries for passenger ferry	To assess the environmental and economic performance of different lithium-ion battery types compared with marine diesel oils for a passenger ferry.	Applied LCA and LCCA to five Li-ion batteries and three MDO options using a passenger ferry in Istanbul as a case study; assessed GWP, NOx, SOx, PM, energy use, water use, carbon credit scenarios, and comprehensive rating metrics.	Transportation Research Part D	2023
16	A framework for determining the life cycle GHG emissions of fossil marine fuels in countries reliant on imported energy through maritime transportation: A case study of South Korea	To evaluate the life cycle GHG emissions of fossil marine fuels supplied to energy-import-dependent countries, using South Korea as a case study.	Developed a WTW LCA framework for HFO, LNG, LPG, and methanol, considering WTT and TtW emissions, import routes, fuel transportation distances, propulsion systems, and regional supply-chain factors.	Science of the Total Environment	2023

No.	Title	Aim	Methods	Journal or source	Year
17	Live LCA in learning factories: real time assessment of product life cycles environmental impacts	To present a concept for performing real-time product LCA in a learning factory environment.	Combined cyber-physical production infrastructure with computational LCA models, sensors, data acquisition, and visualization tools to estimate environmental impacts in real time.	Procedia Manufacturing	2020
18	Life Cycle Assessment: Theory and Practice	To provide a comprehensive textbook and practical guide covering the theory, methodology, and applications of LCA.	Presents LCA principles, ISO 14040/14044-based methodology, goal and scope definition, inventory analysis, impact assessment, interpretation, uncertainty, life cycle costing, social LCA, applications, and a practical cookbook.	Springer / Edited Book	2017
19	Potential for optimized production and use of rapeseed biodiesel. Based on a comprehensive real-time LCA case study in Denmark with multiple pathways	To assess the current environmental impacts of Danish rapeseed biodiesel and evaluate improvement options for its production and use.	Applied LCA using a functional unit of 1,000 km driven by a passenger car; included rapeseed production, carbon sequestration, N ₂ O balances, transport, transesterification pathways, system expansion, and multiple impact categories.	The International Journal of Life Cycle Assessment	2013
20	Prospective life cycle assessment of cost-effective pathways for achieving the FuelEU Maritime Regulation targets	To assess which maritime fuel pathways can meet FuelEU Maritime GHG targets while considering environmental impacts, economic costs, and externality costs.	Conducted prospective WTW LCA of e-ammonia, e-methanol, e-FT diesel, e-LNG, VLSFO, LNG, and ship-based carbon capture, using future background systems, production locations, electrolyser choices, climate-policy scenarios, and cost assessment.	Science of the Total Environment	2025
21	BS EN ISO 14040:2006 — Environmental management — Life cycle assessment — Principles and framework	To define the principles and general framework for conducting LCA studies.	Establishes the conceptual structure of LCA, including goal and scope definition, inventory analysis, impact assessment, interpretation, reporting, and critical review.	British Standard / ISO Standard	2006
22	BS EN ISO 14044:2006 — Environmental management — Life cycle assessment — Requirements and guidelines	To specify requirements and provide guidelines for conducting LCA and life cycle inventory studies.	Defines detailed requirements for goal and scope definition, LCI, LCIA, interpretation, reporting, critical review, and comparative assertions.	British Standard / ISO Standard	2006

No.	Title	Aim	Methods	Journal or source	Year
23	A systematic literature review on holistic lifecycle assessments as a basis to create a standard in maritime industry	To analyze methodological trends in holistic maritime LCA studies and support the development of future standardization in the maritime sector.	Conducted a systematic literature review and snowball search; analyzed 32 maritime LCA studies across key methodological themes such as functional unit, boundaries, databases, impact categories, uncertainty, sensitivity, temporal and spatial aspects.	The International Journal of Life Cycle Assessment	2024
24	Enhanced predictive modeling vs. LCA simulation: A comparative study on CO ₂ emissions from ship operations	To compare predictive modelling and LCA simulation for estimating CO ₂ emissions from ship operations under real operating conditions.	Developed a statistical predictive model based on actual ship operation data and telegraph modes; compared predicted CO ₂ emissions with LCA simulation results; applied ANCOVA to examine trend similarity.	Ocean Engineering	2024
25	Demystifying the lifecycle environmental benefits and harms of LNG as marine fuel	To determine whether LNG genuinely reduces lifecycle environmental impacts from shipping and to clarify the conditions under which LNG is beneficial or harmful.	Applied Parametric Trend LCA to more than 7,000 ships across multiple ship types and LNG engine scenarios; assessed WTT, TTW, and WTW impacts, including GWP, AP, and EP.	Applied Energy	2022
26	Development of Parametric Trend Life Cycle Assessment for marine SO _x reduction scrubber systems	To evaluate the lifecycle environmental impacts of different marine SO _x scrubber systems and develop a wider assessment method beyond single case studies.	Developed Parametric Trend LCA and applied it to 1,565 ocean-going Ro-Ro vessels; assessed wet open-loop, wet closed-loop, and wet hybrid scrubbers across GWP, AP, EP, SO _x , NO _x , and GHG emissions.	Journal of Cleaner Production	2020
27	Parametric trend life cycle assessment for hydrogen fuel cell towards cleaner shipping	To determine whether hydrogen fuel cells can provide a genuine green solution for shipping from a lifecycle perspective.	Applied PT-LCA to around 2,000 ships; assessed hydrogen production pathways including steam methane reforming, coal gasification, methanol cracking, and wind-based electrolysis; considered PEMFC, MCFC, and SOFC fuel cell systems.	Journal of Cleaner Production	2022
28	Evaluation of the Lifecycle Environmental Benefits of Full Battery Powered Ships: Comparative Analysis of Marine Diesel and Electricity	To evaluate the lifecycle environmental benefits of replacing diesel propulsion with full battery propulsion for a Ro-Ro passenger ship in Korean coastal service.	Combined operational data collection, PSIM battery propulsion simulation, laboratory diesel engine emission measurements, and LCA using GaBi; assessed production, transport, and use stages across GWP, AP, EP, and POCP.	Journal of Marine Science and Engineering	2020

No.	Title	Aim	Methods	Journal or source	Year
29	Decarbonization Trend in International Shipping Sector	To review current issues, strategies, and policy trends related to decarbonization in the international shipping sector.	Reviewed international and regional decarbonization initiatives, including the Clydebank Declaration, green corridors, UK and EU policies, FuelEU Maritime, Fit for 55, and LCA-related policy needs.	Journal of International Maritime Safety, Environmental Affairs, and Shipping	2021
30	An integrated assessment of the environmental, human health, and economic impacts based on life cycle assessment: A case study of the concrete and steel sumps	To compare concrete and steel sumps using an integrated assessment of environmental, human health, and economic impacts.	Applied LCA to concrete and steel sump installation scenarios; considered multiple environmental impact categories, human health impacts, construction costs, material quantities, and practical construction methods.	Journal of Cleaner Production	2020
31	An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems	To develop a practical framework that supports LCA and LCCA-based decision-making for selecting optimal marine propulsion systems.	Developed a modular LCA/LCCA framework based on ship life-cycle stages; applied it to two case studies: a short-route hybrid ferry and an offshore tug vessel propulsion configuration.	Journal of Cleaner Production	2018
32	Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping	To evaluate future fossil-free shipping solutions in terms of lifecycle environmental impacts and costs.	Applied prospective LCA and environmental life-cycle costing to eight decarbonization solutions, including e-methanol, hydrogen, ammonia, battery-electric systems, fuel cells, and onboard carbon capture, using MGO as a reference.	Environmental Science & Technology	2022
33	A real-time lifecycle analysis model with digital twin and novel control method for enhancing the environmental performance of electric/hybrid propulsion ships	To develop a real-time LCA model using digital twin technology and optimal load control for improving the environmental performance of electric and hybrid propulsion ships.	Integrated digital twin modelling, real-time operational data, fuel lifecycle inventories, and optimal load-control logic; evaluated multiple vessel types and fuel alternatives, including hydrogen, ammonia, electricity, and MDO.	Ocean Engineering	2025
34	Local added value and environmental impacts of ship scrapping in the context of a ship's life cycle	To assess how environmental impacts and local added value are distributed across a ship's life cycle, with particular attention to ship scrapping.	Combined LCA, local added value estimation, literature review, and an adjusted eco-efficiency indicator across ship production, use, and end-of-life phases.	Ocean Engineering	2016

