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Energy Transition towards Sustainable Shipping: Environmental and Economic Life Cycle Considerations

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DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
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THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Abstract

Shipping accounts for over 80% of global trade by volume. Its heavy dependence on fossil fuels significantly impacts the climate, human health, and the environment. In response to increasing pressure to reduce shipping greenhouse gas (GHG) emissions, the International Maritime Organization has set an ambitious target of achieving net-zero emissions "by or around" 2050. However, the shipping sector remains a hard-to-abate industry due to its international nature and dependence on heavy fuel oil, a cheap and energy-dense option but highly polluting byproduct of crude oil refining. These challenges are compounded by system-level knowledge gaps, which hinder the development of informed decision-making and strategies to identify sustainable and economically viable alternatives.

The thesis adopts a systems-thinking approach to explore the energy transition of the shipping sector, focusing on environmental and economic trade-offs of alternative fuels and technologies for ships. It employs three tools: life cycle assessment (LCA), life cycle costing (LCC), and energy system modeling (ESM). Prospective life cycle thinking is used to assess emerging technologies through a novel Integrated Life Cycle Framework, enabling consistent economic and environmental evaluation of decarbonization scenarios by integrating LCA and LCC. The emerging technologies assessed are grouped into five key mitigation strategies: adoption of electro-fuels (e.g. e-methanol), blue fuels (e.g. blue ammonia), biofuels (e.g. biomethanol), battery-electric propulsion (e.g. lithium battery), and onboard carbon capture technology (e.g. post carbon capture). The assessment is performed for different types of ships.

The ESM tool used in this thesis is the Global Energy Transition (GET) model. The GET model is adapted to analyze possible shipping climate policy measures, with enhanced details (adding different ship types) in the shipping sector module and energy carrier supply chain. Additionally, LCA is integrated with GET to provide a comprehensive understanding of well-to-wake climate impacts while also evaluating other environmental effects linked to energy transitions.

The LCA results indicate that electro-fuels synthesized using wind power and used in fuel cells offer the greatest potential for GHG reduction and other environmental impacts among the assessed fuel and propulsion options. The LCC results show that all alternative fuel options have higher total life cycle costs compared to conventional diesel, with fuel costs being the key component. Among the options, bio-methanol and onboard carbon capture have the lowest carbon abatement costs. For ferries operating on short, regular routes, battery-electric propulsion stands out as the most promising option, offering both significant emission reductions and cost competitiveness. This is also reflected in GET result where battery-electric transition is the preferable option under different policies for ferries and cargo vessels operating in short distances. For long-distance shipping, ammonia is the most cost-effective fuel under different policy scenarios in GET. However, the LCA result shows the importance of reducing the emission of nitrogen-based compounds from ammonia-based engines which could lead to environmental impacts like eutrophication and acidification and limit GHG reductions. This thesis underscores the critical role of alternative fuels and fuel production routes in reducing climate impact and other impacts from the shipping sector. It also highlights the importance of addressing environmental trade-offs and economic challenges to support the development of sustainable and cost-effective strategies for decarbonizing this hard-to-abate sector.

Keywords: LCA, Energy system modeling, Ammonia, Methanol, Hydrogen, Batttery-electric

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List of appended papers

Paper I:

Kanchiralla F. M., Brynolf S., Malmgren E., Hansson J., & Grahn M. (2022). "*Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping*." Environmental Science & Technology, 10.1021/acs.est.2c03016. *https://doi.org/10.1021/acs.est.2c03016*

Author contribution: Writing - original draft, writing-review & editing, conceptualization, methodology, visualization, data collection, and formal analysis.

Paper II:

Kanchiralla F. M., Brynolf S., Olsson T., Ellis J., Hansson J., & Grahn M. (2023). "How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? A life cycle study." Applied Energy 2023 Vol. 350 DOI: 10.1016/j.apenergy.2023.121773

Author contribution: Writing - original draft, writing-review & editing, conceptualization, methodology, visualization, data collection, and formal analysis.

Paper III:

Kanchiralla, F. M., Brynolf S., and Mjelde A. (2024), "*Role of bio-fuels, electro-fuels, and blue fuels for shipping: environmental and economic life cycle considerations.*" Energy & Environmental Science 2024, DOI: 10.1039/D4EE01641F

Author contribution: Writing - original draft, writing-review & editing, conceptualization, methodology, visualization, data collection, and formal analysis.

Paper IV:

Kanchiralla F. M., Grunditz E., Brynolf S., Wikner E., and Nordelöf A. (2024), "*Environmental and economic assessment of electric ferries with different lithium-ion battery technologies*"; Submitted to Renewable and Sustainable Energy Reviews.

Author contribution: Writing - original draft, writing-review & editing, conceptualization, methodology, visualization, data collection, and formal analysis.

Paper V:

Kanchiralla F. M., Brynolf S., Hansson J., Grahn M. (2025) "*Shipping Fuel Choices and Well-to-Wake Environmental Impacts from an Integrated Energy System and Life Cycle Assessment Model under Decarbonization Policies.*"; In preparation

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List of additional publications and reports

B. Thaler, **F. M. Kanchiralla**, S. Posch, G. Pirker, A. Wimmer, S. Brynolf, and N. Wermuth, (2022) "Optimal design and operation of maritime energy systems based on renewable methanol and closed carbon cycles," Energy Convers. Manage., vol. 269, 2022, doi: 10.1016/j.enconman.2022.116064.

F. M. Kanchiralla, S. Brynolf and D. S. Reis de Oliveira (2024). “Heat Pump as an Emission Reduction Measure for Ships” Modelling and Optimisation of Ship Energy Systems 2023, DOI: 10.59490/moses.2023.668.

Selma Brynolf, Julia Hansson, **Fayas Malik Kanchiralla**, Elin Malmgren, Erik Fridell, Håkan Stripple, Pavinee Nojpanya (2022); Life Cycle Assessment of Marine Fuels in the Nordic Region; ; Nordic Roadmap Publication No.1-C/1/2022.

HyMethShip project deliverable for work packages 7 & 8; Selma Brynolf, Elin Malmgren, **Fayas Malik Kanchiralla**, Maria Grahn.

Kanchiralla. F. M, Brynolf. S, Malmgren. E, Grahn. M; “Can Shipping Contribute to Negative CO2 Emissions?”; 2nd International conference on negative CO2 emissions; Gothenburg; June 14 to 17, 2022.

F. M. Kanchiralla, "Life cycle navigation through future energy carriers and propulsion options for the energy transition in shipping," Licentiate of Engineering Licentiate, Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden, Technical report no 2023:05., 2023.

Hydrogen, ammonia, and battery-electric propulsion for future shipping; Brynolf. S, **Kanchiralla. F. M**, Malmgren. E, Ellis. J, Olsson. T, Hansson. J, Fridell. E, Light house report 2023.

Kanchiralla. F. M, Malmgren. E, Grahn. M, Brynolf. S; “Environmental and economic assessment of green and blue fuels for shipping” Joint TAP and S&E conference 2023; Gothenburg; 27-28 Sept 2023, Sweden

Kanchiralla. F. M., Brynolf. S; Integrating life cycle assessment and life cycle costing for evaluating decarbonization pathways in shipping; LCM 2023: The 11th International Conference on Life Cycle Management; , Lille, France, Sep 6-8, 2023

Kanchiralla, F. M., “A Novel Decision Support Platform for Selecting Optimal Decarbonization Strategies for Individual Ships: Integrating Life Cycle Cost and Sustainability Assessment” TRAVISION 2024, Dublin, Ireland

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Energinyckeltal och växthusgasutsläpp baserade på industrins energianvändande processer: Slutrapport; (2021) Patrik Thollander, Magnus Wallén, Curt Björk, Simon Johnsson, Joakim Haraldsson, Elias Andersson, Maria Andersson, Maria Johansson, Noor Jalo, **Fayas Malik Kanchiralla**

Wei S., **Kanchiralla F. M.**, Polinder H., Schulte. F, Tukker. A, Steubing, Bernhard. "Environmental impacts of fuel cell use in deep-sea shipping towards 2050" Submitted to Journal of Renewable & Sustainable Energy Reviews.

Wei S., **Kanchiralla F. M**., Schulte. F, Polinder H., Tukker. A, Steubing, Bernhard. "Life cycle assessment of hydrogen-based fuels use in internal combustion engines of container ships until 2050,"Submitted to Applied Energy.

Contents

Abbreviations, Acronyms, and Terminology

Abbreviations and acronyms

2SICE	2 Stroke Internal Combustion Engine
4SICE	4 Stroke Internal Combustion Engine
NH3	Ammonia
AEC	Alkaline Electrolyzer
AFIR	Alternative Fuels Infrastructure Regulation
ASU	Air Separation Unit
ATR	Autothermal reforming
BE	Battery-Electric
BEF	Battery Electric Ferry
BEV	Battery Electric Vehicle
CO_2	Carbon Dioxide
CO	Carbon monoxide
CAC	Carbon Emission Abatement Cost
CCAC	Climate and Clean Air Coalition
CF	Characterization Factor
CII	Carbon Intensity Indicator
CCS	Carbon Dioxide Capture and Storage
CH_2	Compressed Hydrogen (700 Bar)
cLCC	Conventional Life Cycle Costing
CSP	Concentrated Solar Power
CSI	Clean Shipping Index
DWT	Dead Weight Tonnage
DAC	Direct Air Capture
ET	Emerging Technology
ECA	Emission Control Area
EOL	End Of Life
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EF	Environmental Footprint
eLCC	Environmental Life Cycle Costing
ESM	Energy System Model
ETS	Emissions Trading System
EU	European Union
FC	Fuel Cell
FU	Functional Unit
GET	Global Energy Transition
GWP	Global Warming Potential
GHG	Greenhouse Gas
GT	Gross Tonnage
HC	Hydrocarbons
HFO	Heavy Fuel Oil

HVO	Hydrotreated Vegetable Oil
HYB	Hybrid
ILCF	Integrated Life Cycle Framework
ICE	Internal Combustion Engine
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LFP	Lithium Iron Phosphate
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LH2	Liquefied Hydrogen
LHV	Lower Heating Value
LMG	Liquefied Methane Gas
LNG	Liquefied Natural Gas
LBG	Liquefied Biogas
LPDF	Low-Pressure Dual Fuel
MeOH	Methanol
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MRL	Manufacturing Readiness Level
MRV	Monitoring, Reporting and Verification
N_2O	Nitrous Oxide
NOx	Nitrogen Oxides
NMC	Nickel Manganese Cobalt
NMVOC	Non Methane Volatile Organic Compounds
NV	Normalized Value
NF	Normalization Factors
OCC	Onboard Carbon Capture
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
PostCC	Post Combustion Carbon Capture
pLCA	Prospective Life Cycle Assessment
PEMEC	Proton-Exchange Membrane Electrolyzer
PEMFC	Proton-Exchange Membrane Fuel Cell
PSM	Powertrain and Fuel Storage Mass
PV	Photovoltaic
RCP	Representative Concentration Pathway
RED	Renewable Energy Directive
RoPax	Roll-On/Roll-off Passenger Ferry
SCR	Selective Catalytic Reduction
SEEMP	Ship Energy Efficiency Management Plan
sLCA	Social Life Cycle Assessment
SETAC	Society of Environmental Toxicology and Chemistry
SMR	Steam Methane Reforming

SOEC	Solid Oxide Electrolyzer
SOFC	Solid Oxide Fuel Cell
SIICE	Spark Ignition Internal Combustion Engine
SOP	Surplus Ore Potential
SSP	Shared Socioeconomic Pathways
TtW	Tank-To-Wake
TEA	Techno-Economic Assessment
TRL	Technological Readiness Level
UNEP	United Nations Environment Programme
PSV	Powertrain and Fuel Storage Volume
WtT	Well-To-Tank
WtW	Well-To-Wake

Terminology

Acidification: Acidification is caused by the emission of substances that lead to acid rain and acidification of air, water, and soil. The decline of coniferous forests and the increase in fish mortality have been attributed to acidification. For instance, when released gaseous SO_2 reaches a body of water, it reacts with water to form acid. When acids (and compounds that can be converted to acids) are emitted into the atmosphere and deposited in water and soil, the addition of hydrogen ions (H^+) may cause the pH of the water body to decrease.

Allocation: Allocation refers to the distribution of flows between multiple units. In LCA, the product system is divided into different parts or sub-systems, and then the inputs and outputs of each part are assigned to its corresponding impact categories. Division of flows is done using different criteria such as physical relationship or economic value.

Bio-fuels: Fuels produced from biomass that can be considered carbon neutral as biogenic carbon is released from these sources when combusted and can be absorbed again in the growth of new biomass.

Biogenic: The biogenic refers to carbon from biomass which initially being absorbed in growing biomass, from the atmosphere, and released back into the atmosphere again through e.g., the combustion of biofuels.

Blue fuels: These are fuels synthesized using hydrogen produced by removing carbon from fossil fuels and storing the carbon permanently to prevent its release into the atmosphere.

Characterization factors: Factors derived from the selected characterization model that is used to convert an assigned life cycle inventory to the common unit of the category indicator. There are characterization factors both at midpoints and endpoints.

Climate change: Refers to the climate changes caused by the emissions of greenhouse gases, such as CO_2, N_2O, and CH_4, into the Earth's atmosphere. Human activity has resulted in the accumulation of greenhouse gases in the atmosphere, which over the past few centuries has enhanced the natural greenhouse effect that warms the atmosphere. Consequences include an increase in average global temperatures and abrupt regional climatic changes.

Ecotoxicity – freshwater: Emission of substance that contributes to ecotoxicity that alters the function and structure of an ecosystem by exerting toxic effects on its inhabitants. Toxic effects can occur immediately (acute ecotoxicity) or after repeated or prolonged exposure to the substances (chronic ecotoxicity). Substances that have a low rate of decomposition in the environment and, as a result, can persist for an extended period after their release, are frequently the source of chronic ecotoxicity.

Electrochemical combustion: Electrochemical combustion refers to the chemical reaction between a fuel and an oxidant at the electrodes of the fuel cell, which releases energy mainly in the form of electricity and also some heat.

Electro-fuels: Electro-fuels or e-fuels are synthetically produced energy carriers that contain electrolytic hydrogen produced by the electrolysis of water using electricity, directly or chemically bonded with carbon or nitrogen.

Endpoint: Refers to the final effect on the three areas of protection including human health, natural environment, and natural resources.

Energy carriers: Refers to substance or medium that stores energy in a usable form and can be transported to where it is needed, making it possible to use the energy to perform work, generate heat, or produce electricity.

Energy Systems Modeling: A modeling tool that mathematically represents possibilities and challenges related to energy conversions in energy systems. As a tool, it can represent energy systems at different temporal, sectoral, and spatial resolutions.

Environmental assimilative capacity: Refers to the ability of an ecosystem to absorb and process waste and pollutants without disrupting its balance and functioning. It is a measure of the tolerance of the environment to degradation and depends on factors such as the size and complexity of the ecosystem, the rate of waste production, and the availability of natural resources.

Eutrophication – freshwater: The effect on nutrient balance in freshwater ecosystems due to the emission of substances containing nitrogen or phosphorus. In lakes and rivers, this will be mainly due to the increase of phosphorus. Algae that grow too quickly can deplete the water of oxygen, leaving fish unable to survive once the algae die and decompose (which consumes oxygen). The most significant sources of emissions of phosphorus are sewage treatment plants and leaching from agricultural land.

Eutrophication – marine: The effect on nutrient balance in marine ecosystems due to the emission of substances containing nitrogen or phosphorus. In the marine environment, it is mainly due to an increase in nitrogen levels leading to significant growth of algae and specific organisms disturbing the balance of nature.

Eutrophication – terrestrial: The effect on nutrient balance in terrestrial ecosystems due to the emission of substances containing nitrogen or phosphorus. In general, the availability of one of these nutrients will be a limiting factor for ecosystem growth, and if this nutrient is added, the growth of algae or specific plants will be enhanced. On land, ecosystems that require a low-nutrient environment are vanishing, primarily because of nitrogen fertilization.

Feebate System: A policy tool used to encourage environmentally friendly practices by imposing fees on less efficient or more polluting options and providing rebates or incentives for more efficient or less polluting ones. The term “feebate” is a combination of “fee” and “rebate”.

Functional unit: The reference flow used in LCA to compare the environmental impacts of different products or services. This reference flow should represent the function of the system under assessment.

Fossil Fuels: Fuels origin from ancient organic materials (millions of years ago) including coal, natural gas, crude oil, and their derivatives as petroleum products, coke, and derived gases. Also, non-renewable wastes are defined as fossil. Fossil energy sources are characterized by their finite nature. Carbon emitted from fossil fuels adds to the existing atmospheric CO_2 concentration

Hard-to-abate sector: Sectors that face significant challenges in decarbonization, due to the nature of their operations, processes, as well as involved stakeholders, and thus these sectors show heavy reliance on fossil fuels.

Human toxicity – cancer effects: Environmental exposure to chemicals emitted as a result of human activities can lead to an increased risk of cancer. Additionally, the substance's behavior must be considered, as there are multiple routes of human exposure. The most significant routes of exposure involve inhaling contaminated air or ingesting contaminated food or water.

Human toxicity – non-cancer effects: Environmental exposure to toxic substances damaging human health emitted as a result of human activities. The substance's behavior based on routes of exposure such as inhalation of air or ingestion of other materials, such as food or water must be considered.

Ionizing radiation: Exposure to radiation can have adverse health effects on humans. The modeling begins with releases measured in Becquerel at the point of emission. Given the radiation levels determined by the fate analysis, the exposure analysis computes the dose that a human absorbs. The effective dose is measured in Sieverts, based on human body equivalence factors for the various types of ionizing radiation.

Land use: Due to occupation and transformation of land, changes in the fertility of the soil or have pressures on the availability of soil as a resource. Agricultural production, mineral extraction, and human settlement are examples of land use. The process of converting land from one use to another is known as transformation. Loss of species, soil organic matter content, decreased primary production, and loss of soil ("erosion") are a few of the potential consequences.

Life cycle assessment: Method for the environmental assessment of products and services, covering cradle to grave (raw material extraction to disposal).

Life cycle costing: Method for assessing the economic performance of products and services considering the entire life cycle covering cradle to grave.

Midpoint: Refers to the intermediate environmental impact categories in LCA, such as acidification, resource use, or global warming potential. This is considered a link between the cause-effect chain of impact categories.

Natural resources: Refers to any material or substance that occurs naturally and can be used to produce goods and services. In LCA, it is considered as an area of protection.

Ozone depletion: The stratospheric ozone (O_3) layer (which can range in height from 8 km to 50 km) shields us from harmful ultraviolet radiation (UV-B). Its depletion can result in an increase in the incidence of human skin cancer and plant damage. As a result of human emissions of halocarbons (as CFCs and HCFCs), halons, and other long-lived gases containing chloride and bromine, stratospheric O_3 is degraded. Therefore, the ozone content of the stratosphere was decreasing, and since 1985, a dramatic temporary thinning of the ozone layer, commonly known as an "ozone hole," has been observed annually over the South Pole. In recent years, the issue has diminished as a result of the international ban on substances that contribute to ozone depletion.

Particulate matter: Emissions of primary and secondary particulates increase concentrations of "dust" or particulate matter (PM) in the environment. The mechanism for the production of secondary emissions involves SO_2 and NOx emissions, which produce sulfate and nitrate aerosols. Total suspended particulates (TSP), particulate matter less than 10 micrometers in diameter (PM10), particulate matter less than 2.5 micrometers in diameter (PM2.5), and particulate matter less than 0.1 micrometers in diameter (PM0.1) are all ways to measure particulate matter. Typically, the smaller they are, the more dangerous the particles are because they can penetrate deeper into the lungs.

Photochemical ozone formation: While ozone in the stratosphere is necessary to shield harmful ultraviolet radiation, ozone in the troposphere is harmful to organic compounds and the respiratory systems of humans. This causes an increase in the frequency of respiratory problems in humans during periods of photochemical smog in cities ("summer smog"). Solvents and other volatile organic compounds (VOCs) that are released into the atmosphere (e.g., from combustion processes) can be degraded within a few days. Under the influence of sunlight, ozone formation is possible in the presence of nitrogen oxides.

Resource use – fossils: There is a finite amount of non-renewable resources on Earth, such as coal, oil, and natural gas. Utilization of resources may reduce the availability of their potential functions.

Resource use – metals and minerals: The amount of non-renewable resources, such as metals and minerals, on Earth is limited. Utilization of resources may reduce the availability of their potential functions.

Resource use – water: The extraction of water from lakes, rivers, or groundwater can contribute to the "depletion" of available fresh water for future use.

RoPax: RoPax are roll-on/roll-off ships that are designed to transport freight vehicles along with passenger accommodation.

Service vessel: These vessels are designed to perform support to other vessels such as fairway maintenance, towing vessel, ice-breaking, etc.

Tanker: A tanker is a ship type that is designed specifically to transport liquids or gases in bulk quantities.

Technological system: From a systems perspective, a technological system is a complex arrangement of interrelated components, processes, raw materials, and energy sources that are designed and operated for a specific purpose or set of purposes such as transporting people or goods.

Transport work: Refers to mechanical work performed by a force on an object as it moves a distance in the direction of the force, eg: one tonne-kilometer means a movement of one-tonne goods one kilometer.

1. Introduction

Ships transport over 80% of the volume of global trade and form the backbone of international trade and the global economy [1]. However, ship transport accounts for around 3 % of the global greenhouse gas (GHG) emissions [2] and also the emission of different air pollutants, including sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), and hydrocarbons (HC). Around 70% of ship emissions happen within 400 kilometers of the coast, having short-term and long-term effects on the natural environment and human health [3, 4]. The emissions are directly related to the shipping sector's high reliance on fossil fuels with a predominant share of heavy fuel oil (HFO) (70%) and marine gas oil (MGO) (29%) [2]. By 2050, ship transport is projected to grow by possibly 57% up to 126% by 2050 relative to 2018, depending on different assumptions regarding socio-economic development [2]. If the shipping industry continues to use fossil fuels, these emissions could reach up to 130% of their 2008 levels by 2050 [5].

The pressure to decarbonize the shipping industry is increasing, and the International Maritime Organization (IMO) has updated the GHG targets for international shipping to achieve net zero by 2050. Since ships have a long service life of about 20-40 years, ships built today will have an impact on future GHG targets (unless retrofitted). Therefore, new ships entering the fleet today would need to be able to run on climate-neutral energy carriers (or relatively easily be retrofitted) to meet the GHG targets. In terms of present order booking, there is an increase in the number of battery/hybrid ships but most ships in the order book are still for conventional combustion engines, and a few are capable of operating on methanol and hydrogen [6]. The ordered battery/hybrid are mostly smaller ships like ferries or inland ships [6] and their share in terms of total gross tonnage is meager. Currently, the average ship age of the fleet is increasing indicating that many ships need to be replaced soon [5]. Together with the expected transport growth, this decade would be a decisive decade for taking important steps towards the energy transition of the shipping fleet.

Regarding energy transition, the shipping industry is commonly perceived as hard to abate due to numerous challenges, one of them being the international nature of shipping (like aviation), which complicates the allocation of emissions to individual nations/regions [7]. Another challenge is the heterogeneous nature of ships in terms of function, operation, and size. These are influenced by a variety of factors, including the type of transportation work they carry out, the length of their journey (ranging from a few nautical miles to a thousand nautical miles), the speed at which they are designed, the frequency of bunkering (ranging from several times a day to a few times a year), and the operating routes (ranging from inland to deep sea). Another challenge as already mentioned is that the shipping sector relies on low-cost and heavy fractions of oil (predominantly heavy fuel oil (HFO) whose cost is lower than crude oil itself) that have a high energy density. The main candidates of carbon-neutral energy carriers (e.g. hydrogen, ammonia, methanol, methane) are unable to meet the cost and volumetric/gravimetric energy density of these fuels [8]. In addition to the difference in energy densities, each energy carrier has different properties like toxicity, flammability, ignition temperatures, corrosivity, boiling point, etc [9]. The toxicity associated with fuel will affect its use onboard and may need additional safety measures [10]. Combustion properties including flammability and ignition temperature will affect the efficiency of energy conversion and related emissions [11]. The boiling point, flash point energy density, and corrosivity will define the onboard storage requirements. Because of this, the amount of space or weight that is available will vary for various energy carriers and also depend on the ship's design, as well as its function, route, and mode of operation. This diversity in the vessel's functionality would have different implications for each energy carrier and their adoption.

Apart from the challenges above, when using alternative energy carriers there is risk associated with the transfer of environmental burden upstream in fuel production or supply chain [12]. Presently, most of the alternative energy carriers are produced from fossil fuels (predominantly from coal or natural gas) [13]. This means that the emission of fossil carbon is not prevented, as it will be released during fuel production. Hence it is important to produce the fuels via pathways using renewable energy or pathways where the emission of fossil carbon is avoided [13]. Most of the technologies in the fuel supply chain associated with low carbon intensity are still in the early stage of development and/or are not yet widely available [6] making it difficult to understand the environmental tradeoffs. Also, the energy transition of shipping needs to be supported by the development of new technological systems around the energy carrier like production and distribution infrastructure [6, 14]. These new developments need large investments and regulatory support. From a ship owner's perspective, choosing a decarbonization solution, in the form of an alternative energy carrier, involves a complex tangle of economic, regulatory, and environmental priorities [15]. In this thesis, a decarbonization pathway refers to a particular technological system capable of reducing climate impact. A technological system is a dynamic network of agents engaged in the production, dissemination, and use of technology within a certain economic/industrial domain and operating within a given set of institutions [16]. Transitions facilitate changes in both the technologies and products, as well as in the nature of their interconnections [17]. The technological system includes a combination of an energy carrier's production technology, technology associated with supply and distribution, storage technology, and powertrain technology associated with its use.

The shipping energy transition refers to the global shift of energy used in shipping fleets from fossil-based fuels to alternative energy carriers with low or no GHG emissions or other decarbonization technology aiming to reduce the climate impact of shipping. The shipping transition is complex due to its direct dependence on the fuel supply chain. This complexity increases when considering that the transition is not isolated; it is influenced by various interconnected sectors. For instance, the energy sector's shift towards renewable sources, the industry's adaptation to new energy standards, and the transport sector's move towards alternative fuels all play crucial roles. These sectors collectively impact the viability of the energy transition of shipping. Another example is the role of shipping in the transport of energy related products, these energy related trade dynamics will also change with the energy transition of other sectors. Hence, strategies or regulations for shipping energy transition also must take into account the global energy system, rather than focusing just on the shipping and fuel supply chain.

1.1. Policy landscape

Policies specific to shipping will be crucial in the decarbonization of ships. However, global policies for international shipping are complex to realize due to different aspects including; i) the non-point and mobility nature of the emission sources, ii) national disagreements, iii) many different types of stakeholders (shipowner, ship operator, freight forwarder and, ultimately, the customer), iv) unclear accountability of emissions (i.e. should it be based on where the ship's fuel is sold, where a ship is registered, or the origins or destinations of the ship's cargo?) [18]. Table 1 presents an overview of significant policies at both global and regional levels that can impact GHG emissions from shipping. There are several policies at other levels, e.g., at the port and national level that can also impact the emissions from shipping (e.g. port levy in Sweden). Policies may be further classified based on approach, which can be voluntary, market-based, or regulatory [19].

Table 1: Overview of major policies at global and regional levels that can have an influence on the GHG emissions from shipping.

Scope	Name of policy	Implementation Year	Policy type	Included type, size, and part of the shipping sector
Global (IMO)	MARPOL Annex VI sulfur limits	2005	Regulatory	0.50% m/m sulfur limit on fuel from 1 Jan 2020 in all areas and ECA can have a regulation of 0.10% m/m. Designated areas can have SOx and NOx emission limits
	Energy Efficiency Operational Indicator (EEOI)	2009	Voluntary	Voluntary monitoring instrument which applies to new and existing ships to assess fuel efficiency.
	Ship Energy Efficient Management Plan (SEEMP)	2011	Regulatory	Mandatory energy efficiency management and reporting for ships with more than 400 GT to control CO_2 and other GHG emissions.
	Energy Efficiency Design Index for new ships (EEDI)	2011	Regulatory	Achieve certain level of energy efficiency for new ships using ship designs compared to the reference value and is expected to reduce overall CO2-emissions. Applicable to 12 ship types
	International Code for Ships Operating in Polar Water (Polar Code)	2014	Regulatory	The Polar Code, regulates shipping in Arctica and Antarctica. Ships with more than 500 GT, except fishing vessels and sovereign vessels.
	Data Collection System (DSC)	2014	Regulatory	Data collection is mandatory and has to be reported to the flag State by the end of each year, which submit the data to the IMO Ship Fuel Oil Consumption Database (vessels >5000 GT)
	Carbon Intensity Indicator (CII)	2022	Regulatory	Rating the operational energy efficiency of ships from A to E (based on DCS and the SEEMP) and ship owner to implement a plan of corrective actions. Vessels >5000 GT.
	Energy Efficiency Existing Ship Index (EEXI)	2022	Regulatory	Certification for "technical" or "design" efficiency attained for ship (EEDI levels). Vessels > 400 GT
Global (Others)	Clean Shipping Index (CSI)	2007	Voluntary	Voluntary labeling system of environmental performance for SOx, NOx, CO2, PM, chemicals, water, waste
	Climate and Clean Air Coalition (CCAC)	2012	Voluntary	Voluntary partnerships including transportation with more than 300 partners.
	Environmental Ship Index (ESI)	2011	Voluntary/ Market-based	Voluntary, based on an incentive system that rewards the reduction of air pollutants, CO2, and noise for ships and ports.
Regional	Operational Guidelines – Arctic	2003	Voluntary	Association of Arctic Expedition Cruise Operators (AECO) provides environmental and safety guidelines to its members
	Monitoring, Reporting and Verification scheme (MRV)	2015	Regulatory	Vessels > 5000 GT shall monitor and report annual data on GHG emissions, fuel consumption and other parameters.
	FuelEU maritime Regulation	2023	Regulatory	Ships will have to comply with energy GHG intensity reduction targets: 2% from 2025, 6% from 2030, 14.5% from 2035, 31% from 2040, 62% from 2045, 80% from 2050. Baseline for the calculation of the annual GHG targets is set at 91.16 gCO2e/MJ
	EU emissions trading system (ETS)	2023	Market-based	The extension of the EU ETS to maritime transport stepwise and by 2026 applies to 100% of emissions from intra-EU/EEA voyages, half of the emissions from extra-EU/EEA voyages and emissions occurring at berth in EU ports.
	Alternative Fuels Infrastructure Regulation (AFIR)	2023	Regulatory	Mandatory targets for deploying infrastructure at ports for shore-side electricity or alternative equivalent zero-emission energy sources during berth for passenger ships and container ships.
	Renewable Energy Directive (RED)	2023	Regulatory	Member States with maritime ports should ensure specific share of renewable fuels of non-biological origin in the total amount of energy supplied to the maritime transport sector.