No.	Title	Aim	Methods	Journal or source	Year
35	A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost	To compare alternative marine fuel pathways in terms of lifecycle energy demand, cost, GHG emissions, and non-GHG emissions.	Reviewed and modelled 22 fuel pathways, including HFO, LNG, hydrogen, ammonia, methanol, biofuels, solar-based fuels, electricity, and CCS options; used literature data and ASPEN HYSYS modelling.	Energies	2021
36	Comparative Life Cycle Assessments and Economic Analyses of Alternative Marine Fuels: Insights for Practical Strategies	To compare alternative marine fuel pathways from both environmental and economic perspectives and provide practical strategies for shipping stakeholders.	Conducted LCA and economic analysis for LNG, ammonia, methanol, and biofuels across nine production pathways; included lifecycle carbon pricing, ship lifecycle cost, NPV analysis, sensitivity analysis, and fuel-blending scenarios.	Sustainability	2024
37	Life cycle analysis of gasification and Fischer-Tropsch conversion of municipal solid waste for transportation fuel production	To evaluate the life cycle GHG emissions of Fischer-Tropsch fuels produced from non-recyclable municipal solid waste.	Applied LCA to MSW gasification and FT fuel production; assessed carbon intensities under different waste compositions, fossil carbon contents, landfill diversion assumptions, conversion efficiencies, and carbon capture scenarios.	Journal of Cleaner Production	2023
38	Comparative life cycle assessment of various hydrogen supply methods from Australia to the Republic of Korea in environmental and economic aspects	To compare hydrogen supply methods from Australia to South Korea from environmental and economic perspectives.	Conducted LCA and cost analysis of blue hydrogen ocean transport using different storage/carrier options, including CH ₂ , LH ₂ , LOHC, LN ₂ , and LNG, and alternative ship fuels including MGO, LNG, LPG, hydrogen, methanol, and ammonia.	Science of the Total Environment	2024
39	Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments	To address the lack of temporal information in conventional LCA and propose a dynamic LCA approach for global warming assessment.	Developed dynamic LCA by calculating time-dependent life cycle inventories and characterization factors; applied the method to greenhouse gas emissions and compared results with traditional GWP-based LCA.	Environmental Science & Technology	2010
40	Low-carbon ammonia-based fuel for maritime transport	To review the potential of low-carbon ammonia as a marine fuel and discuss its properties, applications, safety issues, standards, and implementation challenges.	Conducted a review of ammonia fuel characteristics, thermodynamic and physicochemical properties, engine applications, storage requirements, standards, safety risks, and decarbonization potential.	Results in Engineering	2025

No.	Title	Aim	Methods	Journal or source	Year
41	Reduction of maritime GHG emissions and the potential role of E-fuels	To evaluate the potential role of e-fuels in reducing maritime GHG emissions, with attention to energy use, cost, feasibility, and fuel flexibility.	Applied a WTW assessment of e-hydrogen, e-ammonia, e-diesel, e-LNG, and e-methanol; compared emissions, renewable electricity demand, energy efficiency, and cost implications.	Transportation Research Part D	2021
42	A comparative life cycle assessment of marine power systems	To compare the environmental performance of conventional, retrofit, and new-build marine power systems using LCA.	Developed component-level LCA models in GaBi; applied CML2001, ILCD, and Eco-Indicator 99 methods; assessed manufacturing, operation, dismantling, and end-of-life stages with sensitivity analysis on fuel consumption.	Energy Conversion and Management	2016
43	A hybrid model of LCA and energy for co-benefits assessment associated with waste and by-product reutilization	To develop and demonstrate a hybrid LCA–energy model for assessing the co-benefits of waste and by-product reutilization in an industrial park.	Integrated LCA into an energy analysis framework; applied the model to the Shenyang Economic Technological Development Area to assess resource reutilization and co-benefits.	Journal of Cleaner Production	2019
44	The historical evolution and research trends of life cycle assessment	To review the historical development, methodological evolution, and future research trends of LCA.	Conducted a comprehensive review of traditional LCA, attributional and consequential LCA, process-based LCA, input–output LCA, hybrid LCA, dynamic LCA, simplified LCA, and integration with other methods and emerging technologies.	Green Carbon	2024
45	Cutting-edge technologies: Biofuel innovations in marine propulsion systems to lower black carbon emissions	To review biofuel innovations for marine propulsion systems and assess their potential to reduce black carbon emissions.	Reviewed biofuel applications including HVO, biodiesel, algae-based fuels, catalytic cracking, microbial fermentation, and marine engine trials; discussed lifecycle GHG implications and operational performance.	Results in Engineering	2025
46	Sustainable retrofitting for shipping: Assessing LNG dual fuel impact on global warming potential through life cycle assessment	To assess the feasibility and environmental impact of LNG dual-fuel retrofitting for an existing training ship.	Applied LCA to a 9196 GT training ship under 20%, 30%, and 40% LNG replacement scenarios; compared GWP results using LCA database values and engine emission factors; included statistical analysis.	Results in Engineering	2024

No.	Title	Aim	Methods	Journal or source	Year
47	Combined application of life cycle assessment and neural network model for modeling energy and environmental emissions in sugar beet production	To model energy use and environmental emissions in sugar beet production across different farm sizes using LCA and artificial neural networks.	Combined field survey data from 47 farmers with LCA using CML and USEtox methods; applied ANN models to predict energy inputs and environmental impacts for small, medium, and large farms.	Results in Engineering	2024
48	A hybridised framework combining integrated methods for environmental Life Cycle Assessment and Life Cycle Costing	To develop a comprehensive framework for integrating environmental LCA and Life Cycle Costing in decision-making.	Conducted a critical literature review and developed a hybridized framework combining six LCA–LCC integration approaches, including MCDA, MOLP, eco-efficiency, hybrid LCA, and environmental LCC.	Journal of Cleaner Production	2017
49	Attributional and consequential LCAs of a novel bio-jet fuel from Dutch potato by-products	To compare attributional and consequential LCA results for a novel bio-jet fuel produced from potato by-products.	Developed both ALCA and CLCA models for 1 MJ of bio-jet fuel; assessed cradle-to-grave impacts and compared results with conventional jet fuel, considering co-product allocation, displacement, and animal-feed market effects.	Science of the Total Environment	2022
50	Decarbonizing the cement industry: Findings from coupling prospective life cycle assessment of clinker with integrated assessment model scenarios	To assess future environmental impacts of global clinker production under different decarbonization pathways.	Coupled prospective LCA with IMAGE integrated assessment model scenarios; modified ecoinvent databases using premise; assessed global clinker production from 2020 to 2060 under 3.5°C, 2°C, and 1.5°C scenarios.	Journal of Cleaner Production	2024
51	Greenhouse gas emissions of shipping with onboard carbon capture under the FuelEU Maritime regulation: A well-to-wake evaluation of different propulsion scenarios	To evaluate the well-to-wake GHG reduction potential of onboard carbon capture and storage for fossil-fueled ships under the FuelEU Maritime framework.	Defined nine propulsion scenarios combining fossil marine fuels and engine types; calculated WTW GHG intensity with and without onboard carbon capture from the main engine; compared FuelEU compliance and cost implications.	Chemical Engineering Journal	2024
52	Comparative Life Cycle Assessment of Gasification and Landfilling for Disposal of Municipal Solid Wastes	To compare the environmental and human health impacts of municipal solid waste gasification and landfilling without energy recovery.	Conducted ISO 14040-based LCA using 1 ton of MSW as a functional unit; used GREET, LandGEM, HELP, and TRACI 2.1 to assess global warming, acidification, smog, eutrophication, ecotoxicity, and human health impacts.	Energies	2021

No.	Title	Aim	Methods	Journal or source	Year
53	Live-Life cycle assessment of the electric propulsion ship using solar PV	To introduce Live-Life Cycle Assessment and assessing whether solar-electric propulsion ships can provide lifecycle environmental benefits.	Developed a simulation-based Live-LCA approach; modelled PV-electric ship performance in MATLAB/Simulink across coastal regions in 29 countries; fed generated performance data directly into LCA.	Applied Energy	2022
54	Pathways to zero-carbon shipping: Life cycle assessment of energy transition system configurations for container ships	To evaluate alternative energy system configurations for container ships under the IMO net-zero framework.	Constructed 172 configurations combining three power systems, sixteen fuels, and three auxiliary systems; assessed WTW GHG emissions, extended CII, total life cycle cost, and IMO GFS penalty cost; applied SMAA-2 with Choquet integral for MCDA.	Ocean Engineering	2026
55	A review of life cycle assessment studies of maritime fuels: Critical insights, gaps, and recommendations	To review existing LCA studies of maritime fuels and identify methodological gaps, transparency issues, and recommendations for future research.	Systematically reviewed 43 peer-reviewed maritime fuel LCA articles and 429 case studies; assessed fuel coverage, supply-chain coverage, methodological choices, reporting transparency, uncertainty analysis, and inventory completeness.	Sustainable Production and Consumption	2024
56	PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models	To introduce premise, a tool for generating prospective life cycle inventory databases for future-oriented LCA studies.	Developed an open-source Python tool that modifies ecoinvent databases using scenarios from IAMs such as REMIND and IMAGE; applied transformations to energy-intensive sectors, including electricity, cement, steel, transport, and fuel production.	Renewable and Sustainable Energy Reviews	2022
57	Maritime Transport in a Life Cycle Perspective: How Fuels, Vessel Types, and Operational Profiles Influence Energy Demand and Greenhouse Gas Emissions	To assess how marine fuel choice, vessel type, engine type, and operational profile influence lifecycle energy demand and GHG emissions.	Conducted LCA for HFO and LNG using four vessel types: container ship, tanker, Ro-Pax, and cruise vessel; considered European fuel supply chains, dual-fuel engines, methane slip, cargo-capacity effects, and realistic operational profiles.	Energies	2020

No.	Title	Aim	Methods	Journal or source	Year
58	Selection of optimum sustainable biofuel for maritime transportation using analytic hierarchy process	To identify the most suitable sustainable biofuel options for maritime transportation.	Applied the Analytic Hierarchy Process using seven criteria; included expert weighting from 15 experts and literature-based performance data for biofuel alternatives; criteria included safety, well-to-wake emissions, compatibility, and indirect land-use change.	Journal of Marine Engineering & Technology	2025
59	How can patent-based prospective life cycle assessment be used for eco-design?	To investigate how patent-based prospective LCA can actively support eco-design by identifying and evaluating future design solutions.	Developed a method that extracts eco-design solutions and prospective inventory data from patents; applied prospective LCA at the level of design features and technical parameters, following ISO 14040/14044 principles.	Research in Engineering Design	2025
60	Life cycle emission and cost assessment for LNG-retrofitted vessels: the risk and sensitivity analyses under fuel property and load variations	To assess lifecycle emissions, energy performance, and cost implications of LNG-retrofitted vessels under fuel property and engine load variations.	Combined LCA and LCCA for diesel and LNG fuel pathways; considered WTT and TTW phases, fuel property modification, load management, ship routes, RETScreen-based financial analysis, sensitivity analysis, and Monte Carlo risk assessment.	Ocean Engineering	2023
61	Toward more comprehensive environmental impact assessments: interlinked global models of LCIA and IAM applicable to this century	To develop a more comprehensive environmental impact assessment by linking life cycle impact assessment with integrated assessment modelling over long-term future scenarios.	Integrated the LIME endpoint LCIA method with an IAM including resource balance models and a simplified climate model; assessed future endpoint impacts under business-as-usual and 2°C-compatible scenarios.	The International Journal of Life Cycle Assessment	2020
62	Decarbonising international shipping – A life cycle perspective on alternative fuel options	To compare alternative marine fuels from a life cycle GHG perspective and assess their potential contribution to the full decarbonization of international shipping.	Conducted LCA of hydrogen, ammonia, methanol, and waste-derived biofuels using one year of global shipping fleet operations as the common functional basis; compared results with a heavy fuel oil baseline.	Energy Conversion and Management	2024
63	Life cycle greenhouse gas emissions and cost of energy transport from Saudi Arabia with conventional fuels and liquefied natural gas	To assess the WTW GHG emissions and life cycle cost of SUEZMAX tankers operating with HSFO, VLSFO, and LNG on Saudi Arabia–Japan and Saudi Arabia–Netherlands routes.	Used GREET-based WTW LCA, life cycle cost assessment, and sensitivity analysis for methane slip, LNG cost, and anchoring time; assessed a 30-year vessel lifetime and cost of carbon abatement.	Energy Conversion and Management: X	2024

No.	Title	Aim	Methods	Journal or source	Year
64	A critical view on the current application of LCA for new technologies and recommendations for improved practice	To critically examine how LCA is applied to emerging technologies and provide recommendations for improved ex-ante LCA practice.	Reviewed challenges in applying LCA before technologies are commercially deployed; organized recommendations according to the ISO LCA phases, including goal and scope, inventory, impact assessment, and interpretation.	Journal of Cleaner Production	2020
65	Dynamic vs real time life cycle assessment	To review the implementation of dynamic LCA across sectors and clarify the difference between dynamic and real-time LCA.	Conducted a systematic literature review using PRISMA/SALSA-based methods; analysed DLCA applications by sector and examined studies using real-time or near-real-time LCA terminology.	Cleaner Environmental Systems	2025
66	Forecasting meteorological impacts on the environmental sustainability of a large-scale solar plant via artificial intelligence-based life cycle assessment	To develop an AI-based LCA framework for assessing how meteorological uncertainty affects the environmental sustainability of large-scale solar plants.	Integrated LCA with an Artificial Neural Network; assessed 18 impact categories using ReCiPe 2016 in SimaPro and forecasted electricity generation using meteorological inputs.	Science of the Total Environment	2024
67	Life cycle and economic assessment of a solar panel array applied to a short route ferry	To assess the environmental and economic benefits of applying solar panel arrays to a short-route ferry.	Conducted LCA and Life Cycle Cost Assessment for a ferry operating in the Marmara Sea; considered installation, operation, recycling, fuel savings, payback time, and sensitivity to energy efficiency and investment cost.	Journal of Cleaner Production	2019
68	Uncertainties in life cycle assessment of renewable fuels for green shipping corridors	To quantify key uncertainties affecting the life-cycle environmental impacts of renewable hydrogen, ammonia, and methanol in the Singapore–Rotterdam Green Shipping Corridor.	Developed an uncertainty-integrated LCA framework using multi-source renewable energy data, AIS-derived vessel activity, Monte Carlo simulation for WTT variability, and AIS-driven sensitivity analysis for TTW operational uncertainty.	Transportation Research Part D	2025
69	Climate change mitigation of drop-in biofuels for deep-sea shipping under a prospective life-cycle assessment	To assess the climate change mitigation potential of drop-in biofuels for deep-sea shipping under future energy and transport scenarios.	Applied prospective well-to-propeller LCA for biofuels from Norwegian forest residues; included future background system changes, IAM-based scenarios, near-term climate forcings, and Monte Carlo uncertainty analysis.	Journal of Cleaner Production	2022

No.	Title	Aim	Methods	Journal or source	Year
70	Comparative Life Cycle Assessment of Alternative Marine Fuels	To compare a broad range of alternative marine fuels using LCA in line with maritime emission reduction objectives.	Applied WTW LCA to ammonia, biodiesel, DME, electro-fuels, hydrogen, LNG, LPG, marine diesel oil, marine gas oil, marine bio-oil, methanol, pyrolysis oil, renewable diesel, straight vegetable oil, and ULSFO; used GREET 2022 and OpenLCA with Environmental Footprint 3.0.	Fuel	2024
71	Predicting environmental impacts of smallholder wheat production by coupling life cycle assessment and machine learning	To assess and predict the environmental impacts of smallholder wheat production under future climate scenarios by combining LCA and machine learning.	Conducted cradle-to-farm-gate LCA using survey data from 274 smallholder farms; assessed eight environmental impact categories and developed random forest models using 21 input features across SSP119, SSP245, and SSP585 climate scenarios.	Science of the Total Environment	2024

C.3.2 Findings and Critical Appraisal

Table C.4. Key findings, contribution, novelty, and limitations of the reviewed literature.