IMO has revised its GHG target in 2023 aiming for at least a 20% reduction in emissions by 2030, a 70% reduction by 2040 (compared to 2008 levels), and the ultimate goal of achieving net-zero emissions by or around 2050. There are also sub-goals to achieve uptake of zero or near-zero GHG emissions technologies, fuels, and/or energy sources, representing at least 5% of the energy used by international shipping while striving for 10% by 2030. Present policies imposed by the IMO, mainly target the improvement in the vessels' energy efficiency rather than transition towards zero or near-zero-carbon fuels. These energy efficiency improvement policies include the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) with a goal to encourage the utilization of equipment that is more energy efficient in newly constructed ships and to improve energy efficiency from an operational point of view within the ship [20]. Other policies under the framework of the IMO greenhouse gas strategy are the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), both adopted in June 2021 [21, 22]. EEXI certification targets design and technical parameters for existing ships. It is applicable to existing ships of 400 GT and above are required to calculate their EEXI and then reach a reference value. The CII rating targets the operational energy efficiency of ships and is mandatory for ships of 5000 GT and above [23]. The rating (indicating performance level) is given on a scale of A, B, C, D or E, with A for the highest performer and E being the lowest performer [23]. Ships having low ratings (D or E) for 3 consecutive years must develop a Plan of corrective actions [21]. It may also be noted that presently there are no market-based policies agreed upon at the global level that could promote the use of decarbonization technologies. However, there are active discussions on implementing policy measures consisting of two parts, the first one a goal-based fuel standards for the fuels used in shipping and the second one is a market-based tool like credit trading and/or GHG levy [24].

At the EU level, the EU Emissions Trading System (ETS) is extended to cover CO_2 emissions from the maritime sector and is applicable for ships larger than 5,000 GT arriving at EU ports, regardless of their flag. EU ETS is a market-based policy known as 'cap and trade' where shipping companies have to purchase and surrender (use), EU ETS emission allowances for each tonne of reported CO_2 emissions in the scope of the EU ETS system (overall ETS cap) [25]. The cap is reduced over time and hence EU ETS is aimed to incentivize both energy efficiency measures and energy transition to alternative sources [25]. Emissions inclusion in EU-ETS is also stepwise, 40% of verified CO_2 emissions in 2024, 70% in 2025, and then 100% in 2026. From 2026 also CH_4 and N_2O will be included. The new FuelEU Maritime Regulation aims to drive the demand for renewable and low-carbon maritime fuels with targets to reduce the energy GHG intensity reduction. These regulations apply to vessels larger than 5,000 GT and will from 2026 include 100% of emissions on voyages between EU ports, 100% of at-berth emissions, and 50% of emissions on voyages between an EU port and one outside the EU [26]. In contrast to the IMO policies, the FuelEU Maritime Regulation targets fuel switches but not energy efficiency measures for ships. There has also been an addition in the Alternative Fuels Infrastructure Regulation (AFIR) with targets for deploying infrastructure at ports for shore-side electricity or alternative equivalent zero-emission energy sources during berth for passenger ships and container ships [27]. To ensure the availability of the fuel as required, the Renewable Energy Directive is revised to ensure a specific share of renewable fuels of non-biological origin in the total amount of energy supplied to the maritime transport sector [27].

1.2. Motivation and aim

Climate change, air pollution, and biodiversity losses are seen as three interconnected concerns currently confronted by humanity, commonly referred to as the triple planetary crisis [28]. The maritime sector's impact on these planetary crises is significant, including the emission of GHG and other air pollutants from combustion [3], discharge of oily residues and polluted water (e.g. scrubber water) to the marine environment [29], transfer of invasive species [30], leakage of biocides from antifouling paint [31], and discharge of chemicals from tank cleaning operations

[32]. The emission of GHG and other air pollutants and the discharge of oily residues are directly linked to fossil fuel used onboard [33]. Energy transition of shipping primarily targets reducing GHG emissions associated with the energy use however the transition can lead to shifting GHG emissions to other sectors [34] (e.g., using hydrogen produced from coal shifts the GHG emissions to the hydrogen production processes [35] and the use of electricity directly leads to emissions linked to electricity production). The potential for environmental burden shifting is an additional concern to consider during the energy transition [36] (e.g., the emission of nitrogen compounds like ammonia, nitrogen monoxide, nitrogen dioxide, and dinitrogen oxide when using ammonia [37]). Energy transition in the shipping sector also needs to ensure that the shift does not impact environmental assimilative capacity (e.g., the improper disposal of batteries for electric ships) [9]. Also, most of the pathways involved in the energy transition entail higher costs than conventional options with both investment and operational expenditures [8].

The main purpose of this thesis is to employ systems thinking to contribute to a comprehensive understanding of the energy transition of the shipping sector and its associated environmental and economic tradeoffs. A 'systems thinking' of a technological system can provide a holistic view of the performance of the technological system for economic, environmental, and social aspects [38]. Three tools based on the systems perspective are used in this thesis: life cycle assessment (LCA), life cycle costing (LCC), and energy system modeling (ESM). LCA and LCC are used to evaluate the environmental and economic performance of decarbonization pathways respectively [39]. These tools are based on life cycle thinking, a prevalent concept rooted in systems thinking considering the life cycle of a product or service (cradle-to-grave) [40]. ESMs are mathematical models developed to represent selected parts of the energy system or the whole energy system. Many ESMs are optimization models applying cost optimization to identify the lowest cost distribution of different energy carriers satisfying the energy demand from different end-use sectors to achieve environmental and policy targets [41].

For shipping, different decarbonization pathways are evaluated in earlier studies for energy utilization [42, 43], in terms of environmental impacts using life cycle assessment (LCA) [44-47], and cost assessments [43, 44, 48, 49]. Some studies evaluated the cost of different fuels on different vessel types [8, 50, 51]. For example, Korberg et al. [8] have evaluated the cost of ownership for various fuels for large ferries, general cargo, bulk carriers, and container vessels. Horvath et al. [51] have performed techno-economic assessments of short-sea, deep-sea, and container vessels. The aforementioned LCA or techno-economic assessment (TEA) studies are done independently either to understand environmental or cost performance. From the mentioned studies, it would be difficult to understand both environmental and cost tradeoffs consistently because of differences in terms of decision-making perspective, goal and scope, and inventories considered [52]. Most of the previous LCA studies [12, 45, 53] have not considered the impact of the production of capital equipment and infrastructure requirements [33] and have considered different system boundaries. That is, using life cycle tools independently without integrating/harmonizing the data, perspective, and inventories for both cost and environmental assessment can lead to inconsistent or conflicting results [9] (e.g. using the cost of a specific battery type and inventory data of another battery type). The complex nature of emerging technological systems is another challenge associated with the life cycle assessment of emerging technologies, in this case, with ship powertrain and fuel supply chains. Hence in addition to linking both tools, the assessment should include consistent modeling of prospective scenarios of technologies that are not yet fully developed or commercially available [54]. LCA, LCC, and prospective scenario modeling need to be harmonized to understand environmental and cost tradeoffs. The need for harmonization prompts the first research question in this thesis, leading to the development of an integrated tool in this thesis.

RQ1: ***How can life cycle assessment and life cycle costing be integrated for assessing prospective energy transition pathways associated with the shipping sector?***

It is not the same activities and technologies that are needed for various shipping decarbonization pathways. Material, emission, and cost flows associated with these activities are different and result in different energy needs, environmental impacts, and costs. Primary energy, material demand, the inventory flows over the life cycle vary depending on energy demands for ship operation, powertrain efficiencies, and fuel production routes [43]. It is therefore important to understand which factors contribute the most to the overall environmental impact and total cost. Ship's energy demand varies with ship types based on fuel consumption, power capacity, function, voyage length, operation style, and design. Also, the technological systems assessed are diverse, as the power conversion technologies have different power densities and energy efficiencies. In addition, differences in the properties of energy carriers (like energy densities, storage parameters, boiling point, and toxicity) will affect the storage requirement onboard. This diversity may impact the selection of a technological system from a systems perspective for a particular vessel, as different systems have different implications. The second research question analyzed in this thesis is related to the cradle-to-grave performance of different decarbonization pathways.

RQ2: ***How can integrated assessment of environmental, economic, and energy performance of shipping energy transition pathways improve the understanding of the potential for different energy carriers derived from various feedstocks for different ship types?***

The maritime sector is heavily invested in fossil fuel-based technologies and the transitioning to new technologies requires overcoming this lock-in, which involves significant cost and resource investments. Even though life cycle tools like LCC help to understand the cost perspective of the pathways they typically focus only on specific functions and often do not include the market factors (demand and supply) or interaction between sectors. Another aspect that is missing in the LCC is the time evolution of technologies and the availability of resources. An ESM can close this gap by identifying a cost-minimization distribution of different energy carriers, satisfying the energy demand of different end-use sectors, while meeting the emissions constraints implied by climate targets [41]. Only limited ESM studies have focused on the energy transition of shipping fleets from a global context considering other sectors [55-57] and even fewer have considered including representative ship types in the ESM [55, 57]. ESMs can illustrate the regulatory impact, technological development, and transport demand specific to the shipping sector. The influence of different prospective shipping policies on the energy transition, considering other energy sectors and the diversity within the shipping sector, is underexplored in scientific literature. Further integrating life cycle thinking in ESM enhances the understanding of climate and environmental impacts of the entire system. Such an integrated approach is used to understand the environmental impacts of the energy transition of the energy sector [41, 58], however, this study is the first to assess the environmental impact of the energy transition of the shipping sector under different policy scenarios. The third research question explored in this thesis is related to this assessment of well-to-wake environmental impacts of shipping energy transition.

RQ3: ***How can the integration of LCA and ESM increase the understanding of well-to-wake environmental impacts linked to cost-effective fuel transition pathways for decarbonization of the global shipping sector reflecting different policy ambitions?***

Researchers, policymakers, and stakeholders in the maritime industry, including shipbuilders, ship operators, and regulators are the main target audiences for this thesis. It could also be of interest to environmental organizations and academics working in the fields of energy and environmental management. This knowledge could be important when formulating overarching policies and strategies or implementing measures to accelerate the decarbonization of the shipping sector.

Two methodological approaches are used in this thesis: life cycle thinking and energy system modeling. Several tools associated with these overall approaches are used in the thesis and appended papers including LCA, LCC, predictive scenario modeling, and the use of the global energy transition (GET) model. Figure 1 shows the overall research approach used in this thesis, showing how the three research questions are connected to appended papers. It also shows the more specific questions that arose during the time of this thesis resulting in the appended papers. Papers I-IV use integrated life cycle methods, and Paper V uses ESM linked with LCA.

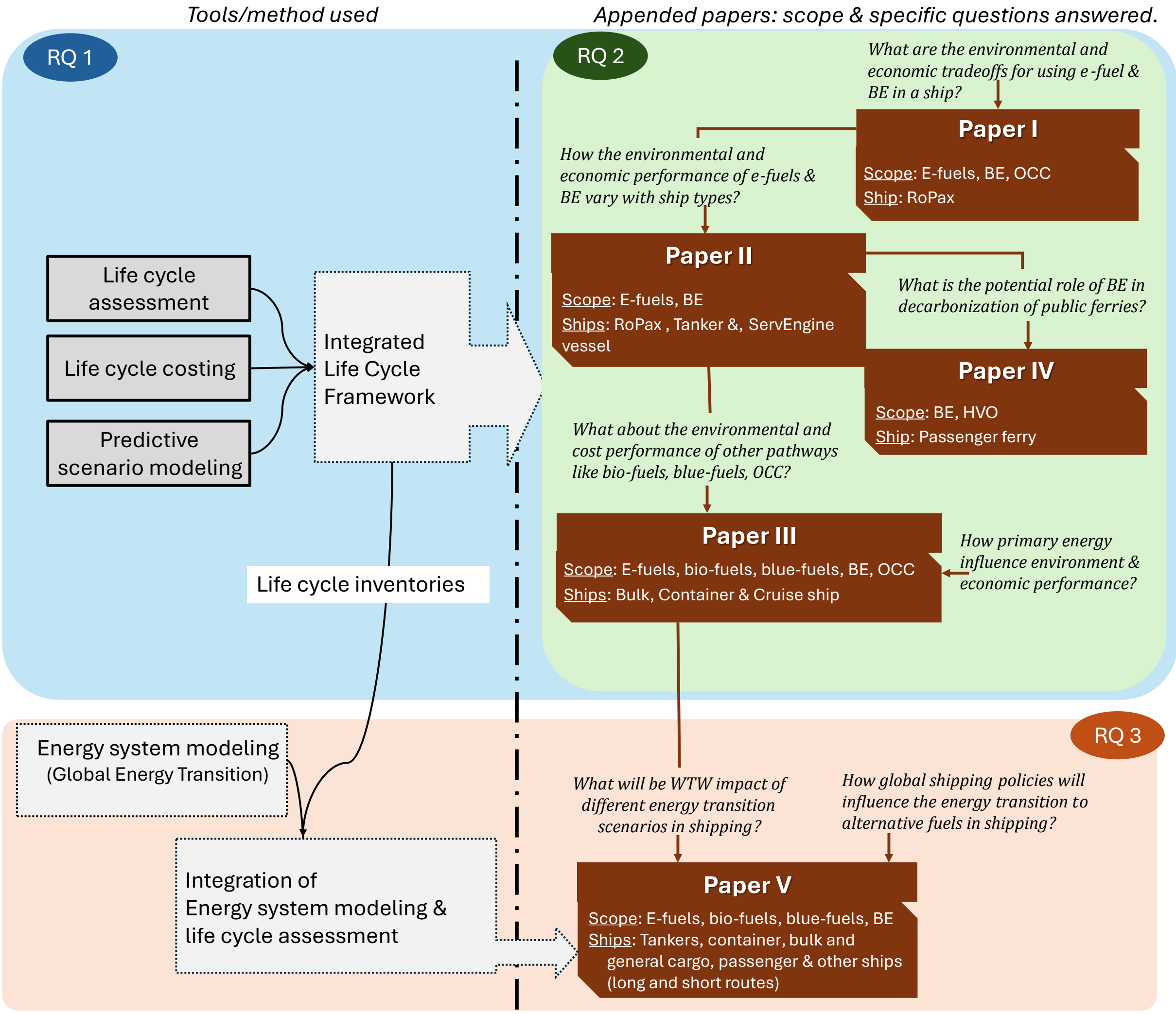

Figure 1: Research approach used in this study and the more specific research questions addressed in different papers, BE: Battery electric, WTW: Well to wake, HVO: Hydrotreated vegetable oil, OCC: Onboard carbon capture, RQ: Research Question.

1.3. Scope and delimitation

In the thesis, five key mitigation routes are considered including direct electrification, onboard carbon capture, and three specific categories of fuel are considered: e-fuels, bio-fuels, and blue fuels. There are several potential candidate of alternative fuels within these three categories of fuels including e.g., methanol (MeOH), ammonia (NH3), methane, dimethyl ether, kerosene, diesel, and hydrogen. However, the choices assessed in this thesis are limited to MeOH (as liquid carbon-based fuel), liquefied methane (LMG) (as gaseous carbon-based fuel), NH3 (as nitrogen-based fuel), liquid hydrogen (LH2) and compressed hydrogen (CH2) (as direct use of hydrogen), and hydrotreated vegetable oil (HVO) (as a diesel alternative). These are in addition to the use of carbon capture storage for fossil fuels (MGO and liquefied natural gas (LNG)) and direct electrification. The environmental impact and cost greatly depend on the feedstock and technology used. More details are given in Chapter 5. Emission of carbon needs to be treated with caution in LCA for carbon-based fuels like methane and MeOH [58] because impacts are different depending on the source of carbon. In the thesis and appended paper, atmospheric CO_2 captured using direct air capture (DAC) is considered for producing e-methanol (eMeOH) and liquefied e-methane (eLMG). Carbon derived directly from fossil sources is disregarded in the thesis as a source of CO_2 because when using fossil carbon, fossil CO_2 emissions to the atmosphere are only postponed [59]. For bio-methanol (bioMeOH) and liquefied bio-methane (bioLMG), the carbon comes from biomass, a biogenic source. Blue fuels considered in the thesis are liquid hydrogen and ammonia. Methanol production from natural gas is not considered a blue fuel alternative since carbon is of fossil origin, and since carbon is part of the methanol molecule, it is not possible to remove all fossil carbon. Another option is capturing and storing fossil carbon and adding carbon from DAC, however, the entire process with such an approach will result in high energy intensity and is not considered.

All fuels studied in this thesis except fossil fuels are investigated in different powertrain configurations including internal combustion engine (ICE) and fuel cell (FC). The battery-electric (BE) option where electricity is the energy carrier is investigated by considering different choices of battery types with different chemistries including nickel manganese cobalt (NMC) and lithium iron phosphate (LFP). Different battery charging scenarios are also included in the scope of the life cycle assessment in Paper IV. This thesis also evaluates the use of post- and pre-combustion onboard a ship for carbon capture of methanol to achieve a circular CO_2 flow, however only post-carbon capture in the case of fossil fuels (MGO and LNG). The appended Papers I-IV use integrated LCA and LCC methods and have different scopes covering different pathways and ship types (Figure 2).

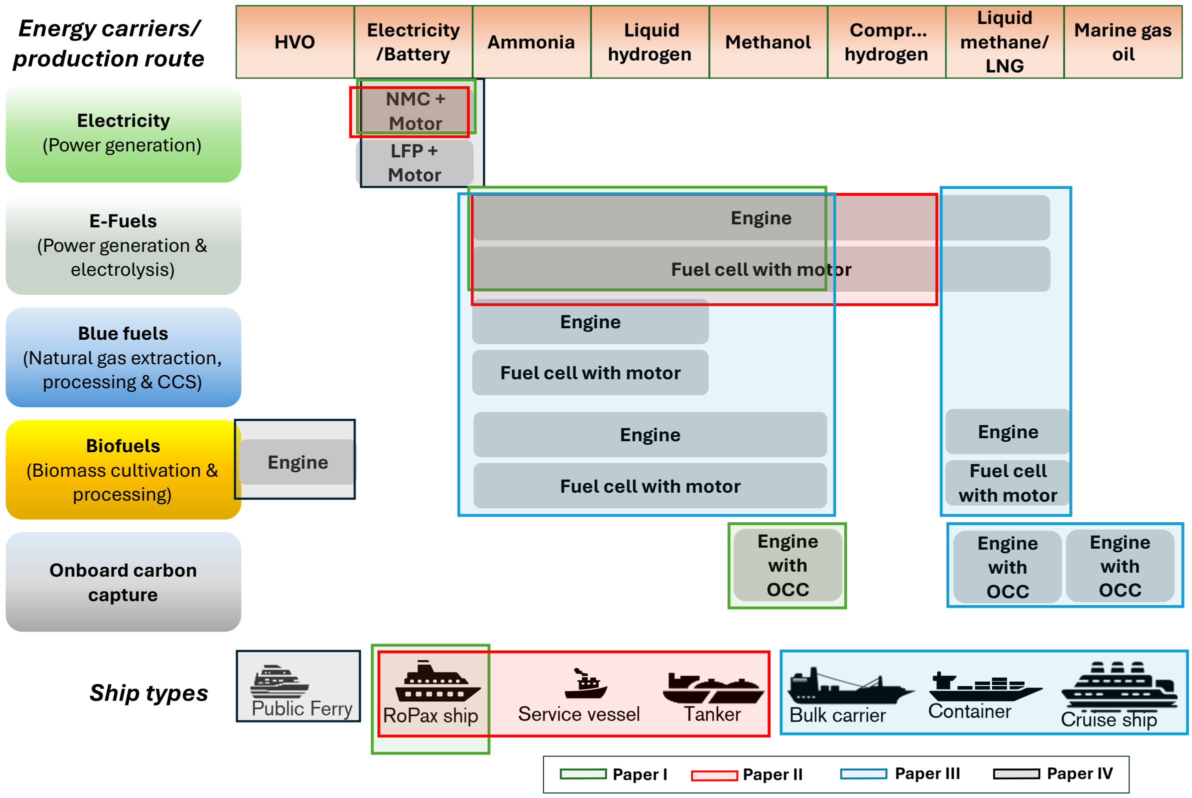

Figure 2: Scope of the LCA and LCC studies covered in Papers I-IV. In Paper I, Engine with OCC is for e-methanol with a circulation of CO_2. HVO: Hydrotreated vegetable oil, CCS: carbon capture and storage. LNG: liquefied natural gas, NMC: Nickel Manganese Cobalt, LFP: Lithium Iron Phosphate.

Regarding the system boundary used in Papers I-IV, cradle-to-grave is used to cover direct impact during vessel operation, also called tank-to-wake (TtW), impact from fuel production and distribution including infrastructure associated, also called well-to-tank (WtT), and ship manufacturing with end-of-life as shown in Figure 3. One criterion that defines the system boundary is the location where the energy carrier is produced and the bunkering point. Regarding geographical scope, energy carriers are assumed to be produced locally near the bunkering port primarily focusing on Europe. This simplified assumption does not consider the availability of primary energy and does not consider the impacts associated with transporting energy carriers from the location where it is available. It may be noted that these papers cover only the case of newly built ships and do not consider retrofitting existing ships. Another limitation of the thesis is the end of life (EoL) is treated as the simplified cutoff method.

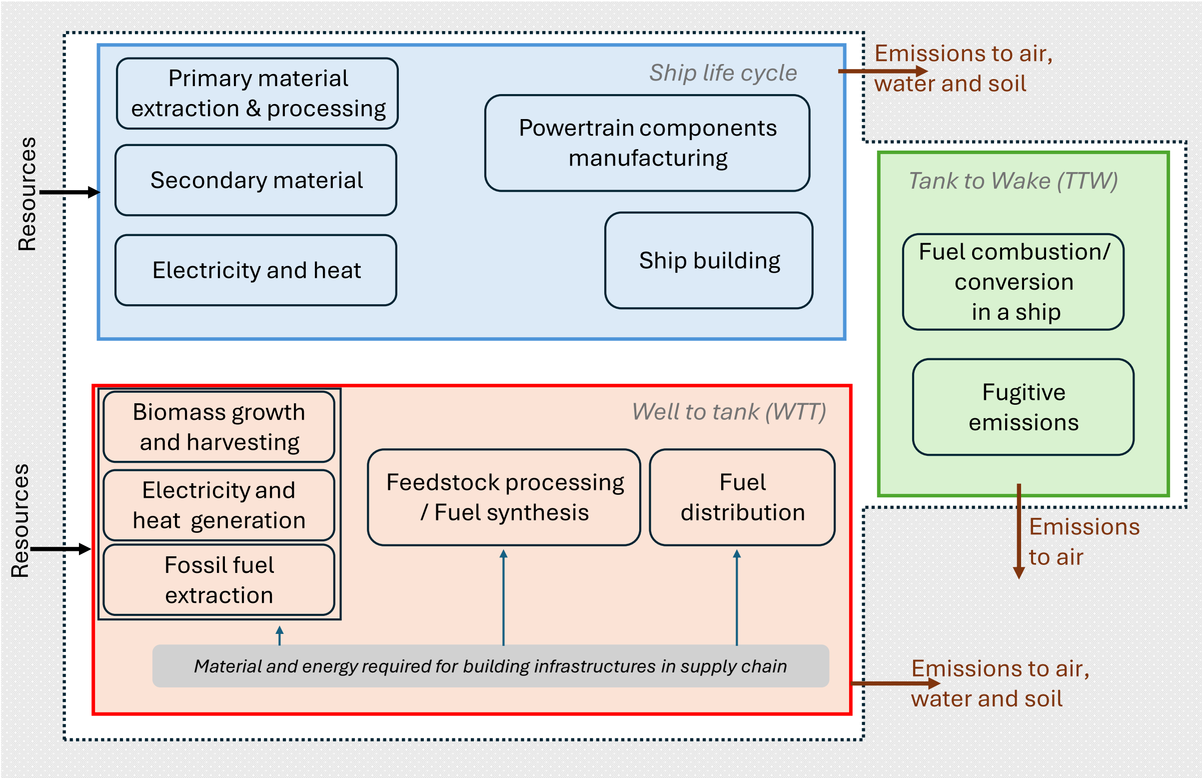

Figure 3: Illustration of the scope of the thesis in terms of various stages involved in the cradle-to-grave analysis.

The energy system modeling used for Paper V differs from the life cycle thinking perspective. The energy system model used in this study is the Global Energy Transition (GET) model where the fuel and propulsion choice for the ship is analyzed based on how it fits into a larger global energy system, where different energy sectors compete for the same energy sources which also have limited availability. Figure 4 illustrates the shipping part of ESM and related energy systems focused on in Paper V. It also shows the connection of environmental impacts to various stages, the life cycle inventory used in the ESM is mainly developed and collected during the thesis (from Paper I-IV).

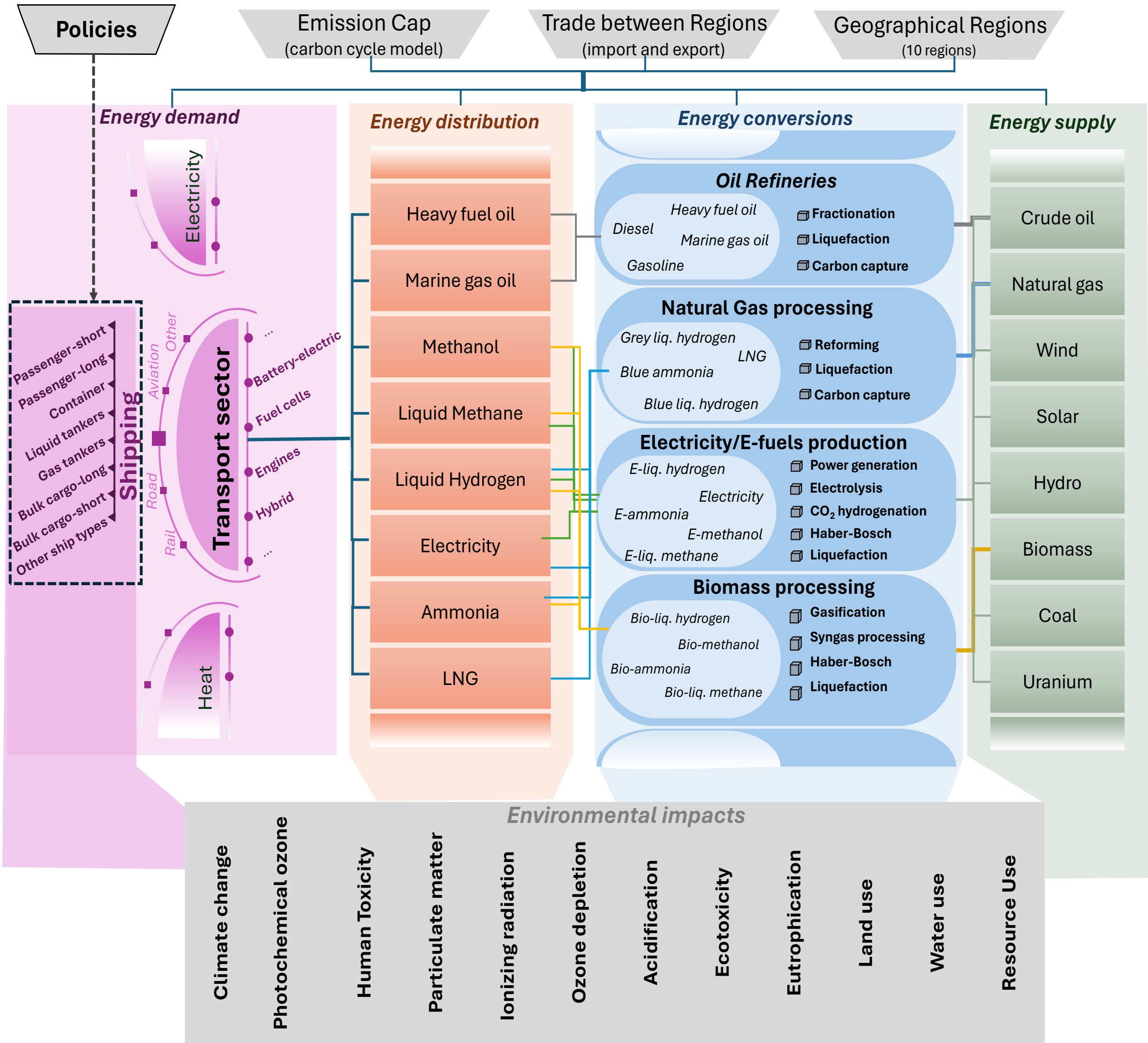

Figure 4: The schematic representation of the shipping sector and energy supply chain used and environmental impacts assessed in the energy system model in Paper V of this thesis.

1.4. Outline of the thesis

This thesis is broken down into seven parts, describing the method and findings of this thesis. Chapter 2 describes life cycle thinking including a prospective life cycle thinking approach, a review of other life cycle studies in shipping, and the latest IMO LCA guidelines. Chapter 2 also summarizes challenges associated with emerging technologies in life cycle assessment and life cycle costing. Chapter 3 describes the framework used for integrating LCA and LCC tools. This tool is used for Papers I-IV and is related to the first research question. This includes describing important methodological steps, such as the goal and scope definition, inventory analysis, impact assessment, and interpretation of results. In Chapter 4, the decarbonization pathways, included in this thesis are described.

Chapter 5 provides an overview of the ESM and GET used in Paper V. This chapter also includes the description of GET model and also describes the framework used to integrate GET and LCA. Chapter 6 summarizes the results from the appended papers including energy, climate impact, and other environmental and economic tradeoffs. These findings bring aspects to the second research question. Chapter 6 ends with the main findings regarding the energy transition under different shipping policy scenarios and the result from the integration of LCA and GET relevant to the third research question. In Chapter 7, discussions regarding the research questions and findings from the results are presented. Learning outcomes and future work are also included in this chapter.

2. Life cycle thinking

Life cycle thinking is an approach based on systems thinking where the material, energy, cost flows, and interactions between the processes and the environment during a product's/service life cycle (from raw material extraction to disposal) are analyzed to quantify the sustainability of the entire system [40]. Life cycle thinking can be used for assessing the three dimensions of sustainability: environmental, economic, and social. LCA, LCC, and social LCA (sLCA) are three methods based on life cycle thinking to assess environmental, economic, and social aspects of a product or service respectively. A life cycle approach known as life cycle sustainability assessment was proposed by the UNEP/SETAC Life Cycle Initiative that addresses environmental, economic, and social dimensions in one assessment [60]. In this thesis, however, only the environmental and economic aspects covered by LCC and LCA are considered. sLCA is not included in this thesis.

2.1. Prospective life cycle assessment

An LCA is a systematic approach used to evaluate the potential environmental impact of a product or service throughout its life cycle, from cradle to grave, from the extraction of resources, production, use, and end of life (EOL) [40]. This holistic perspective of LCA helps track the problem-shifting from one environmental problem to another, from one process to another, and from one region to another. LCA is a useful tool for identifying areas where a product or service can be improved to reduce its environmental impact and for making comparisons between different products or services for decision support. The International Organization for Standardization (ISO) provides standardized guidelines and requirements in ISO 14040 and ISO 14044 for conducting a conventional LCA study. The methodological framework as per ISO 14040 includes four steps: the goal and scope definition, inventory analysis, impact assessment, and interpretation of results [40] as shown in Figure 5.

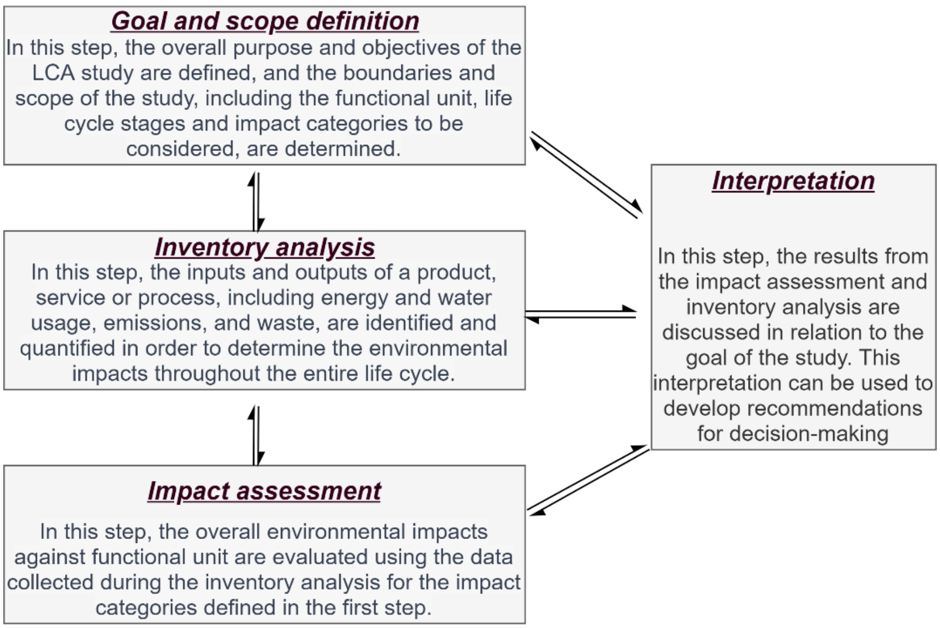

Figure 5: Four phases in the ISO framework for conducting LCA.

In this thesis, technological systems contain multiple emerging technologies calling for future-oriented LCA, and future-oriented assessments do not have standardized or structured guidelines like conventional LCA. Moreover, there are different types of future-oriented LCAs based on the approach and sometimes there is an overlap in the approaches between them in terms of techniques used [61]. These different future-oriented LCAs and their approaches are summarized by Giesen et al. [61] and Cucurachi et al. [62], as shown in Table 2. The terms prospective LCA (pLCA) and ex-ante LCA appear to refer to the same concept and may be viewed as umbrella terms. However, most ex-ante studies are conducted on new technologies that are at an earlier stage of development than those technologies covered in pLCA studies [61]. In this thesis, emerging technologies within a technological system that are in the early stages of the development phase, are assessed, and the environmental LCA performed in this thesis is referred to as pLCA. This term is used in line with the definition listed in Table 2 as used in the study by Arvidsson et al. [54].

In this thesis, pLCA is defined as an environmental assessment method used to evaluate the potential environmental impact of the life cycle of an emerging technological system modeled at a later, more advanced stage. The prospective assessment at the early development stage allows for more flexibility in making changes related to design, investment, etc. The emerging technological systems will have more radical changes in the processes around them. Hence, these processes need to be specifically modeled for the technological system and would be the focus of the assessment. These processes are commonly referred to as "foreground processes,". Other processes, called background processes, provide the context for the assessment of the foreground process and are needed for understanding the overall impact. The background processes are assumed to be static and are modeled at the current stage of development. Together, the foreground and background processes provide a comprehensive view of the environmental impacts of a system throughout its entire life cycle.

Table 2: Future-oriented LCAs used in various literature, adapted from Cucurachi et al. [62] and Giesen et al. [61].

Type of LCA	Description or approach used.
Consequential LCA	This method assesses the consequences caused by changes in the technological landscape, such as the introduction of a new technology or changes in policies [62].
Dynamic LCA	This assessment emphasizes incorporating the dynamics of parameters that are anticipated to change over time and comparing various development pathways over time [61].
Anticipatory LCA	This method focuses on the most relevant uncertainties, exploring both reasonable and extreme scenarios of future environmental burdens, including the values of decision-makers in the analysis to guide research, and development, and innovation [61].
Prospective LCA	This approach is used to assess an emerging technology in its early stages of development (such as small-scale production), but the technology is being modeled at a later, more advanced stage (e.g., large-scale production) [54].
Ex-Ante LCA	An assessment is done on a new technology before it is used commercially to guide R&D decisions so that this technology is more environmentally friendly than the incumbent technology [61].

2.2. Challenges for performing pLCA

Assessment using pLCA involves many challenges due to the difficulty in forecasting the changes and there are no standardized approaches for overcoming such challenges. Hetherington et al. [63] identify the challenges in pLCA during the development of emerging technologies as comparability (how emerging and mature technology can be compared), scaling issues (how the emerging technology is to be scaled), data availability (also quality), and uncertainty (the uncertainties while scaling up). Thonemann et al. [64] identified the challenges in comparability (aim, functionality, system boundary, life cycle impact assessment (LCIA) methodology), data (availability, quality, and scaling), and uncertainty. Arvidsson et al. [54] highlight the importance of modeling the foreground system based on scenarios and predictions and avoiding a temporal mismatch between the foreground and background systems. According to Cucurachi et al. [62] the main challenge is the lack of information on the projected final system and the possibility of new environmental impacts.

In the review study by Giesen et al. [61], it is shown that the challenges vary by discipline and that they can be linked to the four phases of the LCA. The challenges identified in terms of goal and scope are time frame selection (when will the new technology be expected to be operational), functional unit selection (same functionality for technologies compared), and incumbent technology selection [61]. In the life cycle inventory (LCI) phase, challenges identified are: upscaling of technology; availability of data for foreground processes; temporal changes in background processes; and market share [61]. In impact assessment, challenges include the possibility of a new impact not being identified and changes in characterization factors over time [61]. The challenges in the interpretation stage would be uncertainty and unknowns with new technologies [61]. Another review by Moni et al. [65] identifies methodological challenges with regard to technical maturity which includes comparability (uncertainty in functions and system boundary), data availability and quality, scaling up issues, uncertainties in the model, data, and communication, and assessment time.

Most of the above studies also suggest approaches to overcome the challenges. Arvidsson, et al. [54] suggested a method for inventory modeling for upscaling emerging processes based on predictive scenarios or scenario ranges. Moni et al. [65] have compiled some overarching suggestions, but do not mention how they can be integrated into LCA. Similarly, Giesen et al [61], have compiled potential remedies based on challenges specific to each phase. Thonemann et al. [64] have summarized a framework that is integrated into the LCA guidelines to overcome the challenges of uncertainty, data, and comparability. However, it is not clear how the challenge raised during the different phases can be approached for performing a life cycle assessment. Most of the above studies look into challenges associated with a single emerging technology. However, in the shipping sector, there are multiple emerging technologies in the same technological system. For example, the technological system '*liquid hydrogen in fuel cell (FC)*', there are several emerging technologies in the entire life cycle like electrolysis, liquefaction technology, fuel cell technology, etc. Assessing such technological systems, with multiple emerging technologies, is complex and more challenging.

2.3. Life cycle costing

Currently, for economic assessment of emerging technologies, TEA is widely used. However, TEA typically focuses on the production process or only includes cradle-to-gate making it difficult to integrate with LCA in terms of the system boundary, functional unit, and system model [66]. LCC is a tool for assessing the economic dimension of sustainability and is capable of supporting decision-making at different stages of the life cycle and is aligned with the LCA study with a life cycle thinking [39]. Unlike LCA, LCC does not have a general standard that provides guidelines on how it should be performed, but it should cover the cost of the system across the financial life cycle stages, like investment, operation, maintenance, and disposal. One of the guidelines for LCC is ISO 15686-5, which is specifically for planning the life of the buildings and built assets. The standard defines LCC as "a systematic and comprehensive methodology for determining the total cost of ownership of a product or system over its entire life cycle, including all the costs associated with the product or system, including purchase price, maintenance, repair, and disposal costs"[67]. The steps suggested in the guideline include 'identifying the objectives and scope of the analysis', 'determining the life cycle phases to be considered', 'developing an inventory of costs, revenues and risks', 'evaluating the costs, and revenues over the life cycle' and 'interpreting the results of the analysis' [67]. Overall, the guidelines are similar to the LCA methodology.

Rödger et al. [39] distinguish LCC into conventional LCC (cLCC), environmental LCC (eLCC), and societal LCC (sLCC) depending on the purpose and target group. In this thesis, only conventional LCC is used. In LCC, analysis is done based on cost flows in terms of expenses (outflow) and revenue (inflow) over different life cycle phases. Another aspect of LCC is that there are several stakeholders involved in different life cycle phases and each stakeholder has a different type of impact. The cLCC is often performed from the perspective of a single actor, where discounting of the costs is also considered. In the eLCC method, costs for all actors and environmental emissions or wastes from the system would also be internalized in terms of monetary value [39]. In sLCC, apart from the costs for all actors and the internalized environmental cost, the external costs (i.e., impacts on third parties) are also considered. In the cost inventory assessment, it should be noted that aggregating the cost (simply adding the costs of all actors) in the life cycle will not work as the expense of one actor is the revenue of another [39].

2.4. Integration of the LCA and LCC

The integration of LCA and LCC enables the identification of environmental and economic trade-offs while selecting the emerging technology. However, LCA and LCC are often used with little integration or done independently [68]. Franca et al. [68] have reviewed the challenges in the integration and identified the challenges as time- and resource-intensiveness of analysis, lack of combined knowledge, lack of tools to do an integrated assessment, differences in the scope and system boundaries, and differences in the background data. Miah et al. [52] also analyzed the different integrated methods for LCA and LCC. In addition, there are several studies that have tried to integrate TEA and LCA for emerging technologies [66, 69-72], the challenges associated with this integration can be summarized as follows: lack of tools for conducting assessment together, different system boundaries, compatibility of technology development processes, compatibility of cost and technical data, and lack of data availability and uncertainty. The LCA and LCC integration performed in this thesis is explained in Chapter 3.

2.5. LCA and LCC literature in shipping

LCA studies focusing on the prospective assessment of alternative shipping fuels are limited and some are detailed in Table 3, adopted from Brynolf et al. [13]. The studies presented in Table 3 highlight challenges in the shipping sector for decarbonization pathways because of differences and the complexity of the technological systems in the pathways. However, differences in the scope and functional unit between studies should be noted. Most of the studies found in the literature have not incorporated a prospective modeling approach for emerging pathways. Some studies have performed both LCA and cost assessment of the system [43, 49, 73], but it is unclear how they have integrated them in terms of inventory data. Lack of integration can result in discrepancies between the material, energy, and cost inventory data for the same system when, for example, fuel prices are frequently adopted from other studies. A uniform choice of scope and the functional unit can improve the comparability of studies.

Table 3: Summary of LCA studies considering e-fuel and batteries for shipping.

References	Energy carrier relevant to this study	Impact considered	System boundary and functional unit	Costing method
Bicer and Dincer [74]	Hydrogen, ammonia	Global warming, ecotoxicity, ecotoxicity, acidification, ozone layer depletion, and abiotic depletion	Well to haul FU: 1tonnekm	-
Bicer and Dincer [75]	Hydrogen, ammonia	Global warming potential, abiotic depletion, acidification, stratospheric ozone layer depletion, and ecotoxicity	Cradle to grave FU: 1tonnekm	-
Fan, et al. [76]	Electricity	Global warming	Cradle to grave FU: Ship life	LCC
Fernández-Ríos, et al. [77]	Hydrogen	Global Warming, acidification, eutrophication, ozone layer depletion, abiotic depletion potential, ecotoxicity, human toxicity, and photochemical Ozone formation	Cradle to grave FU: 1kWh ICE out	-
Gilbert, et al. [78]	Hydrogen, methanol	Global Warming	Well-to-Propeller FU: 1kWh	-
Ling-Chin and Roskilly [79]	Electricity	Global Warming, acidification, eutrophication, ozone layer depletion, abiotic depletion potential, ecotoxicity, human toxicity, and photochemical ozone formation	Well to wake FU: Ship life	-
Jeong, et al. [80]	Electricity	Global warming, acidification, eutrophication, and photochemical ozone formation	Well to wake FU: Ship life	-
Law, et al. [81]	Hydrogen, ammonia, methanol, battery	Global warming, air pollutant	Well to wake FU: 1kWh ICE out	LCC
Lindstad, et al. [82]	Hydrogen, ammonia, methanol, battery	Global warming	Well to wake FU: 1kWh ICE out	TCO
Malmgren, et al. [83]	Methanol	Global Warming, acidification, eutrophication, ozone layer depletion, abiotic depletion potential, ecotoxicity, human toxicity, and photochemical ozone formation	Well-to-propeller FU: round trip	-
Menon and Chan [84]	Hydrogen	Global Warming	Well-to-propeller FU: daily	-
Mestemaker, et al. [85]	Hydrogen	Global Warming, acidification, eutrophication, and photochemical ozone formation	Well to wake FU: Ship life	NPV
Perčić, et al. [86]	Hydrogen, battery	Global Warming	Well to wake FU:Nautical-mile	LCC
Perčić, et al. [87]	Hydrogen, battery	Global Warming	Well to wake FU:Nautical-mile	LCC
Perčić et al. [49]	Hydrogen, methanol, and battery	Global Warming	Well to wake FU:Nautical-mile	LCC

2.6. IMO LCA guidelines

IMO has adopted specific LCA guidelines for marine fuels with resolution MEPC/81/16 in March 2024 based on the general principles and methodology of ISO 14040:2006 [88]. The aim is to cover the whole fuel life cycle, from feedstock extraction/cultivation/recovery, feedstock conversion to fuel, transportation as well as distribution/bunkering, and fuel utilization onboard a ship [88] but only focus on GHG emissions. Another important part of the IMO guideline is the introduction of the fuel lifecycle label, which is a technical tool that collects and conveys information for the life cycle assessment of marine fuels and energy carriers.

The scope of IMO LCA guideline includes well-to-tank (WtT) and tank-to-wake (TtW) to assess well-to-wake (WTW) GHG intensity and the functional unit is 1 MJ of fuel. The guideline uses the attributional approach expressing the global warming potential over a 100-year time horizon (GWP100) as given in the fifth IPCC assessment report. WtT emissions (GHG_{WTT}) represent GHG emissions resulting from growing or extracting raw materials, producing and transporting the fuel to the point of use, including bunkering. The guideline explicitly does not mention the inclusion of impact associated with the construction of infrastructure or facilities. The WtT calculation (equation 1) includes emissions associated with the feedstock (e_{fecu}), emissions caused by direct land use change (e_l), emissions associated with the conversion of the feedstock to the final fuel product (e_p), emissions associated with the transport of feedstock, transport of finished fuel, storage, local delivery, retail storage and bunkering (e_{td}), emissions from soil carbon accumulation (e_{sca}), and emissions credit from carbon capture and storage (e_{ccs}).

$$GHG_{WTT} = e_{fecu} + e_l + e_p + e_{td} - e_{sca} - e_{ccs} \qquad (1)$$

TtW methodology quantifies and evaluates the intensity of CO_2, CH_4, and N_2O emitted onboard a ship related to the fuel usage, including combustion/conversion and all relevant fugitive emissions, from the bunker manifold up to the energy converter which is leaked, vented or otherwise lost in the system, with a global warming potential. This is given in equation 2, where LHV: lower heating value, $C_{slipship}$: % fuel escaped from the energy converter system, C_{fug}. : %fuel escaped from tank and fuel lines. CF_i: emission factor for pollutant i, GWP_i: GWP100 of pollutant i, C_{sfx}: share of GHG in the component of the fuel, S_{FC}: carbon source factor (0 or 1), e_c: emission credits generated by biomass growth, S_{FCCU} : carbon source factor to determine whether the emission credits from captured CO_2, e_{ccu}: emission credits from the used captured CO_2, e_{occs}: emission credit from carbon capture and storage. The WTW emission (GHG_{WTW}) is the sum of GHG_{WTT} and GHG_{TTW}.

$$GHG_{TTW} = \frac{1}{LHV}\left(1 - \frac{1}{100}\left(C_{slip_{ship}} + C_{fug}\right) \times \left(\sum_i CF_i \times GWP_i\right) + \left(\frac{1}{100}\left(c_{slip_{ship}} + C_{fug}\right) \times C_{sfx} \times GWP_i\right) - S_{FC} \times e_C - S_{FCCU} \times e_{ccu} - e_{occs}\right) \qquad (2)$$

For some of the factors in equations 1 and 2 it is in the LCA methodology noted that they are pending further methodological guidance. These include e_l, e_{sca}, S_{FCCU}, e_{ccu}, e_{occs}.

2.7. Employing life cycle thinking in this thesis

The decarbonization pathways encompass numerous emerging technologies, and in light of the objectives of this thesis, it is essential to evaluate both the environmental impact and the cost of the system concurrently. The interdependence of the parameters, like material, efficiency, emissions, and costs, should be taken into consideration. In line with RQ1, a framework is introduced in this thesis to integrate the LCA and LCC by addressing these challenges at the same time. This framework is formulated as 'Integrated life cycle framework (ILCF)' combining environmental and economic assessment. This integrated framework is explained in detail in Section 3. ILCF is used as the method to perform the life cycle analysis of the decarbonization pathways in Papers I-IV.

3. Integrated life cycle framework

The first research question of this thesis is addressed in this chapter by introducing an integrated life cycle framework to perform combined LCA and LCC for decarbonization pathways. The framework is developed during the thesis in four steps. In the first step, the relevant challenges associated with the pLCA and integration of LCC are identified from the method and review literature as discussed in Chapter 2. In the second step, the LCA steps suggested in the ISO 14044 guideline (Figure 5) are taken as the foundation, and challenges are mapped to the four phases (goal and scope definition, life cycle inventory, impact assessment, and interpretation). In the third step, the approaches used in various literature to overcome the challenges are added to the framework. Finally, the steps are iterated to finalize the structure of the framework.

There are two sets of challenges in the methodology, the first one linked to the assessment of emerging technologies using pLCA (discussed in Section 2.2) and the second linked to the integration of LCC (discussed in Section 2.4). Some of these challenges are directly connected to data availability and quality. The challenges identified from the literature for methodology studies of pLCA [54, 61-65] and of LCC integration [52, 66, 68-72] are summarized in Table 4.

Table 4: Challenges identified for pLCA and LCC integration that are considered in the methodology development.

Challenge	LCA phase
Which functional unit should be used for comparison? What are the changes associated with the new technological system? Where will the changes influence? When can technology be assumed to be mature? What are the changes in other processes associated with the new technological system? Which technology or mix of technologies should be selected when several emerging technologies are under development (e.g., electrolyzer)? Whether processes associated are also emerging and if yes whether it fits with the time horizon?	Goal and scope definition
What would be the parameters of foreground processes once the technology is developed (energy, material, and cost inventories)? What would be the temporal changes in the background system?	Life cycle inventory
Lack of tools for simultaneous assessment of pLCA and LCC using the same inventory. What impact categories and associated characterization factors are relevant over time?	Impact assessment
How the uncertainty in future development can be addressed? If a different technology is selected for a foreground process, how would it impact the result?	Interpretation

The integrated framework proposed in this thesis is shown in Figure 6. The red texts are the challenges identified in Table 4, and the blue boxes are approaches integrated into the framework that is used in this thesis to address some challenges while performing life cycle assessment and costing. As described in the second and third steps, the challenges and approaches are mapped to the four phases specified in ISO 14040/44.

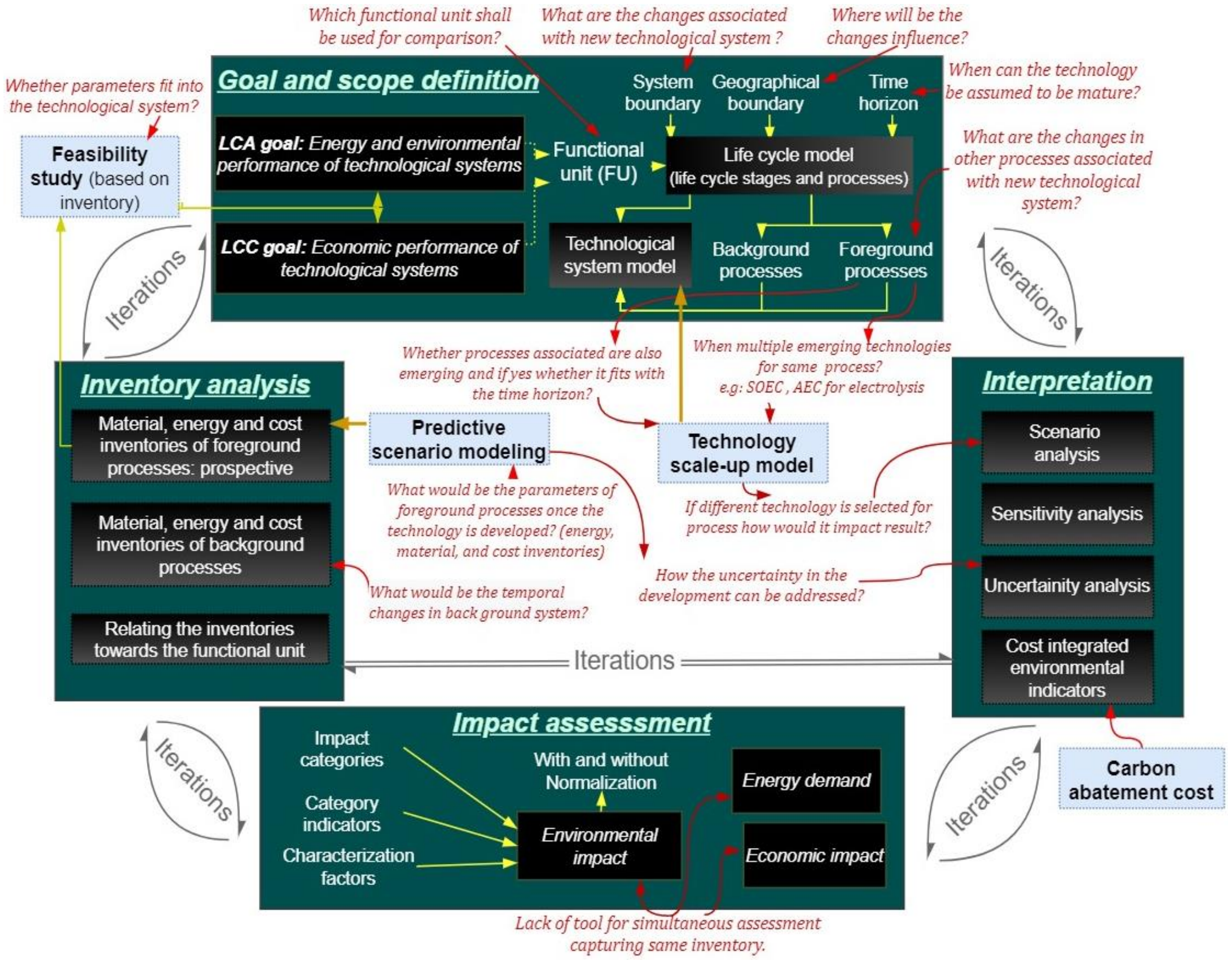

Figure 6: Integrated framework used in this thesis for the life cycle analysis of alternative fuels in the shipping sector.

3.1. Goal and scope definition

The goal should reflect the intended application of the assessment, the intended audience, and the reason for carrying out the study. When conducting an integrated LCA and LCC assessment, it is necessary to state both environmental and economic goals separately or in combination. The goal definition provides direction for all of the specific aspects of the scope definition, which in turn establishes the parameters for the work that will be done for (life cycle inventory) LCI and (life cycle impact assessment) LCIA [89].

In the scope definition phase, the LCC/LCA study's object (product/service) is identified and defined, that is to define the technological systems along with the supply chain to be analyzed. However, for defining the technological system under study, it is important to review the goal definition and intended audience and ensure the use of a consistent method, data, and assumptions while specifying elements like functional unit, system boundary, geographical representation, foreground system, background system, time-related representation (time horizon), and identify the impact assessment categories.

While defining the functional unit, the major challenge for integrated pLCA and LCC is ensuring that all technological systems can be compared based on the same function, both in impact and cost (Figure 6). Common functional units in LCA studies of maritime fuels, as noted in Table 3, are engine or fuel cell output (in kWh or MWh) or the amount of fuel use (in MJ or kg). Using such functional units will not always give a fair relative comparison as the output energy form differs for different energy converters (output for a fuel cell /battery is electrical energy and output for an engine is mechanical energy). Moreover, the conversion losses after the energy converters would be different for different powertrain configurations, which may also influence the life cycle result when the ship's life is considered. Different functional units are used for the appended papers; Paper I: round trip, Papers II and III: GT-km and DWT-NM, and Paper IV: annual operation. This selection ensures the comparison between the technological systems and provides the same baseline for impact and cost evaluation, which is the main challenge in the selection of functional units. Paper II and Paper III use transport work capacity as the functional unit; the main advantage of this approach is that variations in capacity could be included as done in Paper III.

When defining system boundaries, the main challenge is to capture all relevant changes in the life cycle stages and processes while establishing a new technological system (Figure 6). It is difficult to identify all the processes (within the technological system and in the related supply chain) that would be subject to change or influenced by the change. Also, these changes would be different depending on the technological systems under consideration. Hence, while comparing different technological systems all processes that changed in one system should be considered in other systems as well. When building life cycle models, the system boundaries, life cycle stages, and processes within each stage should be defined, and it is also important to show activities not included within the system boundary for clear communication. While conducting pLCA, it is also important to differentiate the foreground system processes from the background processes. The foreground processes are processes that are focused on any study, and it is important to include all processes that will change radically due to the new technological system in the foreground system itself. Background data are required to represent the study's context, typically consisting of data for upstream supply chains required for emerging and incumbent technologies to perform the selected functions. The system boundary including foreground processes and background processes defined in the appended papers are summarized in Figure 7.

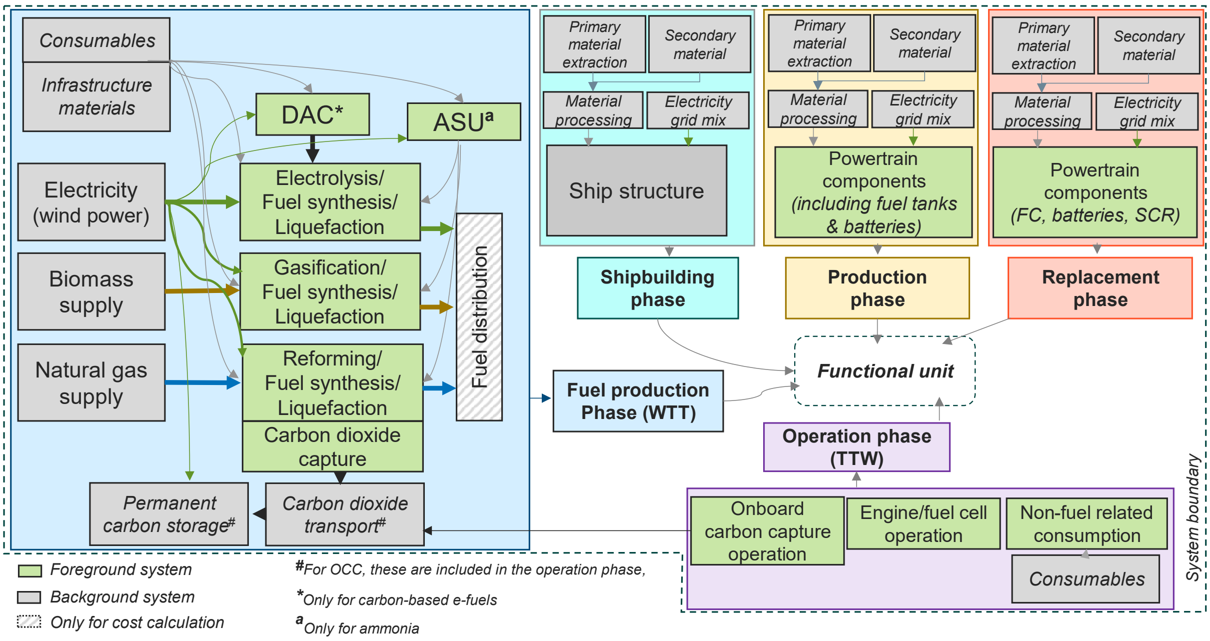

Figure 7: Representative system boundary used in appended Papers I-IV. Green represents the foreground processes and blue represents the background processes. Ship building phase is not included in Paper I.

The geographical and temporal scope must also be defined, as pLCA must consider a hypothetical future commercial state of the assessed technological system. Defining a particular point in time is essential for providing a fair comparison between new and existing technologies. Consequently, an explicit temporal scope will also affect the modeling of competing for incumbent technologies and background systems. One of the challenges while assessing foreground processes is that there would be multiple emerging technologies that would be capable of replacing present technology in the market (Figure 6). Another challenge identified is whether all emerging technologies within the system boundary match the time horizon. Also, if multiple emerging technologies compete for the same function how to decide which process suits the best with the technological system and time? These challenges can be addressed by using the technology scale-up method (Section 3.1.1).

3.1.1. Technology scale-up

To identify the emerging technology to use for a specific process at a specific point in time, a technology scale-up model can be used. To identify the emerging technology for the processes in the foreground system, the level of maturity of the different emerging technologies considered should be compared (indicating the development stage of the technology). Maturity can be evaluated based on qualitative scaling methods like technological readiness level (TRL) or manufacturing readiness level (MRL). In this thesis, only TRL method is used and the definition of different TRL levels is shown on the x-axis of Figure 8. Figure 8 also shows the technology scale-up model used in this thesis adapted from Thonemann et al. [64].