No.	Key findings	Contribution	Novelty	Limitations
1	Current LCA data-quality assessment approaches are inadequate for enterprise-specific data because they mainly focus on industry-average data; organizational data management and control issues are often neglected.	Highlights the need for active organizational data-quality management to improve the usefulness of LCA as a decision-support tool.	Introduces a management science perspective into LCA data-quality assessment by examining enterprise-specific data collection inside an organization.	Not maritime-specific; based on a single organizational case; qualitative and interpretive approach limits generalizability; focuses on data quality rather than fuel or vessel emission assessment.
2	Low-Sulphur fuels reduce SO _x during operation, but their total life cycle impacts can be higher than expected; HFO remains comparatively favorable in some life cycle results.	Demonstrates that regulations focused mainly on operational Sulphur emissions may overlook broader life cycle impacts.	Provides one of the first comprehensive life cycle comparisons of main marine fuels in the specific context of the IMO 2020 Sulphur Cap.	Limited to four conventional oil-based marine fuels; does not assess emerging alternative fuels; limited dynamic operational or route-specific modelling.
3	LCA can provide CO ₂ per transport work results comparable to regulatory metrics while also reporting NO _x , SO _x , hazardous releases, and material and energy use across vessel life cycle stages.	Positions LCA as a complementary environmental performance indicator that can support EEDI, EEOI, and MRV implementation.	Proposes LCA as a parallel and complementary utility to existing shipping energy-efficiency regulations, extending assessment beyond operational CO ₂ efficiency.	Based on limited case-study validation, future work is needed to include more vessel types, retrofit options, and additional modelling parameters.
4	LCA can support shipowners and fleet managers in comparing retrofit options by combining environmental load assessment with cost-benefit considerations.	Provides an early maritime application of LCA for ship retrofit decision-making and shows how environmental and economic criteria can be combined.	Applies LCA specifically to ship retrofitting selection, demonstrating its practical use for comparing ballast water treatment alternatives.	Uses a theoretical case vessel; relies partly on assumptions and available data; focuses on retrofit technologies rather than alternative marine fuels or operational forecasting.
5	Electric RIBs reduce GWP by 34% for recreational use and 52% for harbor-master use but show higher production-phase impacts and higher impacts in several non-GWP categories.	Shows that electrification benefits are strongest in high-utilization cases and cleaner electricity-grid contexts.	Presents the first LCA focused exclusively on electric versus petrol RIBs using real-world usage data and multiple operational scenarios.	Based on current technologies, regionally focused on southwest UK data and disposal practices, it lacks a comprehensive uncertainty analysis; it excludes life cycle cost and social LCA dimensions.
6	LNG and methanol from natural gas improve several environmental indicators but do not substantially reduce climate impact compared with HFO; LBG and bio-methanol show greater potential for climate impact reduction.	Shows that alternative fuels must be evaluated across the full life cycle, not only through onboard emissions.	Provides an early comparative LCA of methane- and methanol-based marine fuels from both fossil and biomass feedstocks.	Methanol engine performance was not fully validated; methane slip strongly affects results; land-use change impacts were not included; limited to selected fuel pathways and a northern European ECA context.

No.	Key findings	Contribution	Novelty	Limitations
7	LCA-based GHG estimates were around 20% higher than IPCC-based estimates because LCA includes upstream and downstream emissions and non-CO ₂ GHGs.	Demonstrates that LCA can provide a more systemic and realistic basis for local climate policy than territorial IPCC accounting alone.	One of the first studies to explicitly compare IPCC and LCA approaches for local-level GHG inventories, including site-specific electricity factors.	Not maritime-specific; focused on one Italian municipality; data availability can constrain local GHG balances; results depend strongly on selected emission factors and local energy data quality.
8	E-methanol produced using solar electricity showed the lowest WTW emissions and aligned best with FuelEU targets until 2045; the electricity source is critical for determining the carbon performance of e-fuels.	Provides a forward-looking LCA framework to support strategic fuel selection and regulatory decision-making for green corridors.	Integrates time-series forecasting, econometric demand modelling, lifecycle emissions, and regulatory cost assessment in a specific green corridor context.	Limited to one route, one vessel type, and selected fuels; infrastructure investments are excluded; forecasts depend on historical GDP, population, and TEU trends; cost assessment focuses mainly on regulatory penalties rather than full fuel economics.
9	WTT emissions dominate ammonia's carbon performance; the 3-step Cu-Cl cycle showed the lowest GWP among the assessed ammonia production routes; regression equations can provide rapid fleet-level carbon estimates.	Supports fleet-level environmental decision-making by moving beyond single-vessel LCA and developing indicators for ammonia as a marine fuel.	Applies PT-LCA to ammonia as a marine fuel across thousands of bulk carriers, producing simplified equations for rapid WTW GWP estimation.	Regression formulas still require further development; R ² values are moderate; ammonia engine and fuel consumption data are uncertain; ME-LGI ammonia application is based on assumptions because commercial ammonia engines were not yet fully available.
10	Under the deep CO ₂ reduction scenario, CO ₂ and major air pollutants decline by more than 71.4%, while major environmental impact categories decrease by 81.8–88.5%.	Demonstrates how LCA can complement energy-system modelling by adding broader environmental impact assessment to future policy scenarios.	Integrates LEAP scenario modelling with LCA at the city level to assess both future energy transitions and lifecycle environmental co-benefits.	Not maritime-specific; focused on one Chinese city; results depend on scenario assumptions, energy-system modelling choices, and LCA database quality; uses soft-linking rather than a fully integrated dynamic LCA model.
11	Real-time monitoring can improve LCA data quality, enable dynamic environmental assessment, and support more responsive decision-making; however, the environmental and practical trade-offs of monitoring technologies must also be assessed.	Highlights the potential of real-time monitoring and IoT technologies to overcome static LCI limitations and improve primary data collection.	Provides a focused, systematic review linking real-time monitoring, sensors, IoT technologies, and dynamic life cycle inventories.	Not maritime-specific; based only on selected peer-reviewed English-language studies; focuses on review evidence rather than empirical model development; real-time monitoring impacts and implementation trade-offs remain underexplored.
12	CLCA has evolved from simple heuristic and partial equilibrium approaches towards more sophisticated economic modelling; however, consensus and standardization remain under development.	Clarifies the methodological evolution of CLCA and identifies future research needs for integrating economic models with LCA.	Provides an early structured review of CLCA as the convergence between LCA and economic modelling.	Not maritime-specific; does not conduct an empirical case study; CLCA methodology remains difficult to standardize; integration with economic models can require data aggregation and may reduce process-level detail.