In Paper I, this model is used to decide on the emerging technologies, e.g., e-ammonia production. Among various technologies possible for e-ammonia production, the Haber-Bosch with electrolysis is selected for the analysis considering the technology scale-up model at the time horizon 2030. This modeling makes use of inputs like interviewing experts, analyzing TEA literature, other literature reviews, etc. As shown in Figure 8, various technologies would have different development pathways and presently (t_o) they would be at different maturity levels. Technology that suits the time horizon of the study should be used in the technological systems modeling. In addition, it is important to check whether the given technology is compatible with other processes in the technological systems. One example is while selecting technology for hydrogen production for application in FC, the purity level of hydrogen produced from the technology should be considered.

This scaled-up scenario may be based on a comparison with an incumbent technology. An incumbent technology refers to a technology that has already achieved a considerable level of market penetration and is in TRL 9. The incumbent technology has been in use for several years and has well-established supply chains, reliable use, and is better understood than emerging technologies. Such comparison also helps to identify the potential changes required for a new technological system in the supply chain and how likely these systems are to be developed. MGO in compression ignition ICE is the incumbent technology considered in the appended papers. In addition to defining the technological systems and supply chain from cradle to grave, major impact categories that need to be assessed are also identified based on the processes and changes considered in the modeling. The technological systems model includes all processes in the fuel pathway and propulsion system technology used onboard within the defined system boundary. The technological systems models are developed after several iterations and the technological systems defined for the papers are given in Chapter 5 (decarbonization pathways).

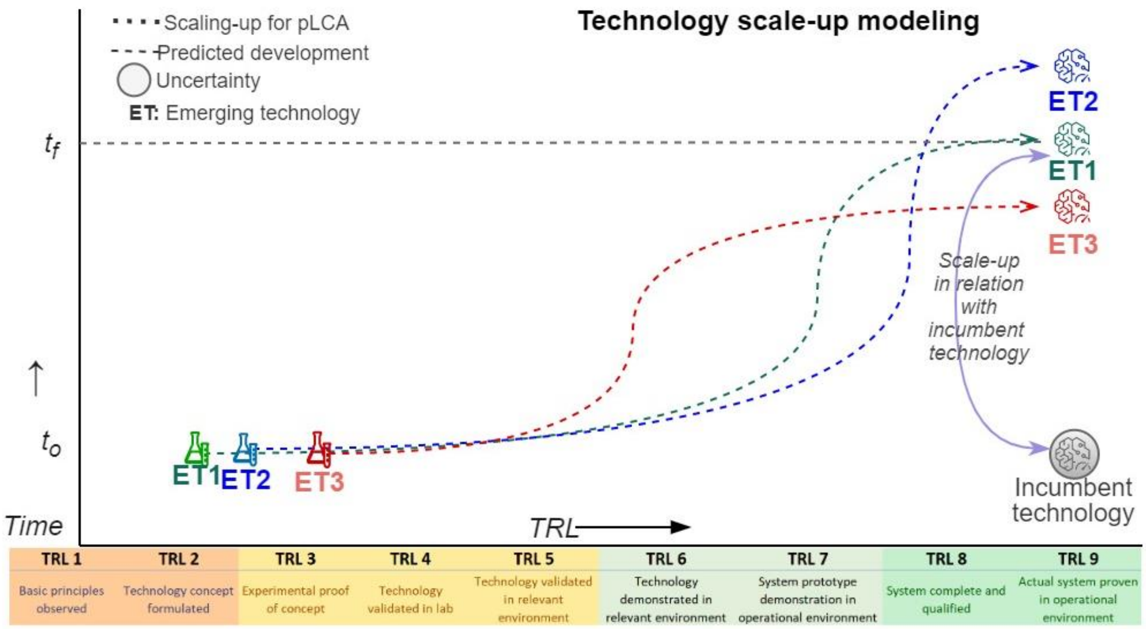

Figure 8: Technical readiness level (TRL) definition and technological scale-up model used in this thesis (adapted from Thonemann, et al. [64]). The Figure shows how ET1 is used along with incumbent technology.

3.1.2. Technical feasibility analysis

One of the challenges associated with replacing an old system with an emerging technological system is the technical limitation of the surrounding system to accommodate the new system. For ships, one of the major limitations may be the available space onboard for new systems operating on lower energy density fuels and lower power density powertrain technologies. For the new technologies to be used in the ship, it may require changes in ship structure, changes in operation pattern optimized for the energy storage required (e.g., bunkering more often), modification of other systems (e.g., ballast water), and modification in the placement of powertrain components (fuel cell or batteries need not be placed near the shaft and probably an exhaust chimney is not required). Hence the feasibility based on the volume need not be directly proportional to the present system and assessed energy carrier. In this thesis, such possibilities are not analyzed in detail but only investigated at a concept level. Three different approaches are used in the Papers II-IV.

In Paper II, a simple screening is performed with respect to space and weight needed for fuel storage and powertrain units. The total dimension (both volume and mass) for storage and powertrain is calculated for components onboard for each technological system and is compared with the dead weight tonnage (DWT) and gross tonnage (GT) of the specific vessel and based on the ratio of space, the options are categorized not feasible, likely feasible and feasible. Additionally in Paper II, safety risks associated with the handling of fuels such as ammonia and hydrogen onboard were assessed, as ammonia is toxic to human health and hydrogen is explosive in nature. A risk assessment workshop was conducted to analyze the safety risks associated with these fuels. In Paper III, the additional volume and weight are included as a loss in capacity, and the loss in capacity reduces the transport work for the same operation, hence this constraint is reflected in the contribution analysis. In Paper IV, assessment is performed both with space available and allowed draught, the volume available was analyzed with the actual volume available, and the change weight is assessed by estimating the draught of the ship. In the first step, it was checked that the new estimated draught is within the allowable draught and in the second step, the change in energy demand due to the change in draught is calculated using Holtrop-Mennen's method.

3.2. Inventory analysis

In the inventory phase, the input and output flows including material, energy, and cost flows for each process within the system boundary are identified and quantified. Lack of inventory data for emerging technologies (mostly included in the foreground system) is one of the major challenges of pLCA. This is mainly because the emerging technologies are to be modeled at a future time and are scaled up to include technology development and using assumed performance at full operational scale [54, 62]. For modeling parameters for the processes in the foreground system, two approaches were suggested by Arvidsson et al. [54]. The first approach includes the use of predictive scenarios, which are essential parameters foreseeing a likely development based on input from a wide range of sources like studies using technology learning curves, expert opinions based on experience curves, or comparing techno-economic studies. The second approach is based on developing scenario ranges where the parameters range between extreme high and extreme low. Papers I - III have used only the predictive scenario method in the upscaling of emerging technologies to identify the parameters linked to energy, material, emission, infrastructure, and cost as shown in Figure 9. The data for the prediction of parameters are collected from expert interviews, analyzing literature containing techno-economic and life cycle assessments of the specific technologies. Three predictive pathways (highly optimistic, present status, and less optimistic values) are analyzed to select three different values. In these three papers, a less optimistic value is taken for the main calculation. The other values are used in the interpretation phase for uncertainty analysis.

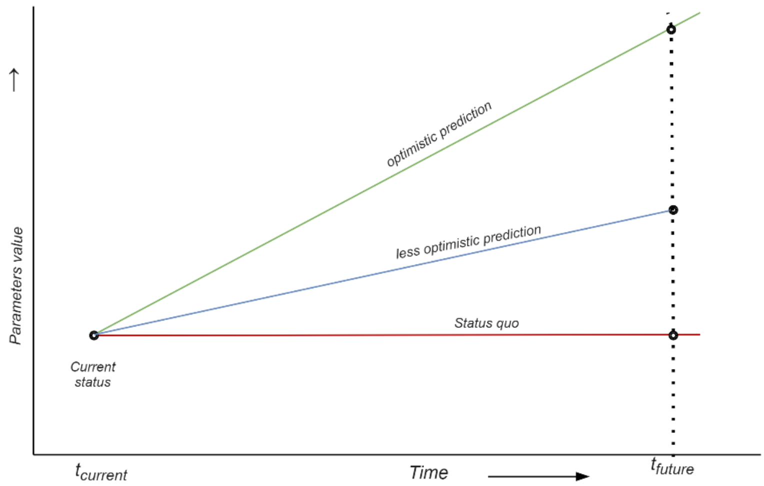

Figure 9: Predictive scenario modeling used in the thesis adapted from Arvidsson et al [54].

It is important to consider the cost and other inventory parameters scaling up simultaneously but they do not need to be linear as the cost flows may not be linear with the material or energy flows [72]. For the background system, while choosing the parameters of the process based on existing data, temporal mismatch with the foreground system should be avoided [54]. One example of adjusting temporal change of the background information used in all papers is the electricity mix of the grid. Different approaches are used in the appended papers, in Papers I-III the electricity mixes are adjusted to the scenario projection for the year 2030 based on different forecasts. In these papers, forecasts of electricity mixes are taken from the IEA for global mixes [90], and EU and Swedish grid mixes from the EU Commission based on the reference year 2020 [91]. In the scenario analysis of Paper III, another approach used for deriving electricity mix from the prospective LCI background database called premise v1.5.8 [92] was used for the analysis that combines the Ecoinvent database [93] and the REMIND model [94]. This approach is also used in Paper IV to derive the electricity mix. The cost inventory data is treated differently from other inventories as the final cost flow of a process represents all upstream flows [43]. One example is that in manufacturing only the final cost of purchasing needs to be considered, upstream costs like the cost of raw material for manufacturing will be already included in the purchased cost. So, integrating the costs and other flows for the same technological systems should be done with caution and it is better to calculate both flows separately. However, it should be ensured that the data are consistent with each other. In this thesis, the fuel costs are calculated from the energy feedstock cost (electricity, biomass, and natural gas cost) considering the energy and consumables required in each stage of the life cycle and the investment cost of the technology under consideration. Also, the parameters are selected based on the same prospective pathway as in the inventory of technological parameters.

3.3. Impact assessment

To assess the environmental impacts, the main challenges are potential new types of environmental impact and possible variation of characterization factors over time. These challenges are not investigated in this thesis. The challenge regarding the integration of LCA and LCC is conducting the assessment with the same set of inventory data, a specific python based codes are made for performing LCA and the LCC assessments performed.

In the impact assessment phase, the total potential environmental impact and total costs are evaluated for the systems throughout the life cycle. The environmental impacts are calculated from the environmental loads that were quantified in the inventory analysis phase. The environmental impacts can be calculated using various life cycle impact assessment (LCIA) methodologies based on either midpoint and/or endpoint approaches. The midpoint level is used in Papers I, II, III, and IV because there are more impact categories and the results are more accurate and precise at the midpoint level than at the endpoint level, which is typically used for three protection areas [89] as shown in Figure 10. In all the appended papers, the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) for calculating GWP [95] has been used. In Papers I to III, the other impact categories assessed are according to the Environmental Footprint (EF) 3.0 LCIA method recommended by the European Commission's Joint Research Centre [96]. In Paper IV, only six different impact categories are assessed including particulate matter formation, terrestrial acidification, marine eutrophication, ozone depletion, freshwater ecotoxicity, and finally mineral resource depletion, using two different and complementary indicators. The mineral resource depletion impact category is first assessed using the crustal scarcity indicator [97] and then using the surplus ore indicator to capture a shorter-term resource availability perspective [98]. The total surplus ore potential (SOP), as well as the results for all impact categories other than global warming and mineral resource depletion, were calculated using the CFs reported in ReCiPe 2016 v1.03 midpoint (Heirarchist view) [98].

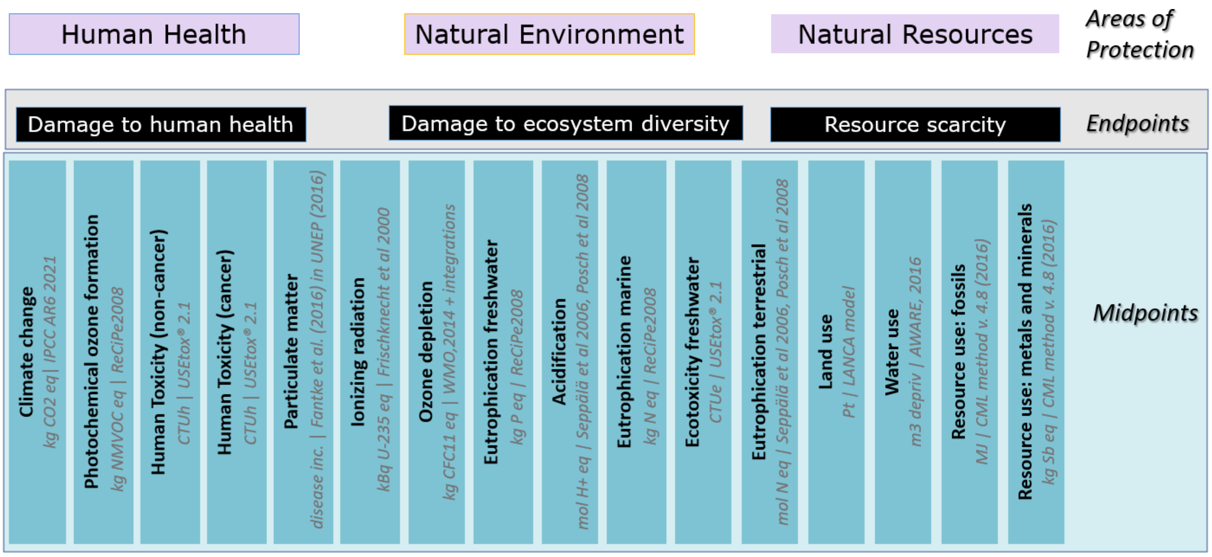

Figure 10: Life cycle impact assessment showing the midpoints, endpoints, and areas of protection. The midpoint indicator shown is used in this thesis for impact assessment.

The total environmental impact results (IR) for various categories (C) are calculated using Equation 1 from the characterization factor (CF) of the substance (i) as determined by the respective LCIA method, and the amount of substance (m_i) emitted into the environment. All cases' results are calculated to the functional unit.

$$IR_C = \sum_i CF_i \times m_i \qquad (1)$$

The environmental impacts are expressed in units that are difficult to interpret because they do not correspond to perceptible problems or prevalent threats [99]. Even though normalization is optional as per ISO 14044 [40], normalization provides a reference situation for the environmental pressures [100]. In Papers I, II, and III, the global normalization factors (NFs) are taken from EF 3.0 [101]. Global NFs represent the relevance of the total environmental impact in a certain category in a global context [101]. Normalized value (NV) is calculated using Equation 2, where c represents the impact category.

$$NV_C = \frac{IR_C}{NF_C} \qquad (2)$$

When comparing different technological options in terms of environmental impacts, it is often difficult to make decisions as the options have different environmental tradeoffs. In this context to compare different alternatives or if none of the alternatives are clearly better than another, a single score weighted value may be used as a tool. To present the overview of the results from the papers, a single score-weighted value is used in this thesis. However, this weighing factor is used in Paper III and also in Section 6.4 of this thesis. Weighting assists in identifying the most relevant impact categories and putting data in an aggregated format for better communication, it also serves to guide decision-makers [102]. However, weighing is based on the value choices of experts and not scientifically based [40]. The weighted value of each category is calculated using Equation 3, where the weighting factor is taken from the weighing approach used in EF 3.0 [102].

$$Weighted\ value = \frac{NV_C}{Weighting\ factor} \qquad (3)$$

The total energy demand for the technological system is calculated from energy quantified in the inventory analysis phase along with the environmental impact. Cost assessment is performed based on the cost inventories. Presently, there is a lack of tools that can perform integrated assessments of the cost and environment. The appended papers use a combination of openLCA, Excel, and Python software for simultaneous assessment, where the customized codes are developed in Python. The code captures the same parameters and inventories for LCC and LCA. Discounting the results of the LCC is often debated as it is inconsistent with the steady-state assumption of LCA [39]. However, for all appended papers discount rate is considered as the assessment was done from the owners' perspective and investors have a time preference for the payment. The future cost is discounted to the present value using the capital recovery factor (*crf*) given in Equation 4, where t is the service life of the ship, and i is the discount rate. The various discount rates are investigated in the appended papers.

$$crf = \frac{i\,(1+i)^t}{(1+i)^t-1} \qquad (4)$$

Total life cycle cost is calculated by adding CAPEX-related cost (includes the acquisition cost, replacement cost, and cost of disposal) with OPEX-related cost (fuel-related cost, consumable cost, and maintenance cost). The capital recovery factor is only used for CAPEX-related costs.

3.4. Interpretation

In the interpretation phase, the results from the inventory analysis and impact assessment are analyzed to ensure they are consistent with the goal and scope. The main method to interpret the results in all appended papers is contribution analysis. Contribution analysis breaks down the contribution from different processes and identifies which parts of a system or process have the biggest impact on the overall outcomes. It is used to understand which processes of the life cycle are the most environmentally or economically significant. Another method used in the interpretation phase is the use of indicators. For example, cost-integrated environmental indicators can support decision-making by understanding the tradeoffs. One such indicator is eco-efficiency assessment which is defined in ISO 14045:2012 as a '*quantitative management tool which enables the study of life-cycle environmental impacts of a product system along with its product system value for a stakeholder' [103]*. In this thesis, a similar quantitative indicator named carbon emission abatement cost (CAC) is used which compares the increase in the cost of technical options with the potential GHG reduction associated with the same technology (Equation 5). Policymakers can use CAC data to monitor and evaluate the effectiveness of policies for different pathways aimed at reducing climate impact.

$$CAC(€/tCO_2eq) = \frac{LCC\ relative\ to\ reference\ (€/kWhprop)}{GWP100\ relative\ to\ reference\ (tCO_2eq/kWhprop)} \qquad (5)$$

During the interpretation phase, it is essential to evaluate the robustness of the results, particularly given the prospective nature of the technologies being assessed. Three approaches are used to assess the robustness of the results in the interpretation phase: i) sensitivity analysis, ii) scenario analysis, and iii) uncertainty analysis (Table 5). Uncertainty analysis is used to evaluate the variation of different parameter values associated with different development predictions. Since uncertainties of several parameters are assessed, a statistical method called Monte Carlo analysis is used. Monte Carlo simulations use random sampling of data, within given ranges, to simulate and analyze the behavior of complex systems with uncertainties in the data. In the appended papers analyses are performed by creating a mathematical model of a system in the program Python and a large number of simulations are run using randomly generated data. Simulation is performed with a uniform distribution of the range of parameters with 100,000 iterations to generate a distribution of possible outcomes for the system. This approach provides a better understanding of the reliability of the data and the possible range of impacts.

Unlike uncertainty analysis, scenario analysis is used to explore 'what if' situations to understand the potential outcome of hypothetical scenarios based on different assumptions. The scenario analysis is used for wider strategies, e.g. charging strategies for battery options are used as separate scenarios in Paper I and Paper IV. Sensitivity analysis can identify the input parameter that has the most influence on the result. The sensitivity analysis helps identify input parameters that have the most significant impact on the results, by only changing the single parameter that needs to be assessed while keeping others constant. This allows for prioritization of efforts to improve the model and also allows a deeper understanding of the system. One example is when the sensitivity of the carbon intensity of the electricity mix is evaluated in Papers I-III.

Table 5: Approaches used in the robustness of results.

Approach	*Purpose*
Uncertainty analysis	Quantifies the degree of confidence in the LCA results by evaluating the uncertainty in the input data based on different projections.
Scenario analysis	Scenario analysis is used to explore 'what if' situations to understand the potential outcome of hypothetical scenarios based on different assumptions.
Sensitivity analysis	Sensitivity analysis helps to identify input parameter that has the most influence on the result by changing the single parameter that needs to be assessed while keeping others constant.

4. Shipping and decarbonization pathways

The decarbonization of shipping can be achieved by a combination of operational energy efficiency measures (mainly related to reducing the energy demand in the way the ship is maintained and operated), technical efficiency measures (mainly related to reducing the energy demand by technological improvement), and uptake of alternative energy carrier or onboard carbon abatement technologies. This thesis focuses only on the third measure, which is the uptake of the alternative energy carrier or carbon abatement technologies. The uptake of the alternative energy carrier and carbon abatement technologies can be categorized in different ways.

In this thesis the pathways are categorized into five key mitigation strategies as shown in Figure 11: 1) E-fuels: E-fuels or electro-fuels are synthetically produced energy carriers that contain electrolytic hydrogen (eH2) produced by the electrolysis of water using electricity, directly or chemically bonded with carbon or nitrogen [9], 2) Blue fuels: Blue fuels are synthesized using the hydrogen produced by removing carbon from fossil fuels and storing the carbon permanently to prevent its release into the atmosphere and, hence limiting the life-cycle climate impact [9], 3) Bio-fuels: fuels produced from biomass and the carbon that is released during combustion or conversion of bio-fuels is sequestered during biomass growth, rendering them as low-climate impact fuels [104], 4) Battery electric: Electricity, stored in onboard batteries, used for the ship's energy demand, and 5) Onboard carbon capture: Carbon abatement technologies onboard the ship, such as post-combustion carbon capture and storage (OCC) capture CO_2 at exhaust when powered by fossil fuels [105, 106] and captured CO_2 can be unloaded at a port reception facility and sent to permanent storage. Additional solutions, such as wind-assisted propulsion and nuclear propulsion can be added as different strategies, however, they fall beyond the scope of this thesis.

4.1. Alternative energy carriers

In this thesis, six main alternative energy carriers are considered other than MGO and LNG, i) methanol, ii) liquid methane, iii) liquid hydrogen, iv) ammonia, v) electricity, and vi) biodiesel (in the form of HVO). Each energy carrier has different properties like energy density, boiling point, etc. (Table 6). Currently, most of these energy carriers are used as chemicals rather than fuels and are derived from fossil fuels. Achieving carbon neutrality in fuel production requires a cautious selection of feedstock sources. This includes avoiding fossil carbon emissions during fuel production when using fossil feedstocks (blue fuels) or by using renewable feedstocks (bio-fuels or electrofuels).

Table 6: Major properties of fuels considered included in the study.

	Liquid NH_3 [107]	*Liquid H_2 [107]*	*Methanol [108]*	*Liquid CH_4*	*LNG*	*HVO*	*MGO*
Boiling point [109]	-33.4	-253	65	-162	-162	>180	>180
Lower heat value [MJ/kg]	18.8	120	19.9	50	48	44	42.7
Auto ignition temperature [°C]	651	585	464	540	540	204	210
Flammability Limits in air [vol.%]	15-28	4.7-75	7.3-36	5.3-15	5.3-15	0.6-7.5	0.5 -5
Density in liquid form (kg/m³)	682.6	70.8	791.4	422,6	468.1	770-790	796-841

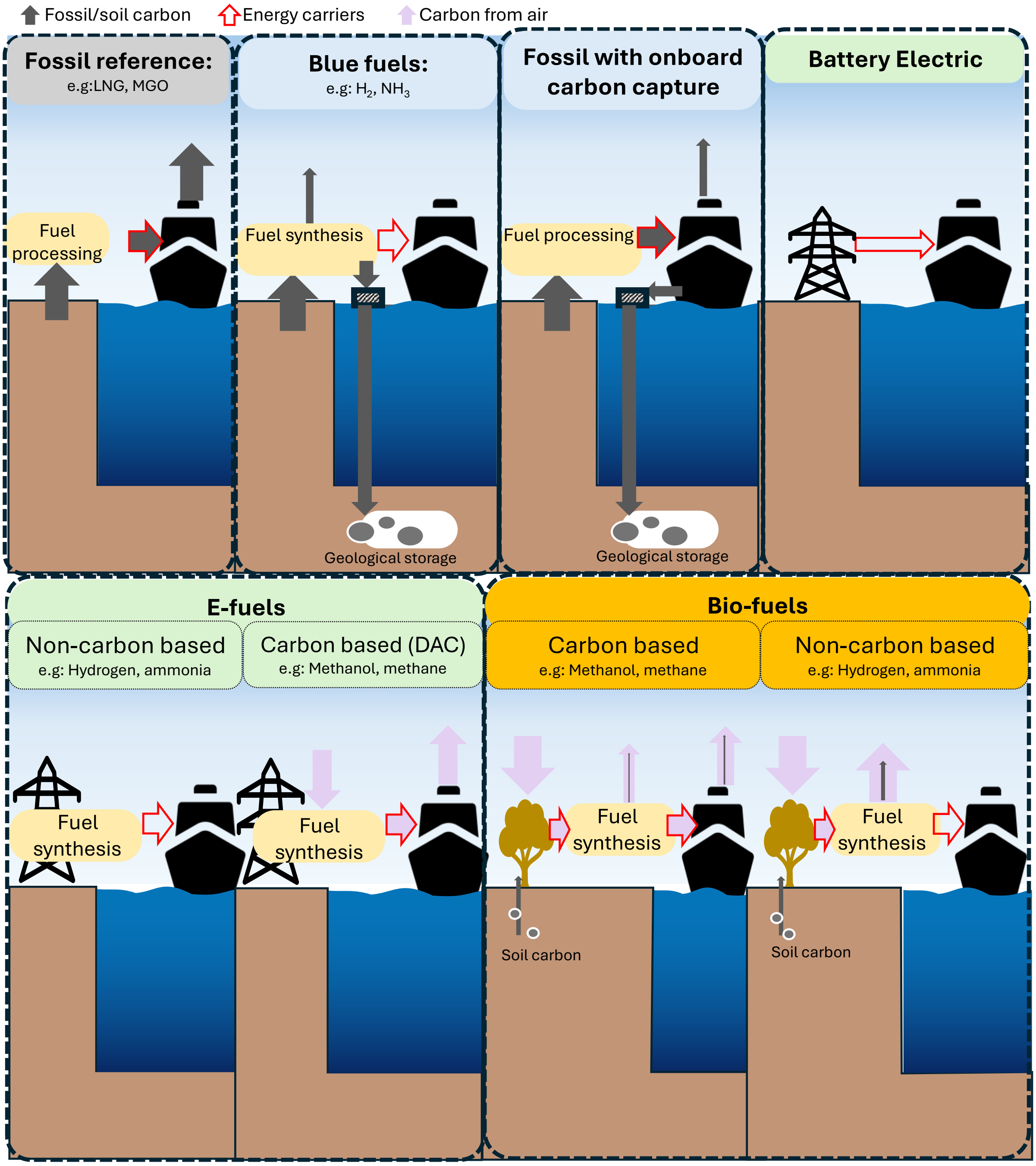

Figure 11: Key mitigation strategies considered in this thesis.

4.1.1. E-fuels

E-hydrogen forms the base for all e-fuels and is produced by electrolysis of water with electricity using electrolyzers. Three electrolyzers constitute the main technologies that currently exist: i) Proton exchange membrane electrolysis cell (PEMEC), ii) solid oxide electrolysis cell (SOEC), and iii) Alkaline electrolyzers (AEC). Comparing the environmental impacts, there is no significant variation between the PEM electrolyzer and the alkaline electrolyzer [110]. Although the SOEC offers better efficiency, the cost of solid oxide electrolyzers is high compared to the other two electrolyzers [111]. After considering the cost-effectiveness of these electrolyzers using the technological scale-up model explained in Chapter 3, AEC is considered in Papers I-III. E-fuel production pathways are shown in Figure 12.

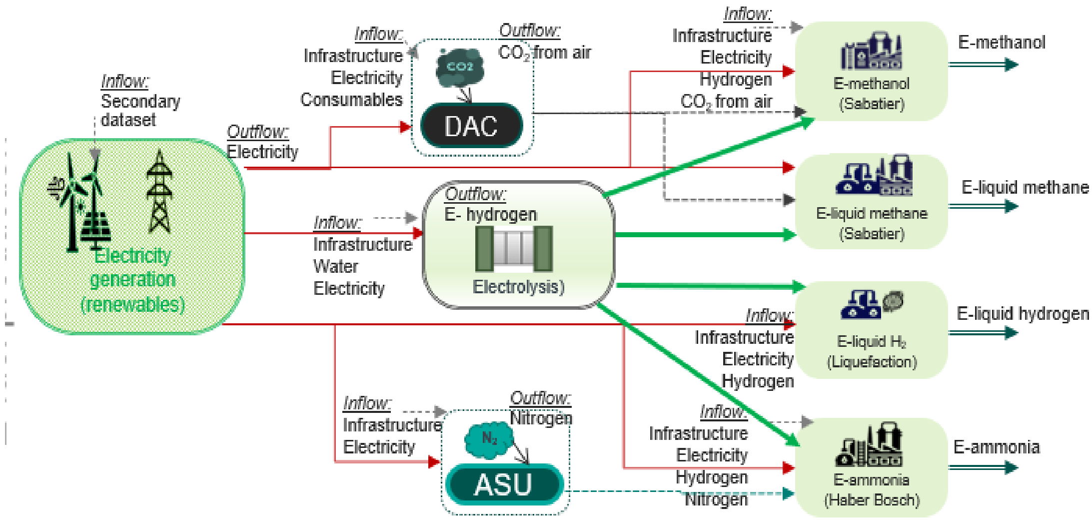

Figure 12: E-fuel production pathways

Compressed e-hydrogen*:* To increase the density and volumetric energy content, the most common method is to compress the gas and store it in pressurized tanks. The most common pressures are 350 bar and 700 bar. Considering the higher energy density of 700 bar compressed hydrogen [112], this was assumed in Paper II. As the results in Paper II for compressed hydrogen were shown to be less promising, these options were not considered in any other studies.

Liquid e-hydrogen*:* Liquid hydrogen has higher energy density by volume than compressed hydrogen but to liquefy 1 kg of hydrogen (boiling point is -253^{o}C), theoretically, a minimum of 3.3 kWh of energy is required [113]. However, it is impossible to achieve this theoretical efficiency, and efficiency will depend on the liquefaction processes. Among many liquefaction cycles, including the Claude Process, Collins Process, Linde Process, and reverse Brayton cycle, this thesis assumes the liquefaction method using a reverse Brayton cycle [114].

E-ammonia: Ammonia is widely produced using the Haber-Bosch process from hydrogen and nitrogen ($N_2 + 3H_2 = 2NH_3$). In the case of the production of e-ammonia, the feedstocks are e-hydrogen and nitrogen. From this process, the output is liquid NH_3. Nitrogen can be obtained with an air separation unit, cryogenic air distillation is a low-cost technology that can deliver high-purity nitrogen in high volumes [115].

E-methanol: E-methanol is assumed to be produced from e-hydrogen and CO_2 by CO_2 hydrogenation ($CO_2 + 3H_2 = CH_3OH + H_2O$). This study assumes the Sabatier process described by Kiss et al. [116] which requires electricity and heat even though the process is exothermic. CO_2 is assumed from DAC technology used in commercial-scale plants operated by Climeworks in Hinwil and Hellisheiöi, capturing CO_2 by cyclic temperature-vacuum swing adsorption [117]. The thermal energy required for the process is assumed to be produced using electricity, hence the electricity input is considered instead of the heat input.