No.	Key findings	Contribution	Novelty	Limitations
13	LNG's lower carbon content and higher engine efficiency can be offset by methane losses across the LNG supply chain; LNG becomes particularly unfavorable when assessed using 20-year methane GWP.	Demonstrates the importance of project-specific supply-chain modelling and methane losses in marine fuel LCA.	Uses bottom-up engineering models for specific oil and gas projects worldwide, rather than relying only on generic LCA databases.	Focuses only on GHG emissions and climate impact; does not assess other environmental impact categories; functional unit excludes cargo-space effects from LNG storage; potential conflict of interest due to oil-industry affiliation.
14	LCA has evolved from environmental burden analysis into a broader framework that can support sustainability assessment across environmental, economic, and social dimensions.	Provides a foundational overview of LCA evolution and frames the future direction of LCA as part of broader sustainability analysis.	Introduces LCSA as a transdisciplinary integration framework linking life-cycle questions to suitable models and methods.	Broad conceptual review rather than sector-specific analysis; not maritime-specific; LCSA operationalization remains challenging; does not provide empirical results or a specific methodological application.
15	LFP batteries show the lowest environmental impact among the assessed batteries; MDO with lower Sulphur reduces SOx but can increase CO ₂ , water, and energy use due to intensive refining; battery feasibility depends on carbon credit scenarios and electricity mix.	Supports decision-making for ferry electrification by combining environmental and economic assessment of specific battery chemistries.	One of the first studies to compare different Li-ion battery chemistries for passenger ferries using both LCA and LCCA.	Excludes end-of-life battery disposal due to GREET 2021 limitations; case-study results are specific to Istanbul; grid electricity mix strongly affects results; broader infrastructure and charging-grid impacts are only partly considered.
16	International maritime transport can significantly affect WTT emissions; LNG transport emissions vary by import country and route; TtW emissions dominate WTW emissions for fossil fuels.	Provides a baseline for developing default life cycle emission values for marine fuels in countries dependent on imported energy.	Highlights the importance of regional supply-chain routes and maritime transport distances in marine fuel LCA, which are often neglected in regulatory default values.	Focused only on fossil-based fuels; methanol WTT data were limited; South Korea-specific case limits generalizability; individual effects of ship capacity, propulsion system, and cargo quantity require further investigation.
17	Live LCA can make environmental impacts more tangible by giving users direct feedback on how production parameters influence product-level environmental performance.	Demonstrates how real-time LCA can be used as an educational and decision-support tool in manufacturing learning factories.	Introduces a Live LCA concept that links physical production systems with virtual LCA models for real-time environmental assessment.	Conceptual and learning-factory focused; not maritime-specific; limited industrial-scale validation; depends on sensor availability, model quality, and accurate background data.
18	LCA is presented as a systematic method for assessing environmental impacts across the full life cycle and avoiding problem-shifting between life stages and impact categories.	Provides a foundational reference for understanding and applying LCA in research, policy, and decision-making.	Integrates LCA theory, methodological guidance, practical cookbook-style instructions, and application examples in one comprehensive volume.	Not maritime-specific; not an empirical study; some methodological and database-related content may require updating as LCA practice, regulations, and datasets evolve.

No.	Key findings	Contribution	Novelty	Limitations
19	Rapeseed biodiesel showed much lower climate change potential than petrochemical diesel, but results are strongly affected by assumptions about substitution effects, straw use, carbon sequestration, and alcohol type.	Provides a benchmark for current biodiesel production and identifies improvement pathways such as rape straw utilization and enzymatic transesterification.	Uses real-time/current Danish production data with multiple production pathways to evaluate optimization potential rather than only theoretical future biodiesel scenarios.	Results should not be interpreted as a general blueprint for increased biodiesel production; uncertainty is strongly influenced by substitution assumptions; some data are producer-specific and context-dependent.
20	E-ammonia, e-FT diesel, and e-methanol could meet the 2050 FuelEU Maritime target; e-LNG and ship-based carbon capture could not; e-ammonia may offer the lowest overall environmental impacts and cost potential despite technological immaturity.	Supports evidence-based maritime fuel policy by comparing future fuel pathways beyond GHG emissions alone.	Combines prospective LCA, FuelEU Maritime compliance targets, future climate-policy scenarios, e-fuel production locations, and externality cost assessment.	Results depend on future scenario assumptions, IAM-based background data, technology maturity, cost projections, and production-location choices; operational variability and infrastructure constraints are not fully captured.
21	LCA is defined as a method for assessing environmental aspects and potential impacts across the full life cycle, from raw material acquisition to final disposal.	Provides the foundational international framework for conducting and interpreting LCA studies.	Consolidates and standardizes the general LCA framework into a harmonized ISO structure, together with ISO 14044.	Provides principles and framework only; does not give detailed methodological requirements or sector-specific guidance; does not directly address economic or social aspects.
22	LCA studies must be transparent, consistent with the defined goal and scope, and supported by appropriate reporting and review procedures.	Provides the main methodological requirements used to ensure consistency, transparency, and reliability in LCA studies.	Complement ISO 14040 by translating the general LCA framework into practical requirements and guidelines for implementation.	Does not prescribe one single method for all LCA applications; detailed modelling choices remain study-dependent; not intended for contractual, regulatory, certification, or registration purposes.
23	Maritime LCA studies are difficult to compare because functional units, boundaries, databases, software, impact categories, and modelling assumptions vary significantly.	Provides recommendations aligned with ILCD guidance to improve consistency and reliability in future maritime LCA studies.	Offers a structured review of holistic maritime LCA methodology specifically aimed at supporting future standard development for the maritime industry.	Limited to 32 selected studies; focuses on methodological trends rather than developing a full standard; public maritime LCA databases, tools, and spatial-temporal characterization factors remain underdeveloped.
24	CO ₂ emissions increase with engine RPM and fuel consumption; the predictive model estimated emissions to be about 83% higher than LCA simulations because it captured operational and external factors not fully represented in LCA.	Shows that LCA simulation can provide a rapid comparative assessment, but real operational data and predictive modelling improve emission estimation accuracy.	Directly compares real-operation predictive modelling with LCA simulation for ship CO ₂ emissions, highlighting the gap between simplified LCA assumptions and actual ship operation.	Based on a specific case vessel and operational dataset; focuses mainly on CO ₂ emissions; LCA simulation did not fully account for engine characteristics, external forces, and detailed navigation conditions.

No.	Key findings	Contribution	Novelty	Limitations
25	LNG's environmental performance depends strongly on engine type and methane slip; low-speed high-pressure dual-fuel engines perform better, while low-pressure engines require further optimization.	Provides environmental indicators to support more standardized LCA of LNG-fueled ships.	Uses PT-LCA across a large multi-ship dataset to move beyond single case studies and demystify LNG's lifecycle benefits and drawbacks.	Results depend on assumptions for LNG production, engine type, methane slip, and operational profiles; future improvements in LNG engines and supply chains may change outcomes.
26	Closed-loop scrubbers performed better than open-loop scrubbers for GWP and AP, while open-loop scrubbers performed better for EP; scrubber impacts vary with ship characteristics.	Provides a fleet-level LCA-based method to support scrubber selection and improve environmental decision-making under SOx regulations.	Introduces PT-LCA for marine scrubber systems, enabling general trend equations instead of relying only on individual case-vessel LCA results.	Focused on Ro-Ro vessels; results depend on assumptions for scrubber operation, ship parameters, and emissions factors; broader validation across more vessel types and operating profiles is needed.
27	Hydrogen's environmental performance depends strongly on production pathway and fuel cell type; fossil-based hydrogen pathways can have high impacts, while renewable electrolysis offers stronger decarbonization potential.	Provides lifecycle environmental indicators for hydrogen fuel cell applications in shipping and supports future regulatory and policy development.	Extends PT-LCA to hydrogen fuel cell propulsion at fleet scale, linking ship characteristics, hydrogen production routes, and lifecycle environmental impacts.	Results depend on hydrogen production assumptions, fuel cell performance data, and future technology maturity; infrastructure, storage, and bunkering constraints are not fully captured.
28	Battery propulsion reduced GWP by 35.7%, AP by 77.6%, EP by 87.8%, and POCP by 77.2% compared with diesel propulsion, but results are highly dependent on the electricity generation mix.	Demonstrates that full battery ships can offer significant lifecycle environmental benefits, while warning that electrification is not automatically sustainable without cleaner electricity.	Integrates real ship operating profiles, laboratory measurements, battery system simulation, and lifecycle assessment for a full battery-powered ship case.	Based on one Korean Ro-Ro passenger ship; results depend strongly on South Korea's electricity mix; battery manufacturing, degradation, charging infrastructure, and end-of-life assumptions may affect outcomes.
29	Green corridors are becoming central to shipping decarbonization, but high lifecycle costs and uneven international participation remain major barriers; stronger policy and financial support are needed.	Provides a policy-oriented overview of international shipping decarbonization trends and highlights the importance of lifecycle thinking in future maritime regulation.	Connects green corridor development, regional policy initiatives, and lifecycle assessment considerations in a concise maritime decarbonization review.	Review-based rather than empirical; reflects policy status at the time of publication; does not conduct quantitative LCA or fuel pathway comparison; policy landscape may change rapidly.
30	Steel sump scenarios generally outperformed concrete sump scenarios; one steel scenario showed 93.04% lower environmental impact, 89.18% lower human health impact, and 81.47% lower construction cost compared with the equivalent concrete scenario.	Demonstrates the value of integrating environmental, human health, and economic indicators when selecting construction materials and methods.	Provides a combined LCA-based sustainability assessment that simultaneously considers material type, construction method, environmental impacts, human health impacts, and cost.	Not maritime-specific; focused on South Korean construction cases; results depend on selected sump scenarios, local construction practices, and LCI data; operational and end-of-life uncertainties may affect outcomes.

No.	Key findings	Contribution	Novelty	Limitations
31	The hybrid ferry showed better economic and environmental performance than diesel-electric and diesel-mechanical alternatives; for the offshore tug, multiple smaller engines performed better than two medium-sized engines.	Provides a practical decision-support framework for ship designers, shipyards, and shipowners to compare propulsion systems from both environmental and cost perspectives.	Introduces a modular ship life-cycle structure that embeds LCA and LCCA calculations into reusable modules for faster propulsion-system assessment.	Case-study based; results depend on the quality of lifecycle databases, cost assumptions, operational profiles, and discount-rate choices; broader vessel validation is needed.
32	All assessed options can reduce GHG emissions if low-carbon electricity is used, but carbon abatement costs remain high at around 300–550 €/tons CO ₂ eq; trade-offs occur in toxicity and ecotoxicity impacts.	Provides a combined environmental and economic comparison of future marine fuel and propulsion options across the full life cycle.	Includes manufacturing and end-of-life phases of propulsion components and evaluates both post- and pre-combustion onboard carbon capture within a prospective LCA/LCC framework.	Results depend strongly on future electricity assumptions, technology maturity, cost projections, and scenario choices; biomass-based fuels are excluded; real operational variability is limited.
33	Real-time LCA enables continuous monitoring of lifecycle GHG performance and supports immediate corrective actions; renewable fuels and electricity show strong potential for emission reduction when regional energy conditions are favorable.	Demonstrates how digital twins can transform static maritime LCA into a dynamic operational decision-support tool.	Successfully integrates real-time digital twin technology with LCA, allowing continuous environmental assessment and adaptive control during vessel operation.	Requires validation against real operational data; sampling intervals and data communication constraints require further study; results depend on digital-twin accuracy, input data quality, and selected vessel cases.
34	European shipowners benefit most during the use phase, while Asian producers and dismantlers bear comparatively higher environmental impacts per unit of added value.	Highlights the uneven distribution of economic benefits and environmental burdens across the ship life cycle.	Develops an adjusted eco-efficiency indicator linking LCA-based impacts with local added value for different ship life-cycle phases.	Human labor and direct worker health impacts in shipbreaking are not fully included; based on simplified value assumptions and one representative ship case, limited environmental indicators are assessed.
35	Battery-electric propulsion is the most energy-efficient pathway but remains impractical for long-distance shipping; fossil fuels with CCS appear low-cost but depend on unresolved CO ₂ storage; biofuels offer a practical compromise; hydrogen and ammonia require high energy and cost.	Provides a broad quantitative comparison of marine fuel options to support fuel-transition decisions.	Combines WTW energy, WTW cost, WTW GHG emissions, non-GHG emissions, fuel mass, fuel volume, and TRL-related considerations across 22 pathways.	Results depend on literature data, ASPEN assumptions, selected pathways, and weighting choices; ship type, voyage route, infrastructure, scalability, and fuel availability are not fully represented.
36	Biomass-based FT-diesel, e-methanol, and e-ammonia achieved high GHG reductions, but were not cost-effective during the target study period under baseline assumptions.	Provides practical insight into the environmental and economic feasibility of alternative marine fuels under lifecycle carbon pricing.	Combines fuel-pathway LCA, lifecycle carbon pricing, NPV-based ship cost analysis, and blending strategies to support realistic fuel-transition decisions.	Results depend on carbon price assumptions, fuel cost projections, selected fuel pathways, and reference vessel assumptions; infrastructure availability and operational variability are not fully captured.

No.	Key findings	Contribution	Novelty	Limitations
37	MSW-derived FT fuels can have carbon intensities of 80–105 g CO ₂ eq/MJ, potentially exceeding petroleum fuels; carbon capture can reduce emissions by 53–64 g CO ₂ eq/MJ.	Shows that waste-derived fuels are not automatically low-carbon and that feedstock composition and landfill counterfactuals strongly influence results.	Provides a detailed LCA of MSW-to-FT fuels that explicitly considers fossil/biogenic carbon, landfill diversion, carbon sequestration, methane avoidance, and CCS.	Not maritime-specific; results depend heavily on waste composition, landfill assumptions, conversion efficiency, and carbon accounting choices; mainly focused on GHG emissions rather than broader environmental categories.
38	LNG showed the lowest emissions and hydrogen price among the assessed hydrogen carriers; results are influenced by storage methods, transport distance, cargo tank size, and ship fuel choice.	Provides a lifecycle and cost-based assessment of international hydrogen supply chains relevant to energy-importing countries.	Integrates hydrogen carrier selection, marine fuel choice for transport vessels, environmental impact categories, sensitivity analysis, and delivered hydrogen price in one framework.	Focused on Australia–Korea supply chains; results depend on blue hydrogen assumptions, ship design, route distance, storage technology, and future fuel costs; broader infrastructure and market uncertainties remain.
39	Temporal treatment can significantly change global warming results and may alter conclusions about whether a fuel or product meets emission-reduction targets.	Establishes the importance of including emission timing in LCA, especially for long-lived systems and climate-impact assessment.	Introduces a dynamic LCA method that links temporal emission profiles with time-dependent characterization factors for global warming assessment.	Mainly developed for global warming impacts; requires detailed temporal emission data; more complex than traditional LCA; wider application to other impact categories requires further development.
40	Ammonia has strong potential as a low-carbon marine fuel due to its carbon-free combustion and existing chemical infrastructure, but toxicity, safety, cost, storage, and engine development remain major barriers.	Provides a broad technical and regulatory overview of ammonia as a future marine fuel.	Combines ammonia fuel properties, safety considerations, regulatory standards, storage requirements, and engine-conversion issues in a maritime-focused review.	Review-based rather than quantitative LCA; does not provide detailed lifecycle emission modelling or cost optimization; ammonia's real decarbonization benefit depends strongly on its production pathway and safety management.
41	E-fuels can support deep GHG reduction only if abundant renewable electricity is available; dual-fuel engines provide a robust transition pathway by maintaining flexibility during fuel-supply uncertainty.	Highlights the practical challenges of e-fuel adoption and emphasizes the importance of energy demand and fuel flexibility in maritime decarbonization.	Focuses on e-fuels not only from a GHG perspective, but also through feasibility, energy-use, and cost considerations within a maritime transition context.	Excludes construction and decommissioning of renewable-energy infrastructure; results depend strongly on future renewable electricity availability and cost assumptions.
42	Retrofit and new-built systems reduced fuel consumption and operational emissions, but increased impacts in some categories due to additional resource use and end-of-life burdens.	Demonstrates the importance of whole-life assessment when comparing marine power systems and warns against burden shifting between operation and other lifecycle stages.	Provides a detailed component-based comparative LCA of marine power-system configurations, including both retrofit and new-build alternatives.	Results depend on selected case systems, assumptions, operational profiles, and LCA databases; advanced systems may reduce GHG-related impacts but increase ecotoxicity and resource-related impacts.
43	Boiler steam generated the highest co-benefits among reutilized resources, while steel and iron scrap produced the largest co-benefits per unit mass.	Shows how combining LCA and energy analysis can provide a broader assessment of environmental and resource-efficiency benefits.	Introduces a hybrid LCA–energy framework to assess the co-benefits of eco-industrial strategies, addressing weaknesses of both methods when used separately.	Not maritime-specific; focused on one industrial park; results depend on local data availability, energy assumptions, and selected co-benefit indicators.