E-methane: E-methane can be produced from e-hydrogen, and captured CO_2 ($CO_2 + 4H_2 = CH_4 + 2H_2O$) [118]. The study assumes that methane is produced by the Sabatier reaction process, which requires electricity and heat even though the process is exothermic [118]. In addition, the methane generated is liquefied using cascade technology [119].

4.1.2. Bio-fuels

The portfolio for producing bio-fuels is broad and includes various biogenic feedstocks (e.g. woody biomass, sugar/starch-rich crops, oil crops, waste oils and fat, sewage waste, etc.) and various conversion technologies (e.g. gasification, anaerobic digestion, pyrolysis, hydro-treatment, esterification, fermentation) [104]. Advanced biomass feedstocks derived from waste and residues, such as agricultural and forest residues, and municipal organic solid waste, do not need the use of dedicated land [120]. Agroforestry residues and waste account for major biomass potential globally even though the current utilization is low [121]. A large amount of agroforestry residues is available across Europe that could be utilized to make bio-fuels [122]. Gasification of forest residue is the main biomass pathway considered in this study, despite there being multiple options for producing bio-fuels from feedstocks that can avoid food vs fuel competition [104]. It is important to ensure that forest harvest residue used as feedstock is obtained from sustainably managed forests in order to prevent detrimental effects on forest health and minimize disturbances to the ecosystem [123].

Gasification of biomass feedstock results in an energy-rich synthesis gas (syngas), a mixture of mostly carbon monoxide and hydrogen with some CO_2 and water, similar to the gasification of coal [124]. The gasifier considered is a heat pipe reformer containing two separate sections: a gasification reactor and a combustion reactor [125]. In the gasification chamber of the reactor, the wood is gasified with steam operated at high pressure [125]. Char from gasification (by-product) and additional wood is combusted with air in the combustion reactor for the required heat [125]. It is assumed that 30% of the biomass is combusted in the combustion chamber, at around 70% gasification efficiency [125]. Syngas cleaning and upgradation are required at different quality levels depending on which bio-fuel needs to be produced. Bio-fuel pathways based on gasification are shown in Figure 13. In addition to the gasification route, hydrotreated vegetable oil (HVO) is also considered in Paper IV.

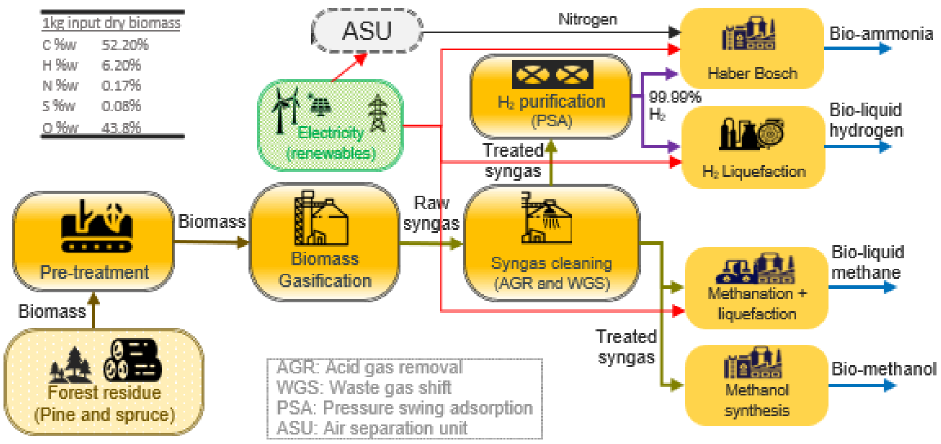

Figure 13: Bio-fuel production pathways based on gasification route.

Bio-methanol: The raw syngas from gasification are treated using acid gas removal and water gas shift reactions are sent to the methanol synthesis plant for the production of bio-methanol. It is assumed that except for the carbon that flows into the methanol, all remaining carbon in the biomass is emitted as CO_2.

Liquid bio-methane: Liquid bio-methane is produced in a similar way as bio-methanol, except that the treated syngas are sent to methanation for the production of methane gas. Similar to bio-methanol it is assumed that the remaining carbon in the biomass other than what flows into methane is emitted as CO_2. Bio-methane is then upgraded and liquefied (same process as mentioned in e-methane) to produce liquid bio-methane.

Liquid bio-hydrogen: Liquid bio-hydrogen is produced using the gasification of biomass in a similar process as bio-methane and bio-methanol. However, syngas is treated differently at acid gas removal and waste gas shift where the H_2 concentration in treated syngas is maximized during syngas treatment. Afterward, the treated syngas containing raw H_2 is purified and separated in pressure swing adsorption to obtain hydrogen with a purity of >99.97% [125]. The tail gas from pressure swing adsorption is combusted with air in the gasification combustion chamber to recover energy. The carbon in the biomass is assumed to be emitted as CO_2 into the atmosphere. The hydrogen is then liquified similar to the liquid e-hydrogen [10, 33].

Bio-ammonia: Bio-ammonia is assumed to be produced from bio-hydrogen and nitrogen using the Haber-Bosch process. The electricity required for the Haber-Bosch process and the air separation unit (ASU) is modeled as the e-ammonia pathway with the only difference being that hydrogen comes from the biomass gasification route.

HVO: HVO is a biodiesel derived from hydrotreated oils and fats sourced from various biological feedstocks. The biological feedstock used for HVO in Paper IV is derived from the current Swedish composition for HVO production, including 76% animal fats, 12% used cooking oil (UCO), and the remainder from various vegetable oils [126]. Animal byproducts from slaughterhouses are transformed into fats and proteins by rendering, and these fats are used for producing HVO via hydrotreatment. UCO and vegetable oils can be hydrotreated directly. The hygenization procedure necessary for the handling of animal byproducts (Categories 1 and 2) is excluded from the analysis, as mandated by the RED regulation [127].

4.1.3. Blue fuels

Blue hydrogen is generated through the process of methane reforming of natural gas, along with CO_2 capture and storage (Figure 14). Methane reforming of natural gas can be achieved through either steam methane reforming or auto-thermal reforming. Simulation results from Rivedal et al [128] show that auto-thermal reforming can attain high CO_2 capture rates, hence auto thermal reforming is considered. Amine-based absorption is being considered for CO_2 capture technology with a 90% capture rate. 1.5% methane leakage is considered in the supply chain for natural gas between the extraction and the production plant. The captured CO_2 is transported from the facilities to the port, then transferred by tanker to an injection site located 1000 km away from the port, where it is injected into geological storage. Inventory data for CO_2 transport and injection is extracted from the study [129].

Liquid blue hydrogen: The blue hydrogen liquefaction is modeled as in liquid e-hydrogen but with blue hydrogen as feedstock. The electricity required for the liquefaction is assumed from renewable electricity.

Blue ammonia: Blue ammonia is produced from the reforming of methane from natural gas and combined with CO_2 capture and storage similar to blue hydrogen. However, additional energy is required for the Haber-Bosch process, and the operation of ASU is assumed from renewable electricity. Parameters for auto-thermal reforming, CO_2 capture technology, CO_2 transport, and storage are assumed similar to the blue hydrogen production mentioned above.

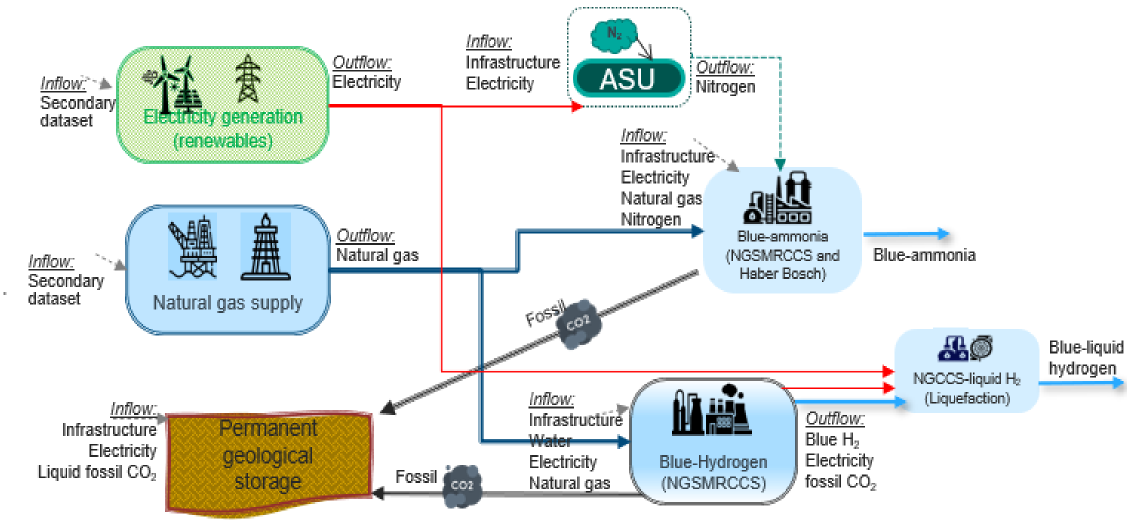

Figure 14: Blue fuel production pathways.

4.1.4. Electricity

Electricity has four types of application in the shipping technological system: i) charging batteries for BE case, ii) fuel production/liquefaction, iii) component production, and iv) direct use while the vessel is docked through onshore power. Considering the type of application, geographical location, and temporal aspects, different types of electricity scenarios are used. e.g. in Paper IV, the Swedish prospective electricity mix from 2025 to 2030 is used for charging but for the ship component manufacturing, the current European electricity mix is considered. These differences are accounted for during the component manufacturing including the supply of material from different locations, and occur in the acquisition phase only. For the fuel production stage, electricity from wind power is considered uniformly as the base case in Papers I-III and sensitivity assessment is performed for different carbon intensities of electricity.

4.2. Powertrain system

Transition to different energy carriers will also need changes in the onboard powertrain technologies including storage tanks, energy converters, drive technology, and additional components like the reformer, onboard post-combustion carbon capture, etc. Similar to the technologies in fuel production, most of the energy converters for using alternate fuels are in early TRL and need a technological scale-up model. Figure 15 shows different powertrains included in the appended articles: spark ignition ICE (SIICE), 2-stroke ICE (2SICE), 4-stroke ICE (4SICE), 4S-diesel electric (4SEICE), proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), Battery-electric (BE), ICE with Pre-combustion carbon capture using methanol reformer (HyMethShip), 4SICE with post-combustion carbon capture and storage (4SICEOCC) and 2SICE with post-combustion carbon capture (2SICEOCC).

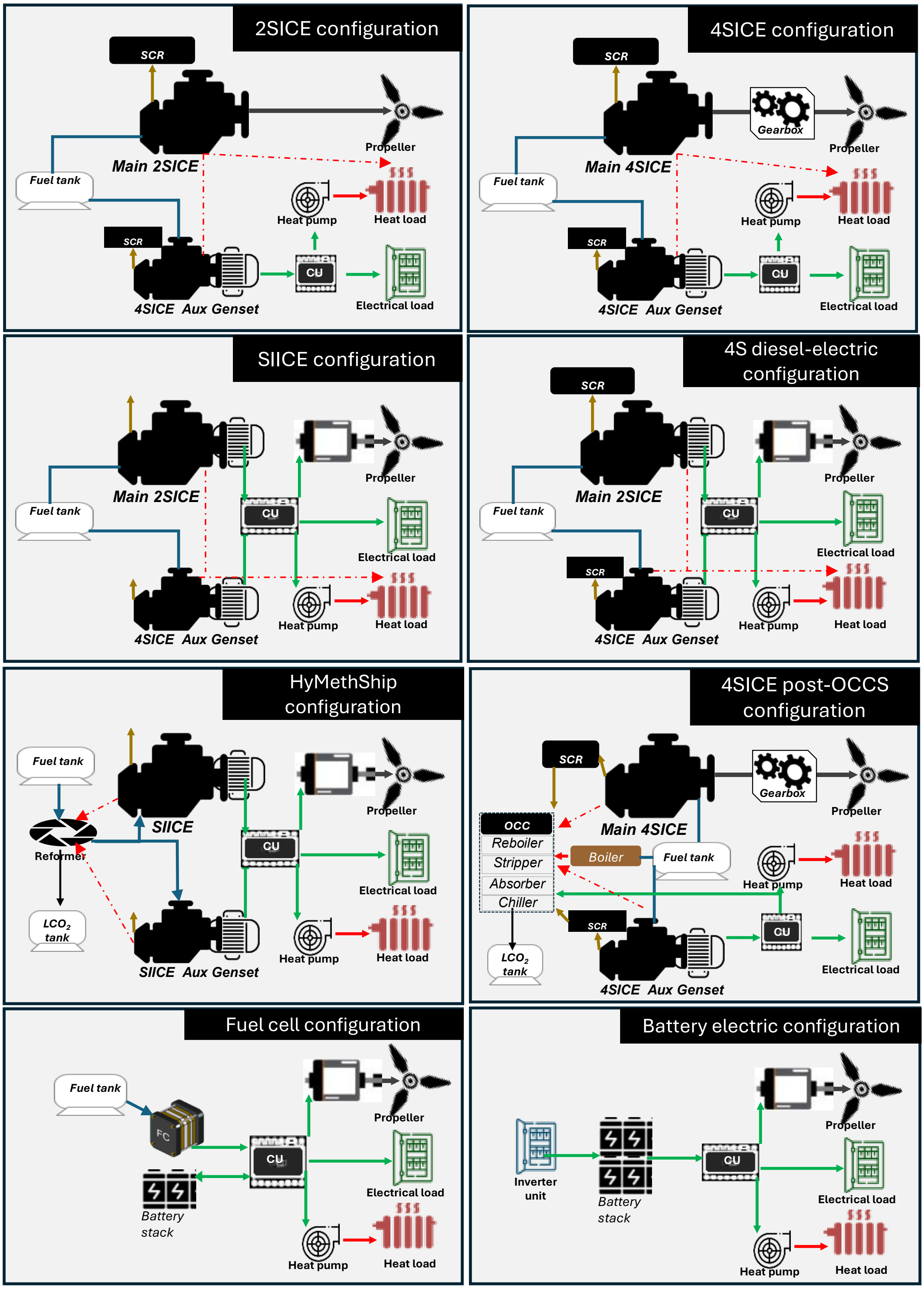

Figure 15: Powertrain system configurations considered in the thesis.

4.2.1. Engine and SCR

Engine configuration depends on the type of ship and on the fuel type. Vessels operating long distances are often 2S engines with slow speeds, 4S engines with medium speed, and diesel-electric which are usually 4S engines with generators and electric motors. While using alternative fuels, in compressed ignition engines (4S and 2S), pilot fuel is needed, and a dual-fuel engine with MGO as pilot fuel is considered in all cases (except for SIICE). Methanol and HVO are used with liquid injection whereas all other energy carriers are used with gas injection systems. To meet the Tier III requirement, 2S engines require SCR as NOx abatement technology. 4S engines have lower NOx emissions than 2S engines but still require SCR although with a lower urea consumption. While using ammonia in engines, the exhaust contains unburned NH_3 and NOx emissions because of fuel-bound nitrogen [32, 33]. The SCR system can convert NOx emissions by utilizing NH_3 in the exhaust. Experts recommend that fine-tuning the engine to optimize NH_3 combustion can effectively reduce NOx in SCR and meet Tier III standards. It is assumed that the NH_3 and NOx emissions post-SCR would be comparable to emissions from existing SCR systems. An uncertainty analysis is conducted in Papers I, II, and III to assess the impact of nitrous oxide (N_2O) emissions on GWP. For methane and LNG, a low-pressure dual fuel (LPDF) engine is the considered technology for 4S engine and SCR is not required for this type of engine (due to lower NOx emissions). However, for 2SLNG/methane engine SCR is considered for meeting Tier III requirements. Methane slip is a major concern for methane/LNG engines and uncertainty analysis is conducted in Paper III to assess the impact of methane slip on GWP.

4.2.2. Fuel cells

Fuel cells (FC) for ships may be selected from an array of options based on electrolyte membranes, including solid oxide fuel cells (SOFC), molten carbonate fuel cells, proton exchange membrane fuel cells (PEMFC), phosphoric acid fuel cells, and alkaline fuel cells. In the papers, PEMFC is considered for hydrogen and SOFC is considered for ammonia, methane, and methanol. The main reason for making this choice is the availability of data. The possibility of cracking fuel to produce hydrogen and using that hydrogen in PEMFC is disregarded due to the reduction in overall system efficiency caused by cracking and purification, as well as the need for additional onboard components [130]. An alternative not examined is the use of hydrogen in SOFC since the electrical efficiency of hydrogen in SOFC would be diminished owing to the greater disparity between Gibbs energy and enthalpy change, as well as higher parasitic losses during operation relative to other fuels [131]. The vessel's fuel cells were scaled according to power needs; however, a battery stack is assumed during startup and power ramping. For PEMFC, the battery is sized to store enough energy required for 10 minutes of operation at an engine load of 20% and for SOFC, the battery is sized for 30 minutes of operation at an ICE load of 20%. In contrast to PEMFCs, a battery is considered necessary for prolonged operation in SOFCs due to their slow response and longer start-up duration. While in operation, this additional battery system can be used to compensate for the peak load by energy management, hence a 10% reduction in power capacity is assumed for FC configuration.

4.2.3. Batteries

Due to the different features of different battery chemistry, it is a crucial element in the design of the onboard battery system. Major features like energy density, cycle life, the internal electrical resistance of the pack, and specific power, will affect the size and therefore the energy consumption of a ship. Two common types of lithium-ion battery (LIB) chemistries are widely used in marine applications: lithium iron phosphate (LFP) and lithium nickel manganese cobalt oxide (NMC). Papers I-III only examined NMC battery chemistry, whereas Paper IV, which focuses on battery electric ferries, evaluated the designs of both LFP-based and NMC-based battery packs. NMC offers a higher energy density [132], resulting in a lighter vessel compared to LFP, and the increased weight of LFP would create a higher draught (draught is the depth of the ferry below the waterline). Higher draught increases the hull resistance, and thus more power and energy are required for the same operational speed. The downside of NMC is that it has a shorter cycle life compared to LFP [133] which results in more replacements. These aspects are included in Paper IV.

4.2.4. Onboard carbon capture

When using fuels with carbon, another technology that has the potential to reduce CO_2 emissions is the use of carbon abatement technologies onboard the ship. Two types of onboard carbon abatement technologies are assessed in Paper I and Paper III: post-combustion carbon capture (OCCS) and pre-combustion carbon capture (HyMethShip). In HyMethShip, a reformer utilizes extra heat from the engine in an endothermic reaction between methanol and water to generate H_2 and CO_2 [33]. This reformer has an inbuilt membrane to separate H_2 and CO_2 and thus acts as pre-combustion carbon capture. H_2 is directed towards the engine as fuel and CO_2 is liquefied and stored onboard with the help of an adsorption chiller. OCCS, on the other hand, captures the CO_2 from the exhaust of the engine based on sorbent using the chemical solvent monoethanolamine (MEA)[33]. To ensure that the ship's design operation is not compromised, the application incorporates additional engine power to meet the additional electricity (for auxiliary equipment and compressor) [134]. The onboard energy requirements for OCC depend on the type and size of the system, fuel type, the target efficiency for carbon removal, and the flow rate of exhaust gas into the system [105]. For LNG cases, the LNG vaporization unit can serve as a heat sink for the CO_2 liquefaction and requires lower reboiler duty compared to MGO/MeOH cases (where also a chiller unit is required). Our simplified energy load assessment indicates that the heat generated in the exhaust after-treatment SCR is inadequate to meet the reboiler's heat requirements, hence a boiler is also assumed. Also, it is assumed that the flue gas from the combustion in the boiler is mixed with engine exhaust before sending it to the OCC system. One of the limitations is the space required for such system onboard, especially if the ships are operating longer routes, where enough space for storage of CO_2 and fuel is required in addition to the OCCS system.

4.3. Ship characteristics

The energy consumption of each vessel differs based on different factors, like transport function, operational profile, weather conditions, sailing distance, engine power, and sailing speed. This diversity in the vessel's functionality would have different implications for each energy carrier. For example, longer voyages and high fuel consumption per trip are key factors when deciding the amount of fuel storage required in the ship which may have a higher impact on the fuels with lower energy density from a system perspective. The constraint for each vessel differs based on the transport work, for example, a tanker is more constrained with an increase in mass onboard as the cargo loaded is based on the mass carrying capacity. For a RoPax vessel, the volume would be critical considering the space available for passengers. The type of engines used significantly influences the result, since emissions and energy consumption vary by ship category, with particular engine types being predominant in specific types of ships (like 2SICE for bulk carriers). The appended papers include different types of ship categories (Figure 2), their powertrain design, and specific transport functions: RoPax (Paper I & II), service vessel (Paper II), tanker (Paper II), container ship (Paper III), cruise ship (Paper III), bulk carrier (Paper III) and passenger ferry (Paper IV). The thesis includes cargo-related transport (container shipping, bulk carrier, and tanker, passenger-related transport (RoPax, cruise ship, and passenger ferry), and service-related transport (service vessel), thereby covering a wide spectrum of transport operations.

Based on the increased understanding from Papers I-IV, on the key parameters for ships and marine fuels, the shipping module of GET is improved. The GET model was modified during the thesis period to include more ship categories covering different transport work. The categories include: 1) container ships, 2) bulk and general cargo carriers, 3) liquid tankers, 4) gas tankers, 5) passenger-long, 6) passenger-short, 7) cargo short, and 8) other ship types. The first four represent the ship categories with the highest energy demand. Passenger long and passenger short represent ship categories related to passenger transport, cargo-short represents inland and coastal cargo transport over short distances, and other ship type refers to all other transport work including the service segment. Such classification helps to understand the influence of transport work and distances in an energy transition model. See also Section 5.1.6 for a more detailed description of the representation of shipping in GET.

5. Energy system model

An energy system model is a system-thinking approach in which the energy system is represented as a mathematical model. The energy system refers to the entire process chain from the supply of primary energy to the final use of energy in different forms in various sectors used to provide services or goods. Energy system models can be used to analyze how resources, technologies, and services can be combined under multiple conditions to inform energy and environmental policies and planning [38]. These models can be applied across different boundaries based on purpose, from the global level to specific regions, countries, or sectors.

Most ships operate in international waters, connecting multiple countries and regions, making it beneficial to analyze this sector within a global context. Therefore, assessing the sector's energy use using a global energy systems model could generate valuable insights. Also, regional availability of different primary energy sources and competition between sectors for the same sources are critical factors when evaluating the feasibility and impact of alternative fuels or technologies in shipping. To include the prospects of alternative fuels or technologies that are still in the development stage, energy system models using a bottom-up approach are often advantageous because they focus on detailed representations of individual technologies, processes, and systems within the energy sector. By building from specific technical and operational data, these models allow for a granular view of the components and interactions within an energy system. This approach contrasts with top-down models, which usually focus on short-term macroeconomic or aggregated data, such as computable general equilibrium (CGE) models, making them less suitable for capturing the unique characteristics of emerging technologies in a long-term perspective [135]. The shipping sector is generally not represented in detail in global energy system models [120, 136]. One global energy system model that does have a relatively good representation of the shipping sector is the GET model, which is used, and further developed, in this thesis.

5.1. The Global Energy Transition (GET) model

GET is a bottom-up energy system model that uses linear optimization to minimize the total cost of the energy system. The model was first developed by Azar and Lindgren [137] and was developed further continuously for different studies [55, 56, 138-140]. The model includes a large number of technologies and also techno-economic interactions between the technologies. The technologies and interactions are parametrized using, e.g. costs, efficiencies, load factors, and lifetime. While the model minimizes total system cost, several constraints including annual or total extraction limits on the respective available energy sources, expansion rates for technologies in the energy system, load balance constraints, atmospheric CO_2 constraints, trading of some energy carriers are restricted (e.g. electricity), and maximum allowable permanent storage capacity for CO_2. Another important constraint is the satisfaction of a set of demands for energy services in all end-use sectors of the economy. The GET model considers both the supply and demand side and includes the following nine modules: primary energy supply, energy conversion and storage, carbon capture and storage or utilization, fuel trade and distribution, emission conversion using a simplified carbon cycle, electricity sector including time slices for regional VRE conditions, transport sector, feedstocks, and heat sector. The over-arching structure of the model is shown in Figure 16. It may be noted that the model (as all models) is a simplification of reality and simplifications in GET include: 1) a limited selection of technologies, 2) demand levels that are exogenous and not responsive to price changes, 3) fuel and technology choices that are determined solely by cost, and 4) do not account for uncertainty around future costs, climate targets, or energy demand. In this thesis, we start out from GET v10 and develop it into v11 where major changes related to this thesis are redefining the ship types and adding different energy carriers and modification in the energy conversion module.

Temporal resolution: In this thesis, the model considers a time horizon of 2010-2150 with optimization accounting for annual and sub-annual (only for wind and solar) operations. The inputs for the time periods are provided for every 10 year time step (2020, 2030, 2040, …). The results are analyzed for the time horizon 2020-2080 and the period 2080-2150 is used as a dummy to avoid end of period distortions.

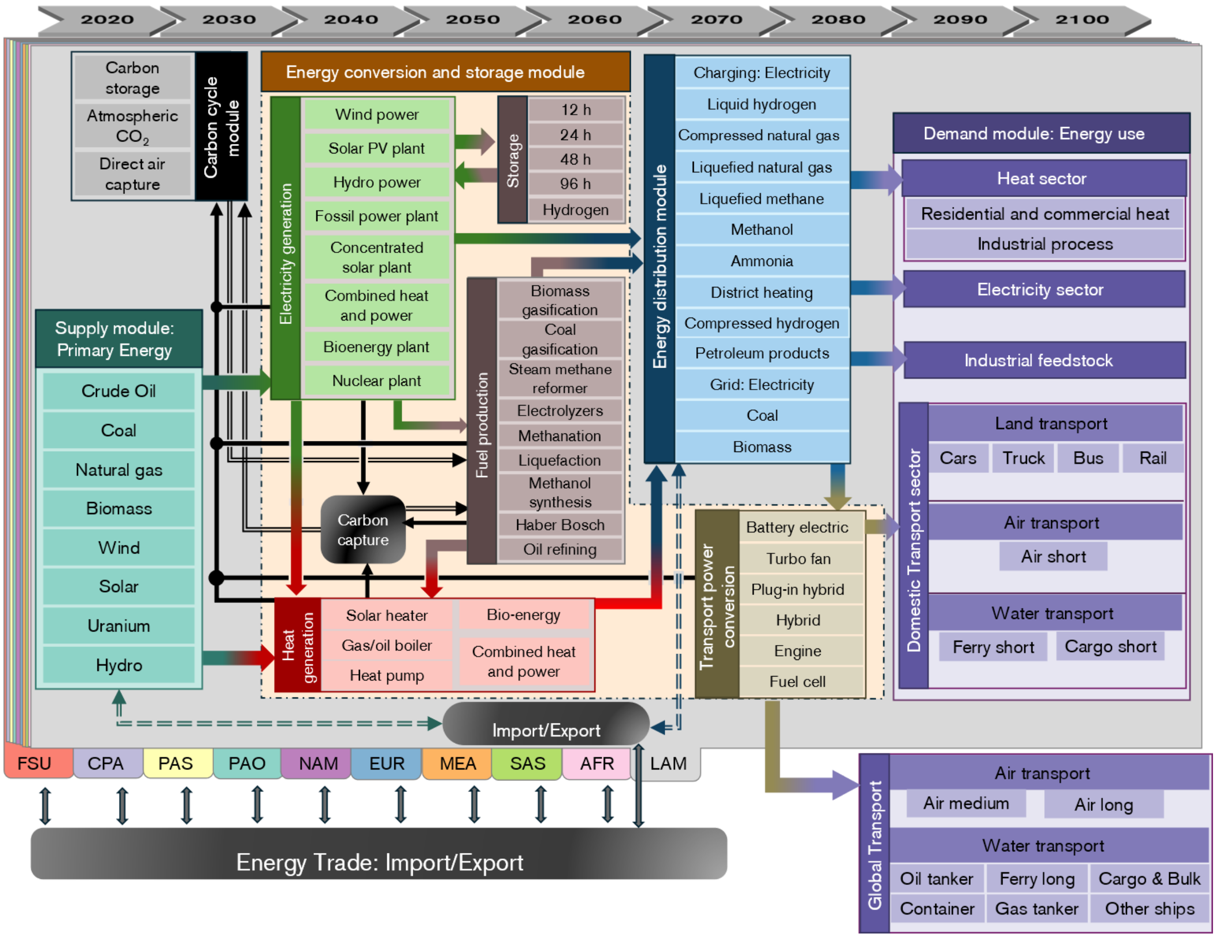

Figure 16: The basic representation of supply, energy conversion, energy distribution, demand, and other modules in GET 11. PV: photo voltaic, FC: Fuel cells, BEV: Battery electric vehicle, PHEV: Plug-in hybrid, h: hours, NAM: North America, EUR: Europe, PAO: Pacific OECD, CPA: Centrally planned Asia, FSU: Former Soviet Union, LAM: Latin America, AFR: Africa, MEA: the Middle East, SAS: South Asia and PAS: non-OECD Pacific Asia.

Spacial resolution: In the model, the world is divided into 10 geographical regions: North America (NAM), Europe (EUR), Pacific OECD (PAO), centrally planned Asia, mainly China (CPA), the former Soviet Union (FSU), Latin America (LAM), Africa (AFR), the Middle East (MEA), South Asia, mainly India (SAS) and non-OECD Pacific Asia (PAS). The distribution of these 10 regions of the world is illustrated in Figure 17. The model allows the trade of primary energy carriers and secondary energy carriers (except for electricity) between regions while deciding the investment, operation, supply, and demand. Trade of energy resources is linked with costs according to the mass and volume of fuel transported and the distance between regions. Regional solutions are aggregated to give global results.