No.	Key findings	Contribution	Novelty	Limitations
44	LCA has evolved from static environmental assessment toward dynamic, multidimensional, data-driven, and integrated sustainability assessment frameworks.	Provides a broad methodological overview useful for positioning modern LCA developments and identifying future directions.	Synthesizes LCA evolution with emerging technologies such as GIS, IoT, AI, big data, blockchain, and machine learning.	Broad review rather than empirical study; not maritime-specific; does not provide detailed guidance for one sector; some emerging LCA integrations remain conceptual or early-stage.
45	Biofuels can reduce black carbon emissions by 50–80% under controlled conditions, with HVO-diesel blends showing strong performance while maintaining engine operation.	Highlights the potential of advanced biofuels to reduce black carbon and support cleaner marine propulsion.	Focuses specifically on biofuel innovation for black carbon reduction, rather than only CO ₂ or GHG emissions.	Review-based; limited quantitative consistency across studies; biofuel scalability, cost, feedstock availability, storage, and lifecycle sustainability remain major challenges.
46	Replacing 20%, 30%, and 40% of MDO with LNG reduced GWP by approximately 23.1%, 32.7%, and 42.3%, respectively, during the assessed operational period.	Demonstrates the potential of LNG dual-fuel retrofitting as a transitional emission-reduction option for existing vessels.	Provides a detailed retrofit-focused LCA using different LNG replacement ratios and compares LCA database results with engine-emission-factor-based results.	Based on one training ship and a 35-day operating profile; focuses mainly on GWP; results depend on LNG assumptions, engine data, operating load, and the selected emission factors.
47	Medium-sized farms showed the lowest environmental impacts; major hotspots were diesel, machinery, seeds, and pesticides; ANN models showed good predictive performance.	Demonstrates how LCA and AI can be combined to predict agricultural environmental impacts and support improved energy management.	Integrates LCA with neural-network modelling to forecast environmental impacts and energy consumption across farm-size categories.	Not maritime-specific; limited to sugar beet production in one Moroccan region; results depend on survey data quality, local farming practices, and ANN training dataset size.
48	No single accepted method exists for integrating LCA and LCC; a hybrid framework can support different decision-making perspectives and combine environmental and economic assessment more systematically.	Provides a structured decision-support framework for combining environmental and economic life-cycle analysis.	Proposes a hybridized framework integrating six LCA–LCC methods, including TOPSIS–AHP MCDA, MOLP optimization, eco-efficiency, and environmental costing.	Conceptual and review-based; not maritime-specific; framework requires case-study validation and depends on data availability, weighting choices, and decision-maker preferences.
49	ALCA suggested around 60% GHG reduction compared with conventional jet fuel, while CLCA showed much lower benefits or even increased emissions depending on the displaced animal-feed scenario.	Shows that LCA modelling choices can strongly affect conclusions for biofuel sustainability.	Directly compares attributional and consequential LCA for the same novel biofuel pathway, highlighting how market-mediated effects can reverse conclusions.	Focused on aviation biofuel rather than maritime fuel; CLCA results have high uncertainty due to displaced-product assumptions; capital goods were excluded; results are context-specific to Dutch potato by-products.
50	Climate impacts could decrease from about 1.03 kg CO ₂ -eq/kg clinker in 2020 to 0.94, 0.20, and 0.16 kg CO ₂ -eq/kg clinker by 2060 under the respective scenarios, but burden shifting occurs in other impact categories.	Demonstrates how pLCA and IAM scenarios can provide coherent long-term assessment of industrial decarbonization pathways.	Couples prospective LCA with integrated assessment model scenarios to align product-level LCA with global transition pathways.	Not maritime-specific; focused only on clinker production; results depend strongly on IMAGE assumptions, CCS, bioenergy, and future technology pathways; some mitigation options are excluded.

No.	Key findings	Contribution	Novelty	Limitations
51	Onboard carbon capture reduced tank-to-wake GHG intensity by 54–68%; oil-fueled ships with OCCS were less GHG intensive and more cost-effective than LNG-fueled ships; OCCS could support FuelEU compliance until 2044.	Provides a regulatory-relevant assessment of onboard carbon capture as a transitional decarbonization option for fossil-fueled ships.	Integrates OCCS performance, fuel-engine combinations, WTW GHG intensity, FuelEU Maritime requirements, and cost implications in one evaluation framework.	Focuses on fossil-fueled ships; carbon capture is mainly from main engines; auxiliary boiler/generator capture and upstream fuel-emission reductions are needed for long-term compliance beyond 2044.
52	Landfilling contributed more strongly to global warming, acidification, smog formation, eutrophication, ecotoxicity, and human health impacts, mainly due to landfill gas and leachate.	Supports waste management decision-making by comparing gasification and landfilling from both environmental and health perspectives.	Provides a US-focused comparative LCA using open-access models and includes human health impacts often omitted in previous MSW disposal comparisons.	Not maritime-specific; focuses on MSW disposal rather than marine fuels; results depend on US waste composition, landfill assumptions, gasification data, and modelling tools.
53	PV-electric ship performance depends strongly on solar irradiance, temperature, and national electricity mix; the same vessel can deliver different GHG reductions depending on geographic and grid conditions.	Demonstrates how simulation-generated operational data can improve LCA of emerging maritime technologies.	Introduces Live-LCA as a method to overcome static or outdated LCI data by dynamically generating performance data for direct LCA input.	Focused on a short-route electric/hybrid ferry; results depend on simulation assumptions, PV performance, regional climate, and grid mix; less applicable to deep-sea shipping.
54	E-hydrogen with mono-fuel ICE or fuel cell achieved full decarbonization; mono-fuel e-hydrogen configurations performed strongly across ship types; wind-assisted systems were preferred as auxiliary options.	Provides a comprehensive decision-support framework for container ship energy transition pathways.	Combines LCA, cost assessment, regulatory penalty modelling, and advanced MCDA with preference uncertainty and criteria interaction across 172 ship energy configurations.	Results depend on assumed fuel prices, IMO penalty parameters, technology readiness, feasible configuration screening, and future infrastructure development.
55	Existing maritime fuel LCAs lack transparency and consistency; only 19% provide complete life cycle inventories, and only 16% include uncertainty analysis, limiting their usefulness for robust fuel decision-making.	Provides a critical methodological benchmark for future maritime fuel LCA studies.	Offers one of the most detailed reviews focused specifically on maritime fuel LCAs, combining technology coverage, methodological choices, transparency, and practical recommendations.	Review limited to peer-reviewed English-language articles up to February 2023; does not conduct new LCA modelling; findings depend on the reporting quality of reviewed studies.
56	Future climate mitigation targets affect the environmental performance of many activities in the LCA database; consistent prospective databases improve the quality and reproducibility of pLCA.	Provides a practical and reproducible tool for integrating IAM scenarios into LCA background databases.	Introduces a streamlined method for creating prospective LCI databases that align LCA with socio-economic pathways and climate mitigation scenarios.	Mainly focused on selected sectors and IAM-compatible transformations; results depend on IAM assumptions, scenario quality, mapping between IAM and ecoinvent data, and the availability of future technology inventories.