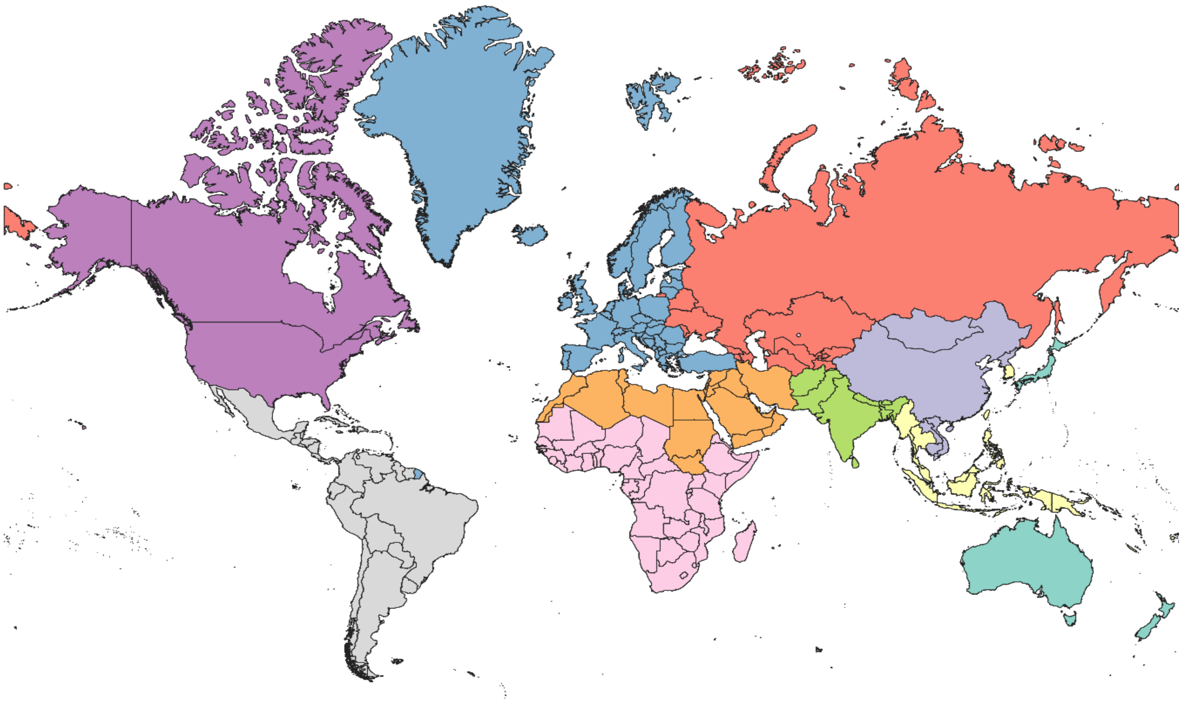

Figure 17: Region definitions in the GET 11 model [141].

5.1.1. Primary energy sources

The model works with the concept of primary energy sources (coal, oil, natural gas, nuclear, wind hydro, solar, and biomass) that are converted using energy conversion technologies into different energy carriers to meet the energy demand in the end-use sectors. All data on primary energy sources are based on GET 10 [142] where assumptions on the regional supply potential of fossil sources are based on estimates made by [143, 144] with a total global supply potential of 80,000, 40,000, 30,000 EJ of coal, oil, and natural gas, respectively. A global bioenergy supply potential of 134 EJ/year is assumed. It may be noted that the potential is divided into grades depending on assumed extraction costs, where regionally varying costs have been assumed for bioenergy whereas costs for fossil sources are assumed to be similar in all regions.

5.1.2. Energy conversion and storage

Electricity generation: The electricity generation module which includes the production of electricity from various types of fossil fuels (coal, oil, natural gas) as well as nuclear and renewables (wind, solar, hydro, biomass) was developed in GET 9.0 [141] and remains in the model version used in this thesis. The model also uses resource-based time-slices where each year is divided into 16 time-slices primarily based on the time of day and season for wind and solar generation (e.g. high solar, medium wind). The model includes direct electricity storage options for 12, 24, 48, and 96 h. For long-term electricity storage, hydrogen is used. Technologies are described by the energy carriers that potentially can be produced from an energy source. Gas, coal, oil, and biomass facilities can be integrated with carbon capture and storage technologies to achieve reduced or negative emissions. GET possesses a singular electricity demand node for each region, hence omitting that electricity is traded between countries within a region. GET encompasses various forms of solar and wind energy: PV (Photovoltaic) rooftop, PV plant A, PV plant B, concentrated solar power (CSP) with storage A, CSP with storage B, onshore wind A, onshore wind B, and offshore wind. The A-versions of each technology possess direct connectivity to the energy grid, whereas the B-versions are situated at a farther distance from demand, needing additional transmission investments.

Heat generation: In GET, the feedstock and heat sectors are modeled based on temperature and process restrictions and are described and motivated in detail in Hedenus, et al. [145]. Residential and commercial low-temperature heat can be generated and distributed through several methods, including localized production from natural gas, biomass, heat pumps, solar energy, waste heat, or centrally produced heat delivered via a district heating system. There are limitations to the use of solar thermal energy and heat pumps for both urban and rural commercial and residential heating requirements. It is estimated that 80% of the heat demand for residential and commercial purposes, in urban centers of colder regions, is met by district heating. It is assumed that only 80% of industrial process heat demand can be supplied by solid fuels and gaseous or liquid fuels must supply the remaining 20% in all regions in the model. It is assumed that only 50% of the total demand may be supplied by solid biomass due to temperature restrictions.

Fuel production: Several fuel production technologies considered in GET 11 are significantly modified from GET 10. The fuel production technologies are modeled as large-scale centralized production. The major alternative fuels considered in GET 11 are hydrogen (base alternative fuel), methanol (liquid alternative fuel), methane (carbon-based gaseous alternative fuel), and ammonia (non-carbon fuel). These fuels can be produced from different feedstock and the processes are modeled in a simplified way only considering the efficiencies, capacity factor, plant lifetime, and investment cost, as given in Table 7. The parameters considered are assumed to represent when the technologies are matured (in the year 2050). In addition, compression and liquefaction are also considered for hydrogen and methane while used in transport. Hydrogen produced from different primary energy sources can also be used for the production of other fuels. The e-fuel pathway is in this way considered in the model when hydrogen is produced from electricity and used to produce ammonia, methanol, or methane in the model. Methanol is included as a proxy for all synthetically produced liquid fuels in the model (that is, fuels such as HVO, FAME, and ethanol are in the model represented by the proxy methanol, as a simplification).

Table 7: Key parameters considered in the study for fuel production technologies.

		Hydrogen	Ammonia	Methanol	Methane
SMR	Efficiency/capacity factor	0.85/0.8	-	0.6/0.8	-
	Investment cost (€/kW)	200	-	500	-
SMR with CC	Efficiency/capacity factor	0.75/0.8	-	0.5/0.8	-
	Investment cost (€/kW)	400	-	1000	-
Coal gasification	Efficiency/capacity factor	0.60/0.8	-	0.6/0.8	-
	Investment cost (€/kW)	1600	-	1600	-
Coal gasification with carbon capture	Efficiency/capacity factor	0.50/0.8	-	0.5/0.8	-
	Investment cost (€/kW)	2000	-	2000	-
Biomass gasification	Efficiency/capacity factor	0.55/0.8	-	0.6/0.8	0.6/0.8
	Investment cost (€/kW)	1600	-	2000	2500
Biomass gasification with carbon capture	Efficiency/capacity factor	0.45/0.8	-	0.5/0.8	0.5/0.8
	Investment cost (€/kW)	2000	-	2500	3000
Oil gasification	Efficiency/capacity factor	0.75/0.8	-	-	-
	Investment cost (€/kW)	700	-	-	-
Oil gasification with carbon capture	Efficiency/capacity factor	0.65/0.8	-	-	-
	Investment cost (€/kW)	1000	-	-	-
Electricity -Electrolysis of water	Efficiency/capacity factor	0.70/0.8	-	-	-
	Investment cost (€/kW)	350	-	-	-
Hydrogen	Efficiency/capacity factor	-	0.85/0.9	0.83/0.9	0.80/0.9
	Investment cost (€/kW)	-	600	300	450

5.1.3. Fuel distribution

Fuel distribution is another aspect considered in the model. Different fuel leakages are introduced in GET 11, assumed to appear in the distribution of gaseous fuels (compressed and liquid hydrogen: 5%, liquid methane: 2%, ammonia: 1%). The grid loss for electricity is assumed as 5% until the final end-use. Distribution costs for energy carriers are assumed being the same as in GET 10, however, an additional cost of 0.5 USD/GJ is considered for the distribution of hydrogen to the fuel production location, and 5 USD/GJ is considered as grid cost for electricity for commercial use and 10 USD/GJ for the residential use. In addition, bunkering, filling, and charging infrastructure costs are assumed as in Table 8.

Table 8: Infrastructure cost for bunkering, filling, and charging.

	Road transport	Water transport	Air transport
Petroleum ($/kW)	700	100	100
Methanol ($/kW)	1200	200	200
Compressessed hydrogen ($/kW)	3500	4500	4500
Liquid hydrogen ($/kW)	2700	3500	3500
Liquid methane ($/kW)	2200	1600	1600
Ammonia ($/kW)	2400	400	400
Electricity-charging ($/kW)	500	750	750

5.1.4. Carbon flows and carbon constraint

The GET model estimates atmospheric CO_2 concentrations, as a function of CO_2 emissions, following a simplified ocean–atmospheric carbon cycle model, originally described by Maier-Reimer and Hasselman [146]. In GET, in the case of carbon capture and storage from biomass a reduction in atmospheric CO_2 concentration is registered. The carbon cycle converts CO_2 emissions into an atmospheric CO_2 concentration. Carbon capture is also considered an option to reduce CO_2 emissions in the energy conversion module, where the model can choose to apply carbon capture to natural gas, coal, oil, and biomass plants for heat generation, electricity generation and fuel production. The possible carbon flows, in GET, are illustrated in Figure 18.

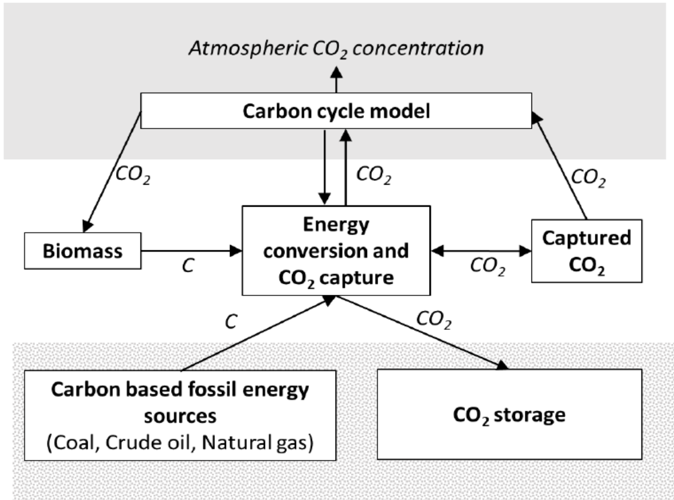

Figure 18: Possible carbon flows in GET [141].

In addition, the capture of CO_2 from air using direct air capture is also included in the model and if stored underground a reduction in atmospheric CO_2 concentration is considered. The model thus allows permanent storage of CO_2 and the maximum allowable storage capacity can be adjusted. Alternatively, the CO_2 captured can be used for the production of methanol or methane from hydrogen (e-fuels). In GET, carbon emissions can be constrained using a carbon budget. The carbon budget can be changed to represent different CO_2 reduction targets (climate goals). In GET 11 the carbon budget is based on the representative concentration pathway (RCP) 2.6, which has been judged as a carbon budget that likely can keep global temperature rise below 2 °C by 2100 [147]. The model allows for an overshoot of the atmospheric CO_2 concentration before stabilization by 2100. GET does not model other GHGs than CO_2 explicitly.

5.1.5. Demand module

All demand projections except for shipping transport demand are modeled using the same principles as GET 10 but updated based on the B2 scenarios from the IIASA GGI Scenario Database1-3 [148, 149]. Demand projections for electricity, feedstock, and heat are based on the SSP scenarios from the IIASA SSP database [150-152]. The transportation demand scenarios are modeled using separate scenarios for passenger and freight movement. The energy demand calculated from transportation activities, except for shipping, is quantified as person-kilometers (pkm) and tonne-kilometers (tkm), with energy intensities expressed as MJ/pkm and MJ/tkm. Total demand for each region is determined based on GDP and population projections (as a driver of the change in transportation activity) from the SSP scenarios in the IIASA SSP database [150-152]. The demand projections for land transport and aviation assume a continued use of conventional technologies and are based on their efficiency. However, if the model finds it cost-effective with a more efficient powertrain (e.g. battery electric or fuel cell) the demand will decrease according to the increased efficiency. The powertrain technologies are modeled similarly to the energy conversion module, covering various powertrain technologies that are used to convert energy carriers to final energy use, characterized by efficiency, investment cost, and vehicle lifespan. Land transport is divided into five segments: 1.) cars (passenger), 2.) trucks (freight), 3.) buses (passenger), 4.) rail (passenger), 5.) rail (freight). The powertrain technologies included are ICE, FC, hybrid (hyb), and plug-in hybrid electric vehicles (PHEV). The aviation sector is divided into four segments based on the range of operation including 1.) short air (passenger), 2.) medium air (passenger), 3.) long air (passenger), and 4.) cargo air (freight). The energy carriers and technologies that are considered for land and air transport are shown in Table 9.

Table 9: Energy carriers and powertrain technologies considered for land and air transport.

	Petroleum oil			Methanol			Methane			Compressed Hydrogen				BE
	ICE	Hyb	PHEV	ICE	Hyb	PHEV	ICE	Hyb	PHEV	ICE	Hyb	PHEV	FC	
Cars (passenger)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Trucks (freight)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Buses (passenger)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Rail (passenger)	Yes	No	No	Yes	No	No	Yes	No	No	Yes	No	No	Yes	Yes
Rail (freight)	Yes	No	No	Yes	No	No	Yes	No	No	Yes	No	No	Yes	Yes
Short air (passenger)	Yes	No	No	Yes	No	No	No	No	No	Yes	No	No	No	Yes
Medium air (passenger)	Yes	No	No	Yes	No	No	No	No	No	Yes	No	No	No	No
Long air (passenger)	Yes	No	No	Yes	No	No	No	No	No	Yes	No	No	No	No
Cargo air (freight)	Yes	No	No	Yes	No	No	No	No	No	Yes	No	No	No	No

5.1.6. Representation of shipping in GET

The shipping sector in GET 11 is substantially modified for improved representation. In GET 10, the shipping sector is represented by three types of ships, and the energy demands are aggregated to these types based on the IMO Third GHG study [153]. During the work of this thesis, the shipping module was modified and represented with eight categories: 1) container ships, 2) bulk and general cargo carriers, 3) liquid tankers, 4) gas tankers, 5) passenger-long, 6) passenger-short, 7) cargo short, and 8) other ship types. The categories are based on transport work and the average distance they operate as mentioned in Section 4.3. Seven energy carriers are included in the model: petroleum products (representing HFO and MGO), LNG, MeOH, NH_3, LH_2, CH_2, and electricity (only for short-range vessels). ICE and FC-based propulsion are considered for all vessels, with the addition of a battery-electric option for short-range vessels. Nuclear and hybrid alternatives are excluded as propulsion technologies for ships. The energy carriers and technologies considered in the model for land and air transport are shown in Table 10. The powertrain technologies for converting the energy from energy carrier to end-use demand are modeled similarly to the energy conversion module, covering various powertrain technologies and separate energy carriers, defined by efficiency, investment cost, and vessel life lifespan.

Table 10: The energy carriers and the powertrain technologies considered for shipping.

	Fossil oil	Methanol		Liquid methane		Liquid hydrogen		Ammonia		Battery electric
	ICE	ICE	FC	ICE	FC	ICE	FC	ICE	FC	
Container ships	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Bulk & general cargo	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Liquid tankers	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Gas tankers	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Ferry-long (passenger)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-	-	-
Ferry-short (passenger)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-	-	Yes
Cargo short	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other ship types	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-

Energy-use demand: The total energy demand for shipping is calculated considering three main factors: (1) projected transport work, (2) energy demand per unit of transport work, and (3) projected future energy efficiency. Projection of transport work is performed through a logistic analysis of global transport data, following methods from the Fourth IMO Greenhouse Gas Study [2]. This approach estimates future transport work growth by examining historical relationships between transport work and relevant growth drivers. The approach treats the transport of energy products, non-energy products, and passenger transport differently. Shipping transport demand connected to non-energy products and passenger movements are projected based on historic growth where the per capita GDP serves as the growth driver. The GDP and population projections are taken from the SSP scenarios in the IIASA SSP database [150-152]. Shipping transport demand connected to the movement of energy products is based on global oil, coal, and gas consumption levels taken from the SSP scenarios in the IIASA SSP database [150-152].

Energy demand per unit of transport work is needed to calculate the transport work into energy demand. The energy per unit of transport work is calculated using fleet data and activity from 2012 and 2018, as described in the Fourth IMO Greenhouse Gas Study [2]. This data is used to assign transport work to the eight selected ship type categories defined in GET 11 and to calculate the average energy consumption per unit of transport work for each ship category. Another aspect that will affect the total energy demand is projected improvements in the operational and technical energy efficiencies other than the efficiency of the powertrain already covered in the model. These efficiency improvements are estimated based on the Fourth IMO Greenhouse Gas Study [2]. Finally, the total projected energy demand for each of the eight ship categories, in GET 11, is calculated by multiplying the three factors mentioned above and aggregating them to the global energy demand for each ship categories. The base demand before considering the supplementary trading demand for SSP2 RCP26 scenario is shown in Table 11.

Table 11: The base shipping energy demand in EJ considered under SSP2 scenario before iteration.

	2020	2030	2040	2050	2060	2070	2080	2090	2100
Ferry short	0.13	0.19	0.24	0.30	0.36	0.43	0.50	0.58	0.66
Ferry long	0.80	0.86	1.10	1.37	1.66	1.97	2.30	2.64	3.00
Cargo bulk	3.90	6.26	7.53	8.99	11.04	13.11	15.38	17.54	19.65
Oil tanker	1.50	1.85	1.57	1.35	0.97	0.64	0.27	0.09	0.03
Gas tanker	0.57	0.61	0.77	0.96	1.15	1.24	1.30	1.34	1.37
Cargo short	0.34	0.33	0.39	0.47	0.56	0.66	0.77	0.88	1.00
Other ship	1.94	2.23	2.77	3.42	4.19	4.95	5.78	6.64	7.53
Container	1.48	2.46	3.21	3.89	4.75	5.59	6.51	7.45	8.43

Furthermore, it is assumed that the trade of energy-related transport work will affect shipping demand. The GET model assumes the transportation of hydrogen in the form of methanol, ammonia, or liquid hydrogen between various regions. These trade pattern changes would be due to changes in the demand for primary and energy carriers in the different regions. The variations in primary and secondary energy demands across different locations are influenced by the availability of primary energy resources. The optimization run is iterated (1 iteration) to add these changes in the transport demand. Demand, measured in tonnes-miles, is based on energy traded in mass (energy density and energy trade) and the distance between regions. This is shown in Figure 19. It can be seen that ammonia and methanol traded between regions in the scenario with the global climate target. It can also be noted that there is a decrease in the coal and oil trade. The change in the net energy demand can also be seen in Figure 19.

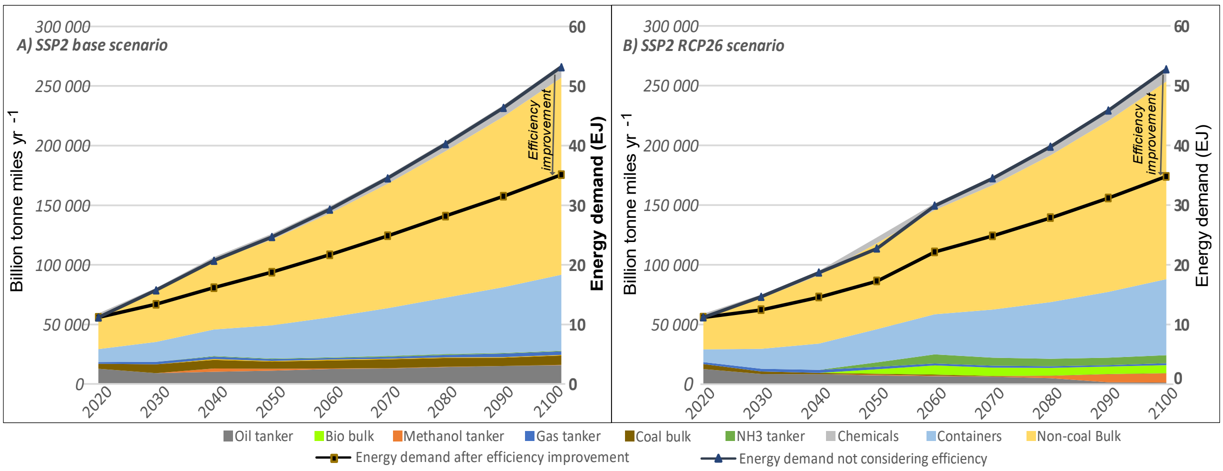

Figure 19: The transport and energy demand for the shipping sector considered in the GET model after the iteration: A) SSP2 base scenario with no global climate targets, B) SSP2 RCP26 scenario with global climate target.

5.2. Integration of LCA and GET

ESMs often neglect other emissions and impacts on the environment than GHGs [154]. The GET model does not account for the full life cycle climate impact, as it only includes CO_2 and methane emissions associated with energy flows. Integration of LCA into GET helps to assess the environmental impact of different energy transition scenarios. This allows us to consider other impact categories than climate change in the assessment and to understand burden shifting and environmental tradeoffs for different scenarios. In life cycle assessment, it is important to consider all environmental flows and go beyond emissions linked to energy flows, for example including emissions related to material flows and fugitive emissions.

Integrating prospective LCA with ESM is not straightforward as the processes need to be harmonized in terms of time evaluation of technologies, availability of the resources, translation of complex energy flows into simpler parameters like efficiencies etc. Different approaches are used in the literature for linking LCA with ESM. One of the approaches is ex-post analysis where the LCA is performed on the output of the energy optimization model (e.g. Choi, et al. [155]). The main challenge with this methodology is to ensure consistency between the data utilized for the processes represented in ESM and LCA. Consequently, the above approach may face challenges in making the processes consistent in both models. Another approach is monetization, where the emissions are considered in the objective function in the ESM through monetization of environmental externalities. The advantage of this approach is its feedback on the optimization problem and its impact on the technology mix. The drawback is the uncertainty in the monetization step as it follows the damage cost methodology rather than including a comprehensive analysis accounting for other impacts [156, 157].

Another state of art approach is integrating life cycle environmental indicators into ESM using environmental indicators (e.g. Xu, et al. [41], Arvesen, et al. [154], Volkart, et al. [158]). The advantage of this approach is the possibility of applying standard process-based LCA to adjust in degree of detail and specificity of the ESM. However, the process data harmonization between both methods (LCA and ESM) is challenging in this approach. As LCI dataset for each process exactly should represent the process in the energy system technology regarding the technology type applied, time period, and modeling region. However, this representation is difficult as LCA includes a detailed model of the process considering energy, material, and emission flows whereas the processes in energy system models are typically represented by energy efficiency and emissions, making this approach data intensive. Another problem highlighted with this approach is the risk of double counting [154, 156].

In this thesis and Paper V, a framework is developed to integrate prospective LCA into the GET model which is depicted in Figure 20. The framework can be divided into five different steps:

1) Modification of key processes in the GET model and adding key processes specific to shipping to the model including characteristics of ship types, parameters for energy distribution, adding more potential marine energy carriers and their production routes, differentiating the production routes for e.g. liquid hydrogen, and adding possibility of trading alternative fuels. This facilitates the compilation of inventory data for the process-specific LCA and also improves the cost assessment for the energy system analysis.

2) Process-specific model for LCA is constructed for 10 year steps (for 2020-2080) for around 90 of the 200+ processes included in the GET model. This includes the processes that are directly or indirectly connected to the ship's energy transition. The processes are related to energy carrier production (~60 technologies), shipping operation (~15 technologies), and fuel infrastructure (~15 technologies). The LCI primarily relies on process-based data sourced from the literature primarily scientific papers, premise v1.5.8 [92], and ecoinvent v3.10 [93].

3) The process-specific LCI data are harmonized with the GET model data by aligning key parameters such as life-time and capacity factors for the technology. The energy flow in the LCA inventory of each technology is harmonized with the input parameters of the technology in the GET, including the carbon balance. Also, inventory data of LCA are adjusted to avoid double-counting impacts in downstream energy system supply chains, where analysis is performed from gate-to-gate. This involves setting the LCI energy inputs to zero, as these inputs are already represented as distinct processes within the GET model.

4) The process-specific LCAs are used to calculate environmental indicators for all processes over sixteen midpoint environmental impact categories including climate change.

5). Total WtW impacts of the cost-effective technology and fuel mixes are calculated as post-processing, considering the environmental impact indicators derived from each process-specific LCAs to assess the total environmental impacts of the energy system related to shipping for each assessed scenario. This is done by adding together the processes in the supply chain considering the energy flow shares for each process.

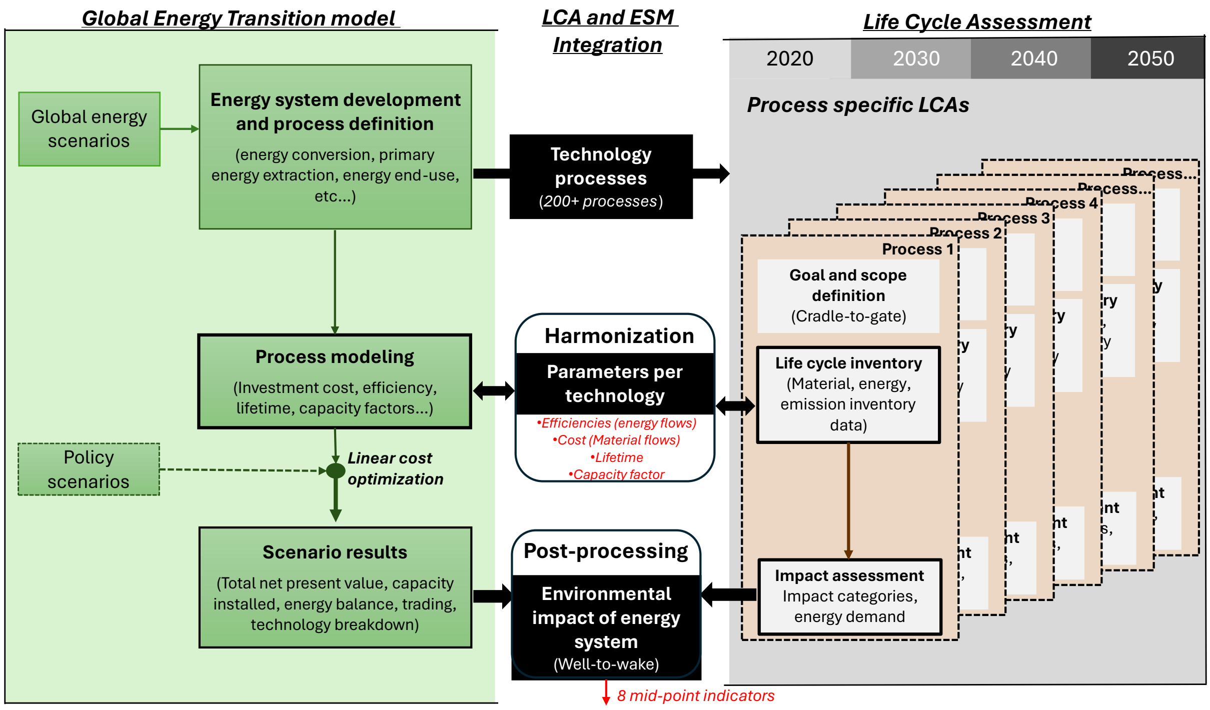

Figure 20: Framework used in the integration of prospective LCA and GET model.

5.3. Policy scenarios

In line with the revised GHG emission reduction target, the IMO has decided to implement a basket of measures consisting of two parts. First, a technical element which will be a goal-based marine fuel standard regulating the phased reduction of marine fuel GHG intensity. Second, a market-based measure which will be some form of maritime GHG emissions pricing mechanism [24]. Two shipping specific policies are investigated: 1) A levy of direct CO_2 emissions from shipping of 50 USD/tCO_2 from 2030 and increased with 50 USD/tCO_2 every 10 years until 2050 and after that kept at the same level for the rest of the century. The levy considers direct CO_2 emissions independent of origin. 2) A feebate system with a fee and a reward for zero-emission ships. The same levels of the fee as for the levy and assume that 20% of the funds collected are used to subsidize zero-emission technologies.

The shipping specific policy measures are assessed for two scenarios first for a world without any global climate reduction ambitions and second for a world achieving a 2-degree climate target. In the first case, the GET model is run without any carbon constraints and in the second case with a carbon budget of 905,000 Gt CO_2 (between 2010-2100) based on the representative concentration pathway (RCP) 2.6 [147].

6. Results

6.1. Technological suitability

The barriers to using alternative fuel technologies including the low readiness level, lower energy density, and safety risk are analyzed in different appended papers and are summarized in Figure 21. TRL levels indicate the development status of a technology and TRL levels over the entire supply chain, examined in this thesis, are shown in Figure 21. Where there are several processes in production, the least matured technology is considered a bottleneck (e.g., fuel synthesis category for methanol production includes several emerging technologies including electrolysis, methanol synthesis, and DAC). The lower volumetric energy density of alternative energy carrier storage systems, suggests that increased space requirements may impact the practicality of certain solutions compared to present designs. In the analysis, the technological feasibility is assessed by summarizing three approaches as described in Section 3.1.2 as there are both pros and cons for each approach. It can be noticed that some energy carriers will not be feasible at all due to storage constraints, as e.g., the BE option and the compressed hydrogen option for tanker, container, bulk, and cruise.

Another area highlighted in Figure 21 pertains to risk assessment related to safety, primarily examined in Paper II. It may be noted that most concepts are deemed feasible with additional safety measures, such as gas detection, adaptations to fire detection and suppression, double-walled piping, ventilation in general, determination of safety distances for any venting in the case of hydrogen, and requirements for ensuring no NH_3 gas release through scrubbing of vent gases. For the protection of the crew in the case of an NH_3 leak, personal protective equipment (with required respiratory protective equipment) should be available onboard. For passenger ships (RoPax, cruise ships, and ferries), the risk gets higher due to the potential exposure of passengers to NH_3, rendering it potentially unfeasible for these ship types.

The intact stability of the service vessel was checked with the new components and tank weights (both tank and fuel) and placement. Regarding placement of tanks for both H_2 and NH_3 was assessed during the safety workshop. The majority of participants felt that the tanks should be on deck, rather than under deck as shown in the conventional design. Under deck, storage was selected based on the current vessel design with cranes and three boats (lifeboat, large work boat, and small work boat) above deck. Positive aspects for under deck storage were noted to be easier detection of small leaks and more protection for the tanks. This also ensures that capsizing will not occur during the vessel's various loading conditions. Intact stability checks were done for the service ship and the tanker vessel with the liquid H_2 and compressed NH_3 systems.