No.	Key findings	Contribution	Novelty	Limitations
57	Raw material extraction dominated total energy use, while liquefaction and methane slip strongly influenced GHG results; switching from HFO to LNG depends on engine type, supply chain, and cargo-capacity penalties.	Demonstrates that maritime fuel assessment should account for vessel-specific operation, fuel supply chain, and engine technology rather than relying on generic assumptions.	Combines fuel supply-chain modelling with vessel type, engine type, and operational profile in a maritime life-cycle perspective.	Limited mainly to HFO and LNG; European geographical focus; uses selected representative vessels and operational profiles; results depend on methane slip assumptions and LNG supply-chain modelling.
58	Safety was ranked as the most important criterion, followed by WTW emissions and compatibility; Fischer–Tropsch diesel and third-generation HVO were identified as optimum biofuel options.	Supports maritime biofuel selection by combining lifecycle, technical, safety, and sustainability criteria.	Integrates AHP with LCA-related criteria, including WTW emissions and ILUC, to compare biofuels according to feedstock and production pathways.	Results depend on expert judgement, criteria weighting, and literature data; limited by uncertainty in biofuel availability, scalability, cost, and future regulatory development.
59	Patent-based prospective LCA can support eco-design not only by evaluating existing options, but also by identifying future design solutions that may reduce environmental impacts.	Provides a methodological bridge between prospective LCA, technological forecasting, patents, and eco-design.	Uses patents as both a source of future design solutions and as data input for prospective LCA, enabling environmental assessment at the design-feature level.	Not maritime-specific; method depends on patent availability and quality; prospective estimates remain uncertain; requires further validation across different product systems.
60	Replacing diesel with LNG under optimized conditions can reduce GHG emissions by 39% and improve fuel efficiency by up to 22%; fuel quality has a stronger economic influence than load variation, and the payback period can decrease from six to four years under favorable load conditions.	Provides a combined environmental and financial assessment of LNG retrofitting under operational and fuel-quality uncertainty.	Incorporates fuel property variation, load variation, sensitivity analysis, and financial risk assessment into LNG-retrofit LCA/LCCA.	Focused on LNG and diesel pathways; results depend on fuel price, Wobbe Index, engine load, route assumptions, and retrofit cost assumptions; methane slip and future LNG market uncertainty remain important concerns.
61	The 2°C scenario generally reduces inventories and endpoint impacts compared with business-as-usual, but biodiversity impacts may increase due to land-use expansion linked to forestry and renewable energy scenarios.	Demonstrates how LCA-based impact assessment can be linked with IAMs to evaluate long-term environmental consequences beyond climate change alone.	Provides an interlinked LCIA–IAM framework covering energy, mineral resources, land use, waste, air pollution, acidification, ozone depletion, and endpoint impacts over the twenty-first century.	Highly model-dependent; global-scale modelling may reduce process-level detail; results depend on IAM assumptions, endpoint characterization, resource models, and selected climate-policy scenarios.
62	Green hydrogen, waste-derived biodiesel, and bio-methanol showed strong emission-reduction potential, but no single fuel option achieved the 100% reduction required for full sectoral decarbonization by 2050.	Highlights the need to combine alternative fuels with wider decarbonization measures such as slow steaming, wind propulsion, fleet renewal, and fuel-supply-chain expansion.	Uses global fleet annual energy demand as the LCA comparison basis, allowing fuel options to be assessed against Paris-aligned sectoral decarbonization needs.	Results depend on fuel production assumptions, allocation choices, ammonia N ₂ O uncertainty, biofuel availability, and future scale-up; it does not model all operational efficiency measures in detail.

No.	Key findings	Contribution	Novelty	Limitations
63	LNG reduced life cycle GHG emissions by around 11–12% compared with conventional fuels, while the cost of GHG abatement varied strongly depending on methane slip, LNG price, and operational assumptions.	Provides route-specific environmental and cost evidence for LNG use in crude-oil tanker operations.	Combines route-specific tanker operation, regional fuel production assumptions, WTW emissions, LCC, and cost of carbon abatement for Saudi energy export routes.	Focused on SUEZMAX tankers and two routes only; results depend on LNG price, methane slip, anchoring time, fuel production data, and regional cost assumptions; LNG provides limited decarbonization potential.
64	Ex-ante LCA faces major challenges related to future foreground systems, future background systems, technology scale-up, uncertainty, and stakeholder involvement.	Provides methodological guidance for using LCA to support early-stage technology development and avoid future environmental lock-ins.	Frames ex-ante LCA as a structured approach for assessing new technologies before commercial deployment, combining learning curves, scenarios, IAM-informed background systems, and responsive evaluation.	Review and guidance paper rather than empirical modelling; recommendations require practical validation; future uncertainty remains difficult to quantify and communicate.
65	DLCA is increasingly used, mainly in buildings, waste management, agriculture, and utilities, but real-time LCA remains rare and has not yet been widely implemented in real industrial systems.	Clarifies conceptual and practical differences between dynamic LCA and real-time LCA, supporting more precise terminology and future methodological development.	Specifically distinguishes dynamic assessment from real-time assessment and identifies opportunities for real-time LCA in Industry 4.0 and cyber-physical industrial systems.	Review-based; real-time LCA evidence remains limited; implementation barriers include data integration, monitoring infrastructure, modelling effort, and uncertain added value for industrial plants.
66	Solar panel production created the highest environmental burden, contributing around 30–34% of impacts; forecasted electricity generation avoided environmental impacts by 12–98 times the burdens created.	Shows how AI can strengthen LCA by forecasting operational variability and improving the environmental assessment of renewable energy systems.	Combines ANN forecasting with LCA to quantify how meteorological uncertainties influence life-cycle environmental performance.	Not maritime-specific; focused on one Malaysian solar plant; results depend on meteorological data quality, ANN accuracy, PV assumptions, and regional electricity context.
67	The solar panel system had an estimated payback time of around three years and could save more than \$300,000 in fuel costs over the vessel's lifetime.	Demonstrates that solar-assisted propulsion can provide environmental and economic benefits for short-route ferry operations.	Provides an integrated LCA–LCCA assessment of onboard solar panels for a real short-route ferry application.	Limited to short-route ferry operation; solar contribution is constrained by available deck area and weather conditions; results depend on investment cost, fuel price, solar efficiency, and route-specific operation.
68	Solar-based fuels achieved only 71–81% of the emission reductions of wind-based fuels; pilot fuel ratios can reduce dual-fuel benefits by up to 12.5%; fuel cells improved reduction performance compared with dual-fuel engines.	Provides corridor-specific evidence on how renewable fuel pathways, production regions, and onboard technologies influence decarbonization outcomes.	Integrates renewable fuel LCA with AIS-based operational data and uncertainty analysis across both WTT and TTW stages for a green shipping corridor.	Focused on one green corridor and selected renewable fuels; results depend on AIS data, renewable electricity assumptions, fuel production efficiencies, pilot fuel ratios, and onboard technology assumptions.

No.	Key findings	Contribution	Novelty	Limitations
69	Biofuels showed 65–85% mitigation potential using GWP20 and 78–87% using GWP100 compared with fossil fuels; future system changes could reduce biofuel climate impacts by up to 54% by 2050.	Demonstrates that drop-in biofuels can support deep-sea shipping decarbonization, especially where electrification is not feasible.	Combines prospective LCA, near-term climate forcers, future background system changes, and forest-residue biofuel pathways for deep-sea shipping.	Focused on Norwegian forest residues and selected biofuel pathways; results depend on biomass availability, conversion yields, transport distances, future scenarios, and climate metric selection.
70	Marine bio-oil performed best across the assessed criteria due to CO ₂ and methane consumption during production and low emissions during combustion.	Provides a broad comparative assessment of many marine fuel options across several environmental impact categories.	Evaluates a wide set of conventional, bio-based, electro-fuel, and alternative marine fuels using a harmonized WTW LCA framework.	Results depend on GREET assumptions, fuel pathway data, selected tanker model, impact categories, and fuel availability; economic, infrastructure, scalability, and operational variability are not fully captured.
71	Future climate scenarios increase environmental impacts, mainly due to precipitation variability; standardized fertilization and straw recycling can reduce environmental impacts by 12.31–63.38%.	Demonstrates how LCA and machine learning can support future-oriented environmental assessment and policy guidance for smallholder agricultural systems.	Couples process-based LCA with random forest machine learning to forecast environmental impacts under future climate and farming-practice scenarios.	Not maritime-specific; focused on wheat production in Gansu Province, China; results depend on survey data, climate scenario assumptions, machine-learning model accuracy, and selected farming-practice scenarios.

C.4 Role of Appendix C in Supporting the Thesis

The critical review matrix serves as the documented evidence base for the synthesis outlined in the thesis literature review. Recording both the contributions and limitations of each source facilitates the identification of methodological gaps concerning prospective, forecasting-oriented, dynamic, and real-time applications of LCA in maritime decarbonization. It also illustrates the foundation upon which the thesis situates its green corridor and port-level case studies within the broader literature.