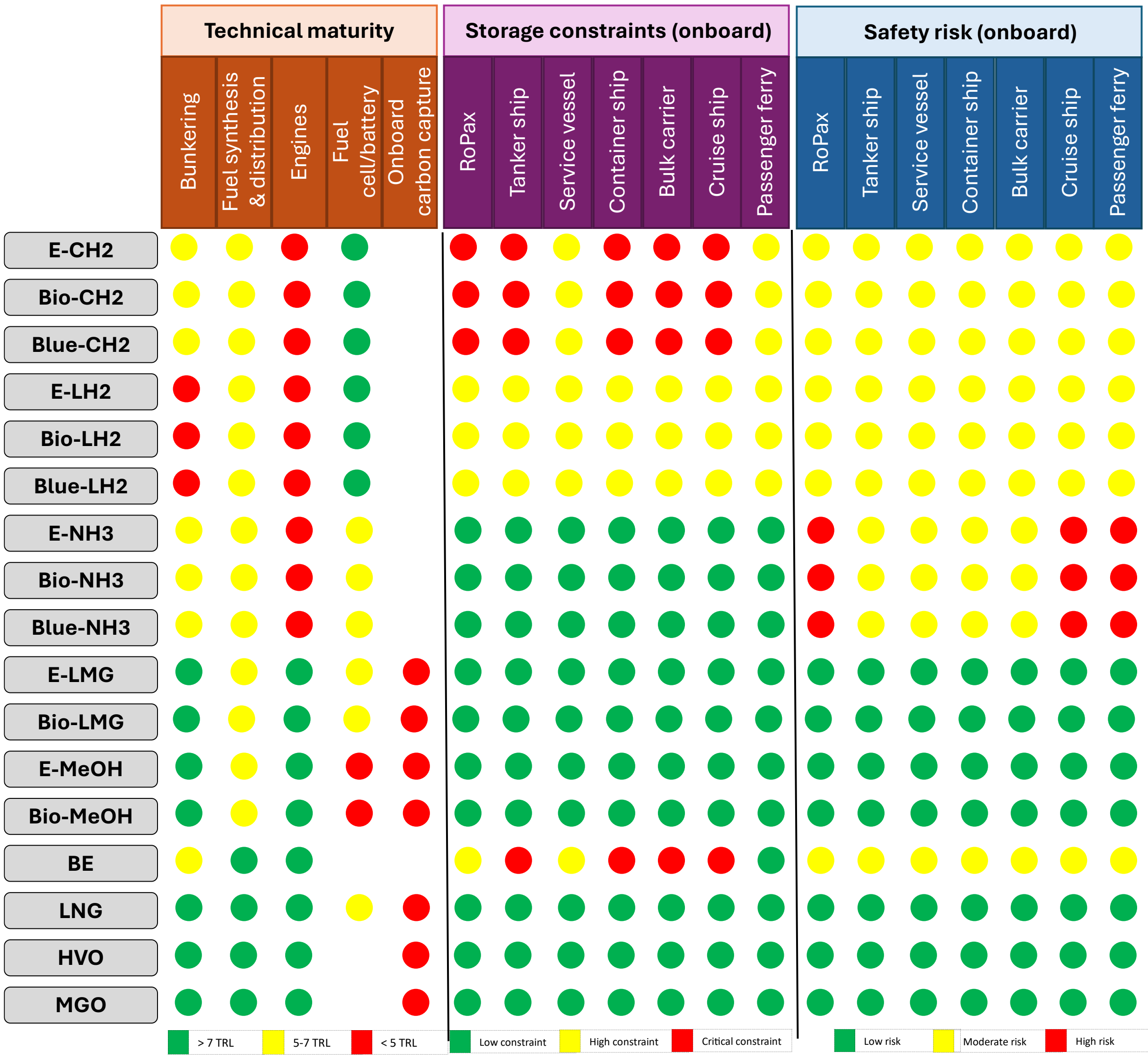

Figure 21: Technological assessment in terms of TRL, feasibility, and safety onboard. CH_2: Compressed hydrogen; LH_2: liquid hydrogen, NH_3: ammonia, LMG, liquid methane, MeOH, Methanol, BE: Battery electric, LNG: liquefied natural gas, MGO: marine gas oil

6.2. Energy intensity

Figure 22 (ammonia), Figure 23 (Liquid hydrogen and battery electric), Figure 24 (Methanol), and Figure 25 (Liquid methane) show energy flows involved in the different decarbonization pathways. The energy flow and primary energy intensity depend not only on the powertrain and production pathways but also on the chemical property of the energy carrier (e.g., carbon content).

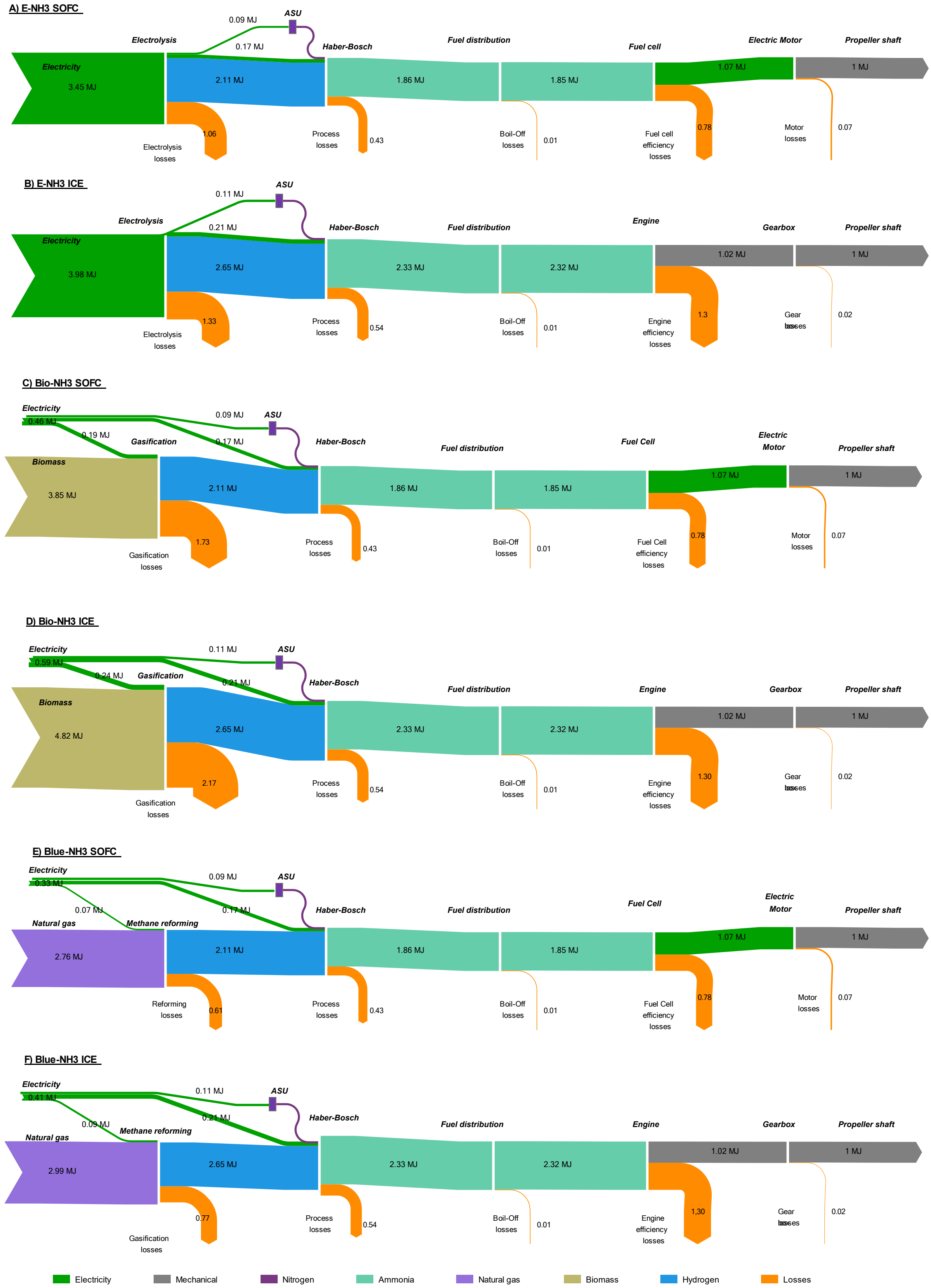

Figure 22:Sankey diagram illustrating energy needed for different ammonia pathways to provide 1 MJ to propeller for following options. A) e- ammonia in fuel cell, B) e-ammonia in engine, C) bio-ammonia in fuel cell, D) bio-ammonia in engine, E) blue ammonia in fuel cell, and F) blue ammonia in engine.

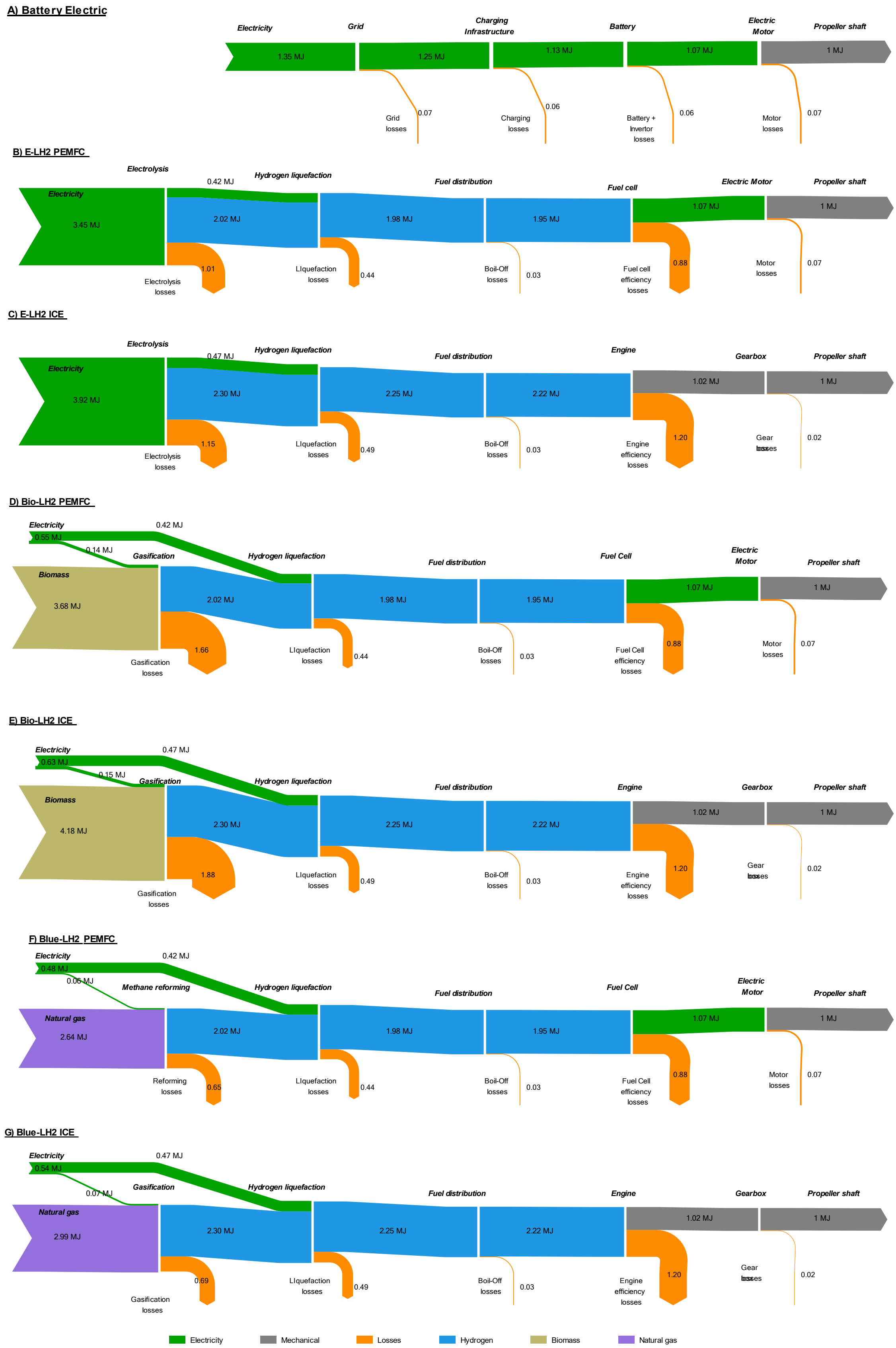

Figure 23: Sankey diagram illustrating energy needed for different liquid hydrogen pathways and battery electric to provide 1 MJ to propeller for for following options. A) Battery electric B) e- liq. hydrogen in fuel cell, C) e-liq. hydrogen in engine, D) bio-liq. hydrogen in fuel cell, E) bio-liq. hydrogen in engine, F) blue liq. hydrogen in fuel cell, and G) blue liq. hydrogen in engine; liq. : liquid

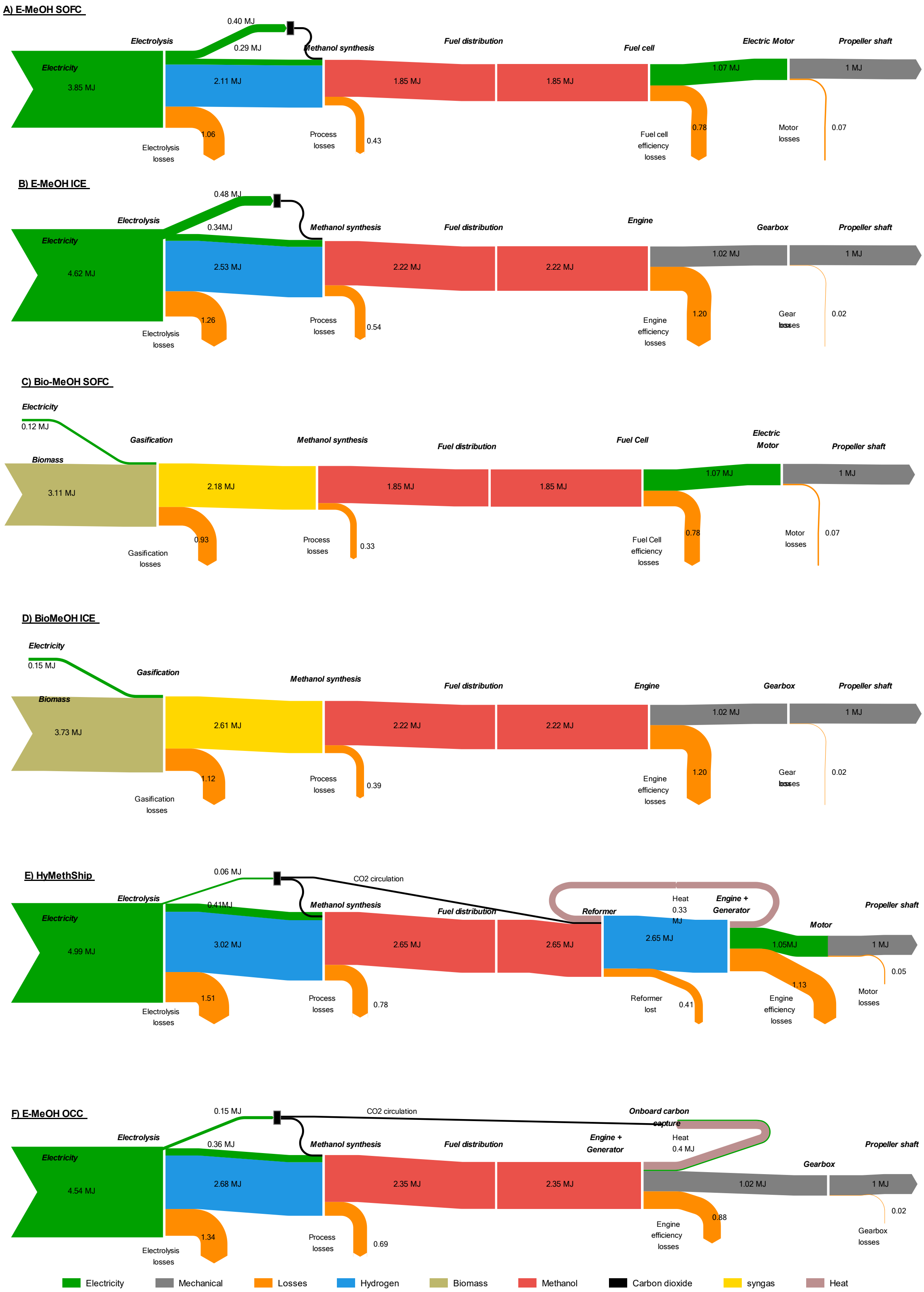

Figure 24:Sankey diagram illustrating energy needed for different methanol pathways to provide 1 MJ to propeller propeller for following options. A) e- methanol in fuel cell, B) e-methanol in engine, C) bio-methanol in fuel cell, D) bio-methanol in engine, E) e-methanol in HyMethShip and F) e-methanol in engine with Onboard carbon capture .

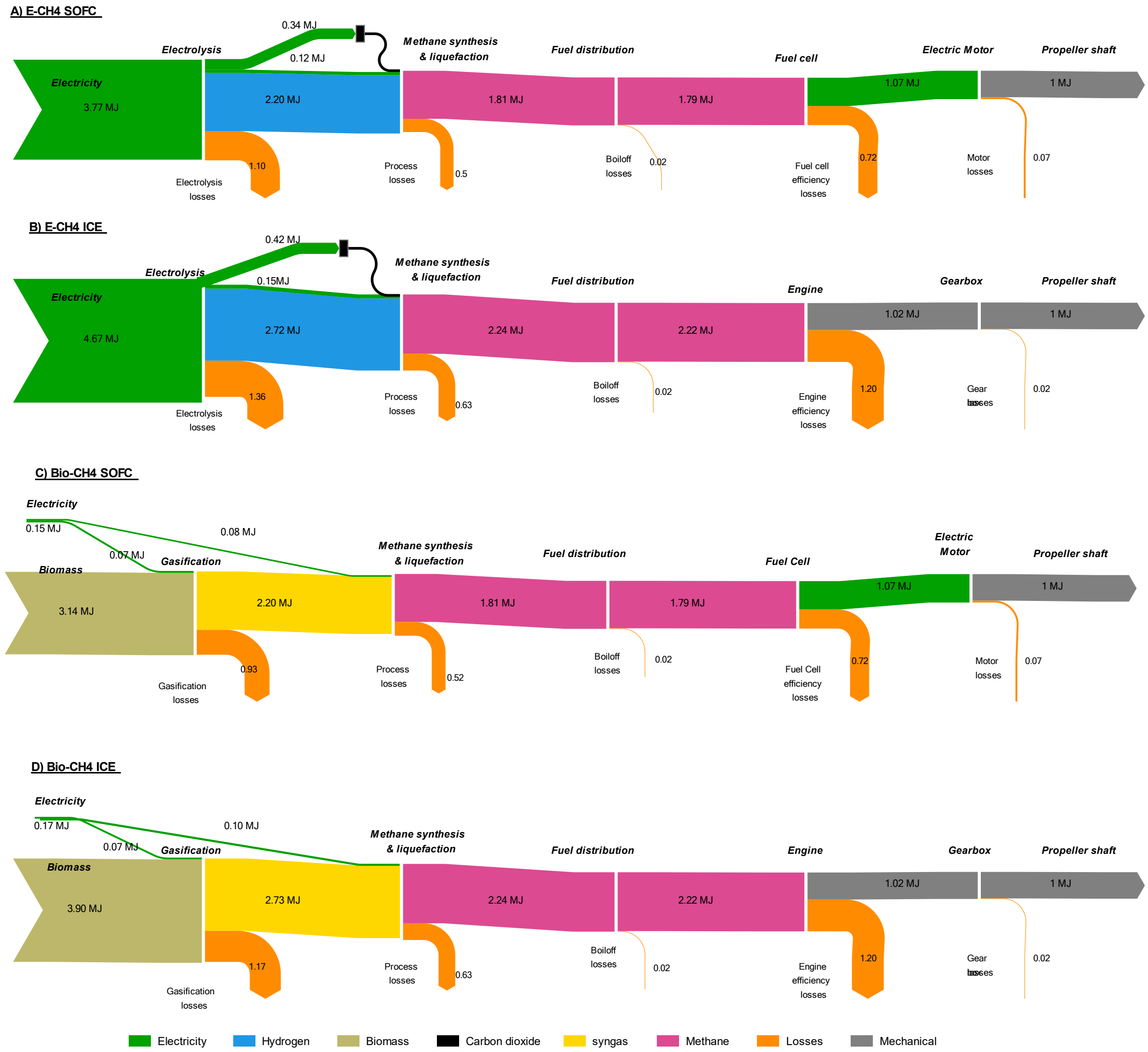

Figure 25:Sankey diagram illustrating energy needed for different liquid methane pathways to provide 1 MJ to propeller propeller for following options. A) e- liq.methane in fuel cell, B) e-liq.methane in engine, C) bio-liq.methane in fuel cell, D) bio-liq.methane in engine, E) blue liq.methane in fuel cell; liq. : liquid

6.3. Environmental and economic tradeoffs

The life cycle assessment and costing results from Papers I-IV are summarized in Figure 26 showing the primary energy demand, GHG reduction potential, other environmental impacts, and CAC. The results from Papers I-IV are categorized into three scales based on relative values. The life cycle energy demand results show that the primary energy demand for decarbonization pathways related to e-fuels and bio-fuels (based on gasification) is high. This is due to the energy losses during the conversion during the upstream (production of fuel) and downstream (energy conversion onboard) steps. The major energy conversion losses of bio-fuel and e-fuel synthesis are associated with the gasification and electrolysis processes, respectively. The higher demand for electricity for e-fuels makes the carbon intensity of electricity used in production important. The transition of the shipping sector toward e-fuels or bio-fuels will necessitate increased demand for electricity and biomass, respectively. Compared to bio-fuels and e-fuels, blue fuels and OCC have lower primary energy requirements due to better process efficiency, even when considering the supplementary energy needs for carbon capture. The battery-electric alternative has the lowest overall energy use throughout its life cycle since energy losses within the powertrain system are minor.

The second aspect, summarized in Figure 26, is the climate impact in terms of GWP100 expressed as reduction potential from the MGO case. Among the pathways assessed, e-fuels have the highest reduction potential followed by bio-fuels. Blue fuels and OCC pathways demonstrate limited potential for reducing GHG emissions. It may be noted that a significant proportion of GWP emissions can be attributed to WtT processes for all alternative pathways, except for onboard carbon capture and battery-electric options. Compared to the reference case with MGO, for OCC pathways share of TtW emissions arises due to additional fuel consumed to power the carbon capture systems and the liquefaction of captured CO_2. When examining GWP across fuel cells and engines utilizing the same fuel type, it is evident that fuel cells generally are associated with lower GWP. This advantage is attributed to their higher efficiency, cleaner electrochemical combustion process, and the absence of pilot fuel requirements, resulting in reduced TtW GWP. However, the manufacturing and replacement phases of fuel cells exert a higher impact due to the increased material demands, although these impacts do not negate the overall benefits. The methane options have higher GWP than other fuels from the same feedstock in most cases. This is largely due to methane leakage during transportation and liquefaction, a factor that also affects the reduction potential of blue fuels. Also, utilizing methane as fuel in engines leads to significantly higher GWP values, primarily due to methane slip associated with engines, which is negligible in fuel cells due to the circulation of the anode gas. Another aspect that can be noted is that bio-methane and bio-methanol present more energy-efficient production pathways compared to their respective e-fuels, which require energy-intensive direct air capture (DAC). This efficiency contrasts with bio-ammonia and bio-liquid hydrogen, which necessitate additional energy for air separation and CO_2 separation from syngas, respectively. Similarly, ammonia combustion in engines can produce N_2O, which is a much stronger GHG than CO_2 and CH_4, while this factor is largely insignificant during electrochemical combustion in fuel cells.

In the case of battery electric ships, the production of batteries also has a substantial influence. In Paper IV, the battery-electric option is studied in detail as several parameters will affect the size of the battery including charging strategy, number of cycles, and battery chemistry. Implementing suitable charging procedures for improved opportunity charging strategies (opportunity charging is the practice of charging a battery in short intervals throughout the day instead of charging it in full all at once) may decrease the number of battery packs, hence reducing GHG contribution from the battery.

Papers I-IV extensively evaluate also other environmental impacts associated with the assessed options for decarbonizing shipping. These results are summarized in Figure 26 using normalization and weighting (see Section 3.3.). E-fuels in the fuel cells have the lowest aggregated score on environmental impacts, while blue fuels in engines and OCC have the highest aggregated score. The high impact on many environmental categories (like resource use-fossil, acidification, particulate matter, and photochemical ozone formation) for the blue fuels and OCC can be linked to the continued use of fossil fuel and additional fossil fuel that needs to be burned to meet the energy required. The carbon capture system captures only the CO_2, not other air pollutants. Bio-fuels have aggregated scores in between e-fuels and blue fuels. Another observation from the contribution analysis in the appended papers is that for all alternative fuels, except batteries, the major contribution of impact is from the WtT phase, this indicates the importance of using life cycle thinking while evaluating the shipping transition. For e-fuels, the impact categories having the highest contribution are water usage (related to electrolysis), human toxicity, and resource use-metals and minerals (both related to materials used in the wind power infrastructure and fuel production infrastructure). The major impact categories associated with bio-fuel pathways are acidification potential, land use, eutrophication, and water use. Among different energy carriers, ammonia has a high impact on some categories including eutrophication and acidification. This can be linked to ammonia leakage in the supply chain and the emission of NOx and N_2O from the engine.

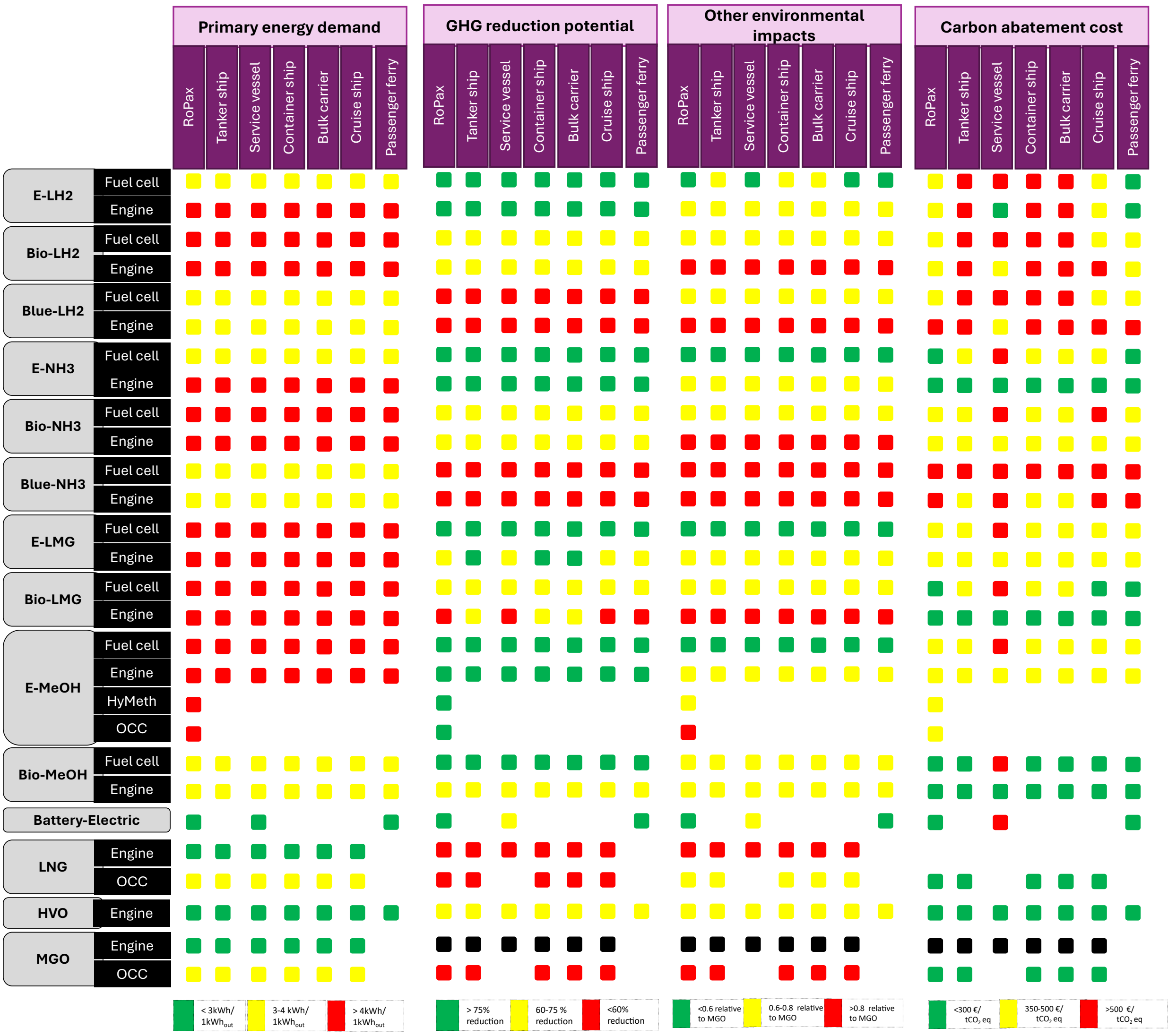

Figure 26: Summary of pLCA and LCC results detailed in Papers I-IV in comparison with the MGO case. The black squares represent reference case with fossil. LH2: liquid hydrogen, NH3: ammonia, LMG, liquid methane, MeOH, Methanol, BE: Battery electric, LNG: liquefied natural gas, MGO: marine gas oil; OCC: onboard carbon capture

Cost will probably be the most important factor in the energy transition. The LCC and CAC are assessed in Papers I-III, and results indicate that fuel costs constitute the majority of the overall cost for all technical pathways, except for battery-electric pathways. For batteries, the major cost is associated with the battery system cost (investment and replacement). CAC results from the appended papers are summarized in Figure 26. Bio-methanol represent one of the most promising decarbonization solutions, with a CAC of around 200€/tCO_2-eq for all vessel types. Nonetheless, for passenger ferries, battery electric (BE) technology is the most promising option, mostly because of the short and regular routes they travel (hence require smaller batteries). Among e-fuels and blue fuels, the ammonia-based pathways have the lowest costs. E-methanol and e-methane options have higher costs which can be associated with the assumption that CO_2 comes from an energy-intensive DAC process, unlike in the case of bio-methanol and bio-methane which do not need a sub-system for CO_2 supply. Although blue fuel alternatives are less costly than other fuel choices, they have a high GWP over the life cycle, resulting in a higher CAC compared to e-fuels and bio-fuels.

For the same fuel in FC and ICE, the overall cost is higher for FC alternatives compared to ICE options for most ship types. This means that the savings in fuel costs due to reduced fuel use in fuel cells are not enough to offset the higher initial investment and replacement costs of fuel cells. However, the CAC varies with ship types; e.g. liquid methane, ammonia, and liquid hydrogen options for the cruise ship, and RoPax fuel cell options have a lower CAC for FC than ICE options. On the other side, for the service vessel, FC options and BE have significantly higher CAC than ICE options. This variation is associated with the investment cost of the propulsion system and utilization rate. Higher utilization of capital equipment for batteries and FCs benefits more as lower energy consumption (due to higher efficiency) can compensate for the higher capital cost.

Except for the BE option, it is the fuel production part, in the supply chain, that contributes the most to both total cost and environmental impact for all decarbonization pathways. The energy conversion efficiencies for e-fuel and bio-fuel routes are low, and the cost and carbon intensity of electricity and sustainability of biomass substantially influence the overall cost and GHG potential of both pathways, respectively. It can also be noted that for the same pathways, the environmental impacts and total cost vary with ship types. These variations can be linked to four key ship characteristics: 1) The energy required for the design range of the ship (also depends on many factors like speed, distance, installed power, etc.), 2) the power and type of engine installed (different engine types have different emissions and efficiencies), 3) total energy consumption (the energy required will influence the amount of fuel burned), 4) utilization rate (can be referred to as the annual energy use per installed capacity). The energy required for the design range of the ship determines the required fuel storage capacity. The environmental impact and costs will be highest for energy carriers with extremely low energy density for ships that require larger energy storage, such as liquid hydrogen and battery electric systems. The emissions will vary depending on the engine type, where e.g. methane emissions are higher for 4S engines compared to 2S engines, which will impact the total GWP results. The total energy consumption determines the total fuel required for the transport work which affects both TtW and WtT emissions.

6.4. Robustness of result

Uncertainty analysis is performed in the appended Papers I-IV using Monte Carlo simulation to assess the impact of the variability of various parameter values. For environmental impacts associated with GWP the following parameters were identified as important: the effect of electricity production, leakages in the fuel supply chain, the efficiencies of engines/FCs, the energy required during different processes, fuel production, possible N_2O emissions from NH_3 based ICEs, battery energy density, carbon capture rates, and emissions from engine based on changes in efficiency. The uncertainty is further evaluated to understand the key parameters. The key parameters observed from the uncertainty GWP results include N_2O emissions for ammonia in ICE, methane emissions when methane is used in ICE, CO_2 capture rate for OCC cases, biomass gasification efficiency for bio-fuels, fugitive emissions in the natural gas supply chain for blue fuels, and prospective electricity mix for e-fuels and battery electric. The uncertainty analysis is also performed for cost and in addition to changing the efficiencies of engine/FC and energy required for fuel production processes, the investment cost related to the fuel supply chain, the capital cost of ship powertrain system, and various feedstock costs (electricity, natural gas, and biomass). The uncertainty in the feedstock costs has the highest influence on the total cost of the parameters investigated, i.e., biomass costs for bio-fuels, natural gas prices for blue fuels, and electricity prices for e-fuels. For BE options, the cost of battery systems and electricity prices are the most important cost parameters. Figure 27 shows Monte Carlo simulation results for liquid hydrogen production costs from different pathways.

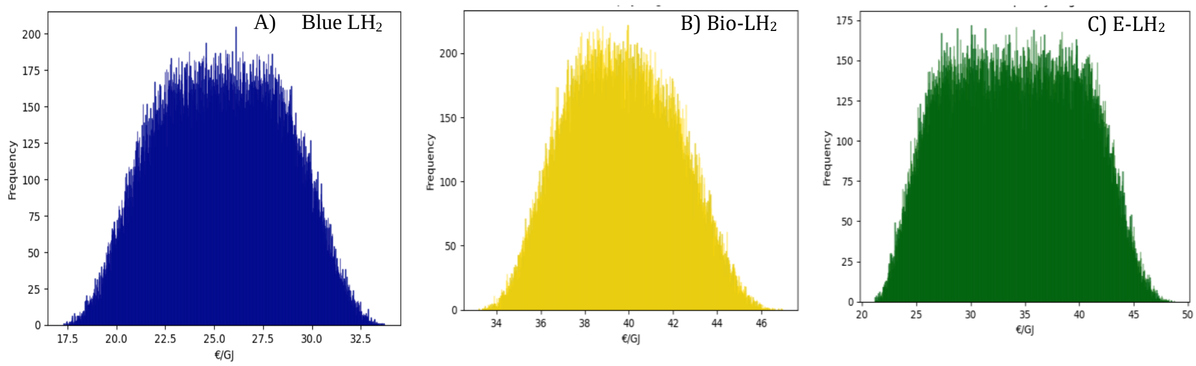

Figure 27: Monte Carlo simulation results for liquid hydrogen production costs from different pathways

Sensitivity assessment: Sensitivity analysis on total GWP is performed by varying methane leakage in the natural gas pathway (Paper III), biomass gasification efficiency (Paper III), and the carbon intensity of the electricity mix (Papers I and III). Sensitivity analysis on total cost is performed in Paper III by varying natural gas prices, biomass prices, and electricity prices and Figure 28 shows sensitivity results for total cost, for different pathways, for a bulk carrier.

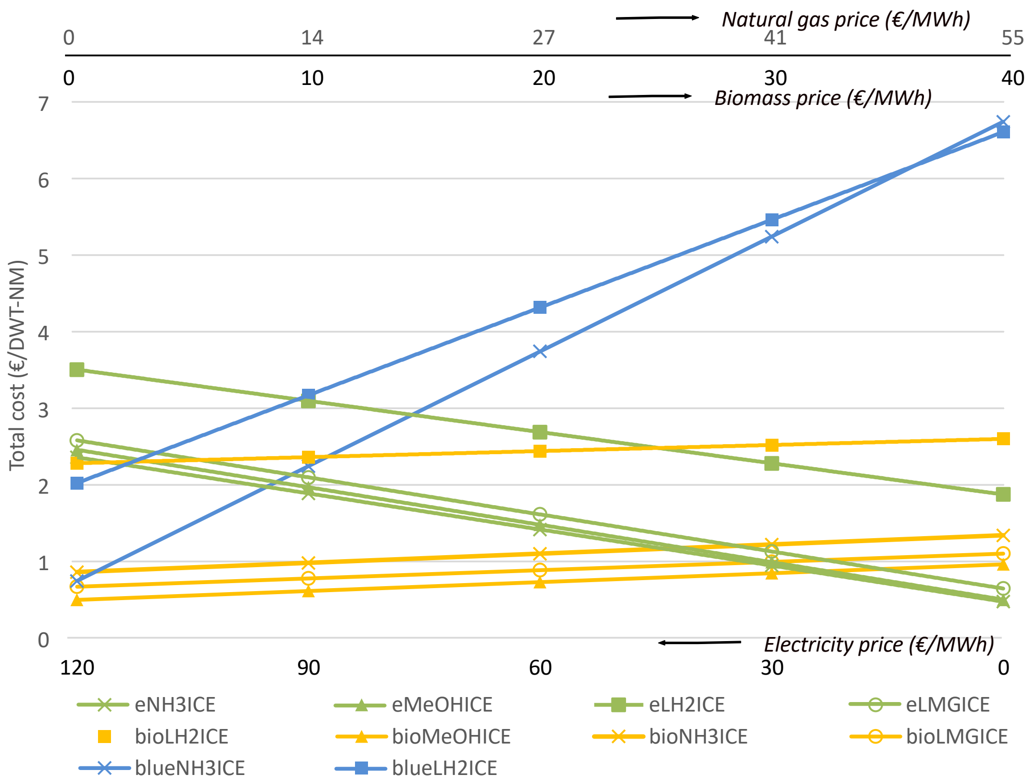

Figure 28: Sensitivity assessments on total cost based on different feedstock cost for a bulk carrier. LH_2: liquid hydrogen, NH_3: ammonia, LMG, liquid methane, MeOH, Methanol, ICE: Internal combustion engines.

6.5. Energy transition under different shipping policies

The revised GET model is used to analyze the global shipping transition and cost-effective energy carrier and technology mixes for various ship categories under selected shipping policies in Paper V. Selected parts of the result are shown in Figure 29.

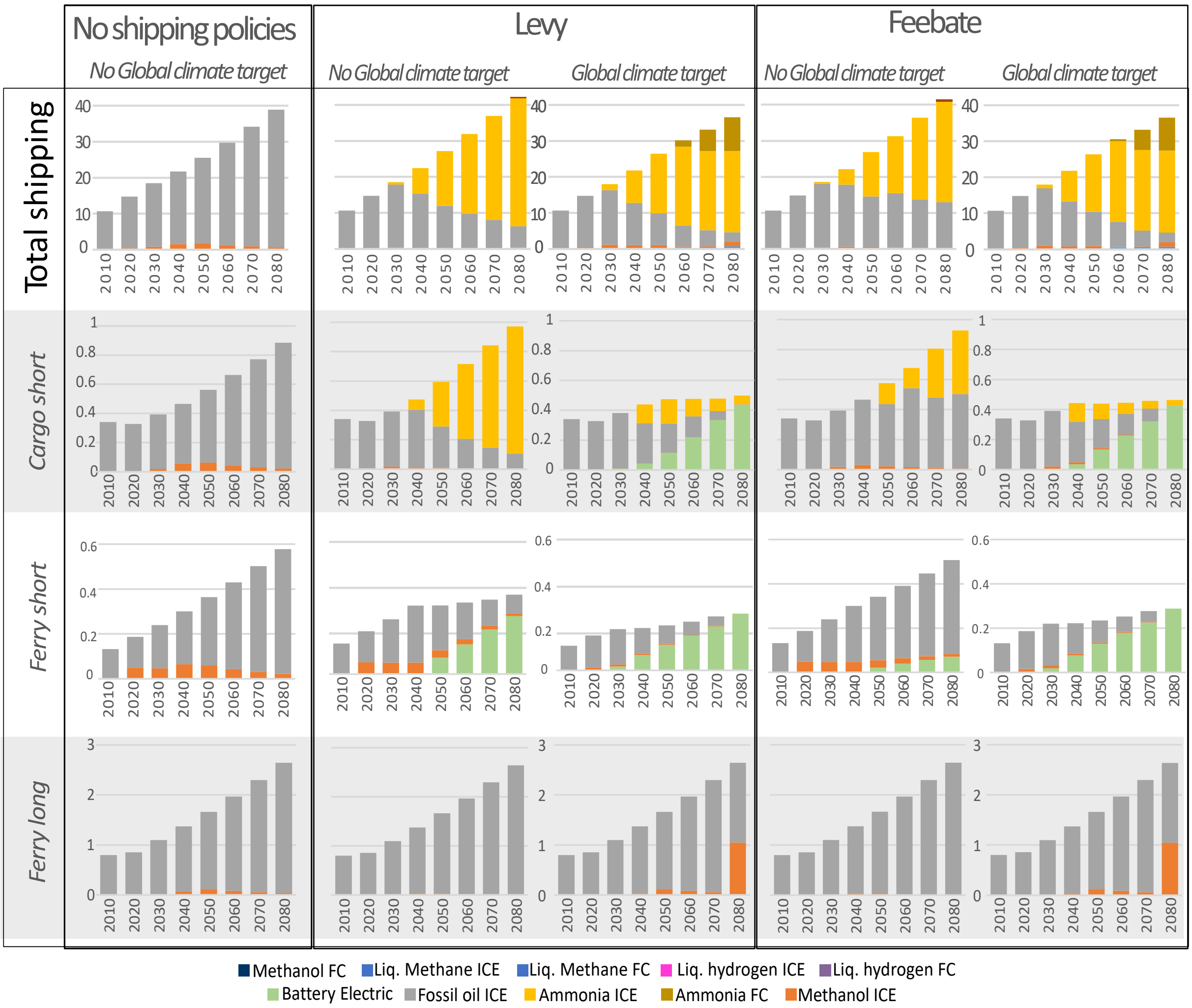

Figure 29: Energy carrier and technology mixes (in EJ) for global shipping (first row of figures) and specific ship categories (other rows) under different shipping policy scenarios with and without global climate targets (for details on the policy scenarios, see the text and appended Paper V). FC: fuel cell, ICE: internal combustion engine, Liq. Liquid.

Base Scenario (No Shipping Specific Policies, No Global Climate Targets): In the base scenario, the shipping fleet continues to rely predominantly on fossil oil across all ship categories. This reliance is accompanied by an increase in energy demand driven by rising transport needs.

Policy Scenarios: Under different policy scenarios (including a levy and feebate), the model indicates that it is cost-effective for ships operating over shorter distances (cargo short and ferry short) to undergo gradual electrification. Fuel switching from fossil oil for ferries operating over longer routes is largely delayed, compared to the other ship categories, despite introduced policies, primarily due to the higher costs associated with adopting alternative energy carriers other than the lowest cost option ammonia. This is because of the constraint in the model that ammonia is not a feasible option for passenger transport (for safety reasons). Methanol is identified as a cost-effective option for the ferry long segment, in connection with global climate targets. This is despite the fact that the model imposes a levy on CO_2 emissions from methanol combustion, irrespective of the methanol production route. For all other ship categories, a gradual transition to ammonia is found to be a cost-effective transition under both policy scenarios. Our findings suggest that global climate targets are fundamental to drive the energy transition in the shipping sector. And, in the absence of specific shipping policies, fuel switching will be delayed across all ship categories.

Fuel Cells: Fuel cells are found to be cost-effective only in the bulk and tanker ship segments, which have lower installed engine capacities. The higher investment costs associated with fuel cells pose a significant barrier to their widespread adoption in other vessel types. This can also be linked to the utilization rate, where the higher utilization rate of the smaller engine capacities makes fuel cells more cost-effective by taking benefit of efficiency gains.

Fuel Demand: Scenarios predominantly utilizing ammonia engines exhibit higher fuel demand, whereas scenarios incorporating fuel cells and battery-electric options show a reduction in fuel demand. This can be attributed to the lower efficiency of ammonia engines and the higher powertrain efficiency of fuel cell and battery-electric options.

Liquid Methane and Hydrogen: The transition to liquid methane is not found cost-effective for any ship categories due to higher GHG emissions resulting from methane slip and leakage, as well as higher investment costs. Similarly, liquid hydrogen is not cost-effective due to the substantial investment costs associated with fuel storage tanks and infrastructure.

The shipping policies assessed in the model drive fuel switching towards ammonia for a major part of the shipping sector. However, this fuel switching is also closely connected to other sectors, particularly fuel production and primary energy sectors. Figure 60 illustrates the fuel pathways for the energy mix for 2050 and 2080 assuming the introduction of a shipping levy. The policy scenarios without a global climate target, drive a shift to ammonia predominantly produced from natural gas. This shows that the fossil fuel use is shifted from downstream (onboard ships) to upstream (fuel production) which also increases total fossil fuel consumption due to efficiency losses in fuel production.

The fuel shift in the scenarios with a global climate target involves multiple fuel production pathways. The scenarios generated when applying climate targets prioritize low-carbon intensity ammonia production pathways, including: 1) Ammonia production using hydrogen from gasification of bioenergy with carbon capture and storage (BECCS-ammonia), 2) blue ammonia, and 3) e-ammonia. Nonetheless, early transition (by 2050) indicates that it is most cost-effective with BECCS-ammonia and blue ammonia which comprise over 90% of the sector's share. In the more long-term, e-ammonia is found cost-effective to a larger degree and the proportion rises to roughly 80% by 2080, whereas BECCS-ammonia maintains a share of around 20%. The electricity mix used for e-ammonia synthesis consists of around 90% renewable electricity.

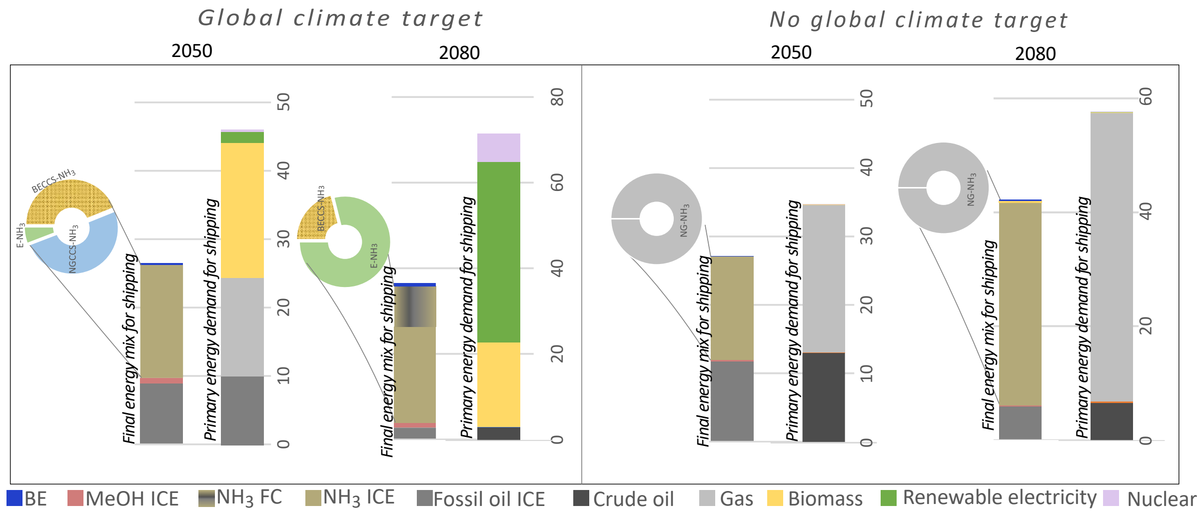

Figure 30: Cost-effective fuel pathways, and the model's corresponding choices of primary energy sources, for transition scenarios with a marine levy under global climate targets and no global climate targets for year 2050 and 2080. BECCS: bioenergy carbon capture and storage, NGCCS: natural gas carbon capture and storage, NH3: ammonia.

6.6. Environmental impact assessment from LCA and GET integration

This section includes the environmental impact results derived from the integration of pLCA with the GET model for the cost-effective fuel and technology mix of shipping under the investigated policy scenarios. The climate impact assessment results indicate that the investigated shipping-specific policies alone are insufficient to meet the climate targets set by the IMO. The detailed results are shown in appended Paper V. The results suggest that TtW emissions will continue to rise until 2030 under the assessed policies. With more adoption of ammonia, the TtW emission reduces afterward, however, net-zero emission by 2050 is unattainable with the levels of these policies alone.

In the base scenario, which lacks shipping policies and global climate targets, climate and other environmental impacts increase over time alongside the rising energy use associated with growing transport demand. Figure 31 shows the results relative to the base case scenario (without policy and without climate targets) for impact categories climate impact, particulate matter formation, acidification, marine eutrophication, material resource use, fossil energy resource depletion, ozone layer depletion, and land use. Compared to the base scenario, the energy transition under all policy scenarios, without a global climate target, have higher impacts for all assessed categories except land use (in 2050). The shift towards ammonia increases TtW emissions for marine eutrophication. For all other categories, the increase is primarily from the well-to-tank (WtT) phase, indicating a shift in the environmental burden upstream. This is mainly due to the increased natural gas consumption required for ammonia production. The WtT impacts rise significantly in these cases due to methane slip in the supply chain and GHG emissions from steam methane reforming. Land use remains relatively unchanged as the transition still relies on fossil fuels.

The energy transition in the policy scenarios under global climate targets demonstrates a significant reduction in climate impact. It is also evident that shipping policies accelerate the decarbonization process, compared to the base case scenario, with the well-to-wake (WtW) climate impact peaking in 2030. In contrast, without shipping specific policies but with global climate targets, results present a peak in 2040. Notably, model results show net negative emissions by 2060 when shipping policies and global climate targets are considered. The negative emissions are attributed to a higher share of BECCS-ammonia in shipping. The production of BECCS-ammonia involves the permanent storage of carbon from biomass, thereby reducing atmospheric CO_2 concentrations.

In addition to climate impact reduction, there are decreases in marine eutrophication, ozone depletion and fossil energy resource depletion. While there are TtW reductions in particulate matter and acidification impacts, the total WtW impact is higher due to pollutant emissions during biomass gasification and biomass growth. A significant increase can be noted for land use and mineral resource depletion.

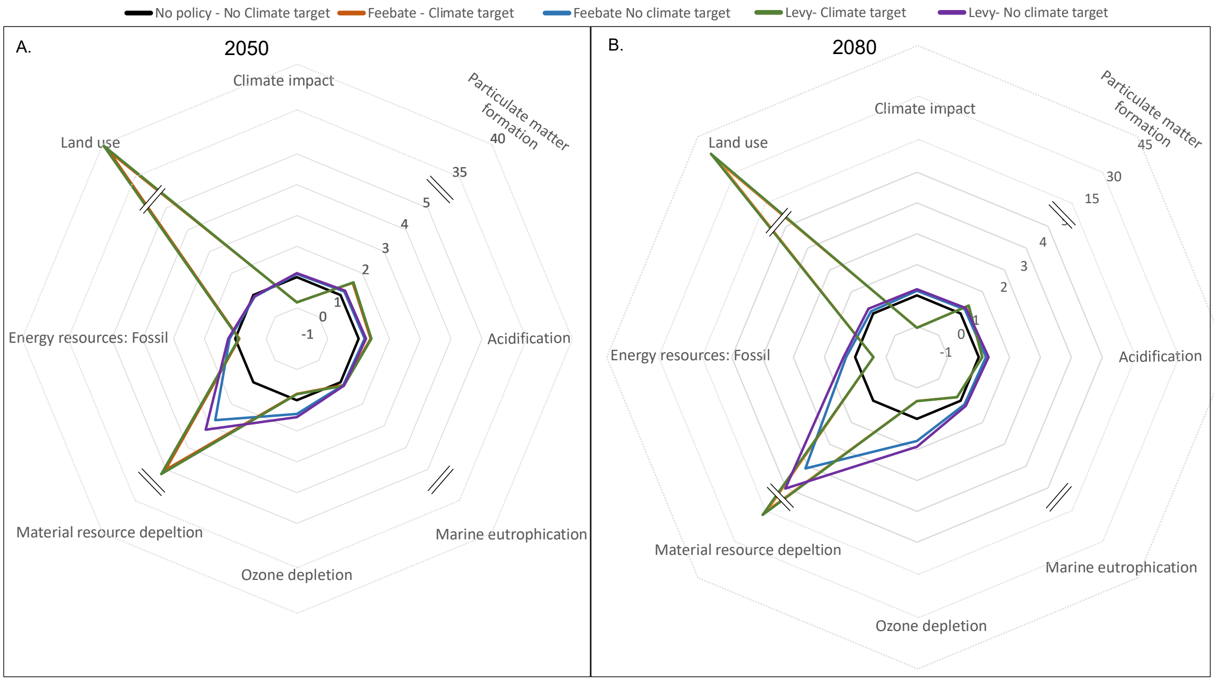

Figure 31: Selected environmental impacts LCA results for the cost-effective marine fuel choices in the assessed policy scenarios relative to base case (no-policy and no global climate targets) including climate impact, particulate matter formation, acidification, marine eutrophication, material resource use, energy resources: fossil,ozone depletion and land use.

7. Discussion and conclusion

The energy transition of shipping towards decarbonization is complex and most of the decarbonization pathways are still in the early stages of development. It is important to understand the transition from different perspectives at the early stages for decision support, to prevent unintended environmental impacts and avoid costly mistakes. This thesis addressed key gaps in methodology for assessing environmental and economic sustainability while also expanding the understanding of environmental, economic, and technical implications across various transition pathways for individual ships as well as for the entire global shipping fleet. The thesis' discussion is formulated around contributing to the methodology and contribution to scientific knowledge of shipping energy transition.

7.1. Contribution to methodology

7.1.1. Integrated life cycle framework

The thesis' methodological contribution primarily relates to RQ1, focusing on the integration of LCA and LCC through the ILCF. The ILCF was developed during this thesis by integrating LCA and LCC along with other tools to ensure consistent evaluation of energy, environmental, and economic performance. The ILCF sets guidelines on how and where different external approaches can be used to address specific challenges. The methods are integrated from the first phase goal and scope, this allows comparability throughout the evaluation process. For example, defining the system boundaries and functional units by integrating the goals of LCC and LCA allows model development and inventory model in the initial stage itself. This allows us to identify any inconsistencies and discrepancies in the early stage of evaluation. For example, defining the technological system at the goal and scope stage ensures the same processes/technologies are used in the selection of energy, material, and cost inventories. The ILCF methodology developed during this thesis is used in the appended Papers I, II, III, and IV.

One of the challenges while using ILCF was the selection of functional units that can ensure comparability. In this thesis, Paper I uses the functional unit 'round trip' to represent the reference flow, however, it was later realized that this functional unit may not be the best way to fully capture the main function of a vessel transporting cargo or passengers. Some of the technological options would occupy more space and will affect the cargo or passenger carrying capacity for the same trip length, thereby resulting in a reduction of transport work. Considering this, the functional unit was selected in terms of transport work (considering full capacity) for Papers II and III. In Paper IV, instead of considering a change in transport work, draught change is considered based on the weight change related to the alternative powertrain. Both these functional units allow to capture impacts and costs due to differences in energy density of alternative energy storage.

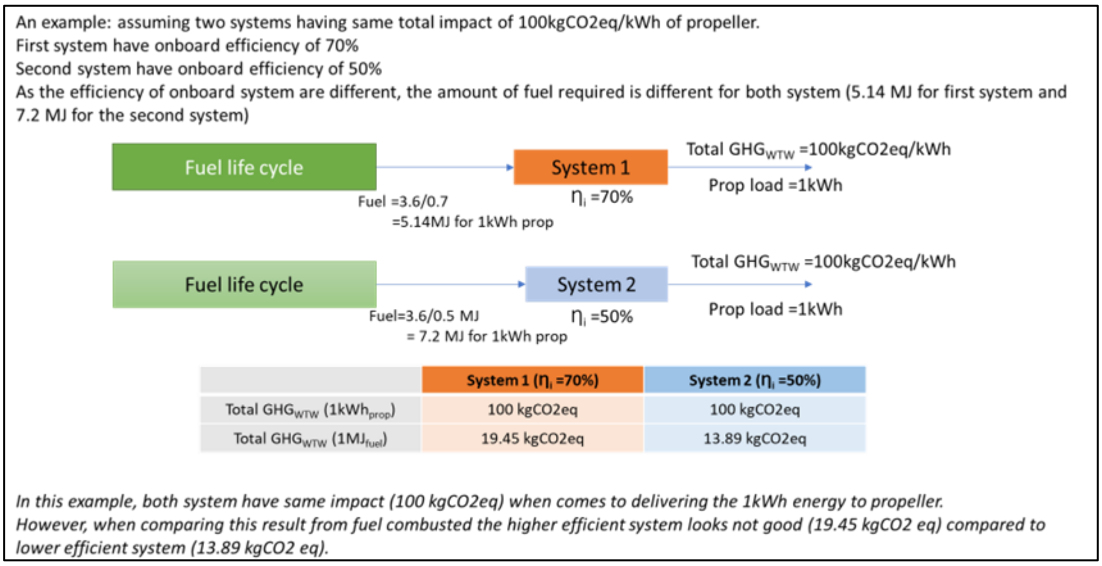

Figure 32: An example illustrating the importance of considering the energy converter efficiency in LCA methodology for alternative marine fuels and propulsion systems.

Most of the earlier LCA studies used 1 MJ fuel as a functional unit which is also suggested by IMO LCA guidelines. However, it is important to consider the efficiency of the energy converters onboard the ship in LCAs of marine fuels and propulsion systems when comparing different options. Comparing the environmental impact per MJ can give a wrong interpretation of the impact of energy converters' efficiencies on environmental impact, the explanation is given in Figure 32. When comparing the results of fuel combustion, the more efficient system appears to have a higher impact and this gives a wrong interpretation of total emissions. This would be also problematic when considering engine-based emissions like NOx which depend on the energy output, not on the fuel alone.

"Choosing a valid functional unit is critical, and functional units such as 1 MJ of combusted fuel should be avoided when evaluating various alternatives since it will penalize solutions with better onboard conversion efficiencies."

Major aspects of ILCF covered in the appended Papers I, II, III, and IV, are defining the same system boundaries, foreground, and background processes for both LCA and LCC. When considering inventories, there are differences in the properties of inventory/flow between LCA and LCC. There would be a difference in the environmental and economic data because the economic data is more dependent on the market data and is more volatile [68]. In cost inventories, the final cost flow represents all the upstream flows in the background system (e.g., the capital cost of equipment includes the cost of raw material, production costs, energy cost, value-added cost, etc.) hence upstream flows do not need to be aggregated. However, for material and energy flows, all upstream flows need to be aggregated while evaluating the environmental impact. Similarly, LCC calculations in all appended papers have considered interest rates for capital equipment considering the owners' perspective that the time of investment is important. This is a challenge in integration, as the LCA follows a steady state process, and a discount rate is usually applied for the cost. One suggestion is adding time-dependent changes that are part of dynamic LCA in the ILCF framework.

Considering the predictive scenario method employed for scaling up, one key challenge is the availability, quality, and uncertainty of data. In the appended papers of this thesis, data is collected by conducting expert interviews, literature reviews, and modeling. Also, uncertainty, scenario analysis, and sensitivity analysis are tools used in the thesis, while assessing energy transition, as they can address the inherent complexity and unpredictability of future developments. The assessment of the uncertainties in data provides a better understanding of the reliability of the data and the possible range of impacts. Scenario analysis is used to explore 'what if' situations to understand the potential outcome of hypothetical scenarios based on different assumptions and is used for wider strategies, e.g. charging strategies. Sensitivity analyses is used to understand how sensitive the results are to specific parameters, such as feedstock cost, carbon intensity, etc. Together, these analyses enhance the robustness of results, identify key parameters, and offer a comprehensive view of how various pathways may impact outcomes. This would help in guiding stakeholders towards making informed decisions so that investments in future technologies align with long-term sustainability goals.

"Sensitivity analysis, uncertainty analysis, and scenario analysis enhance the result robustness providing a comprehensive view of the potential for different energy transition options for shipping to support decision-making."

In this thesis and appended papers, CAC is used as an integrated indicator that combines cost considerations with climate impact, offering a quantifiable measure of the economic trade-offs associated with each option in terms of reducing GHG emissions. CAC allows for comparison of the cost of implementing new technologies, such as alternative fuels or emissions-reducing retrofits, against the climate benefits they provide. This is particularly valuable when assessing the viability of policy measures, such as carbon taxes or emissions regulations. By quantifying CAC, stakeholders can determine the level of policy intervention—such as the required carbon price—that would likely make low-carbon technologies competitive with traditional fossil fuels.

Limitations: It was noticed that external factors can also influence the scale-up phase while defining the technological system. One specific example is the influence of electricity price in determining the technology for the electrolyzer that will be used for the assessment. As shown in Figure 33, SOECs are preferred for higher electricity prices. The reason is that the benefit of higher efficiency offered by SOEC kicks in only when the cost saved from reduced electricity use is higher than the investment cost. Such external factors have to be treated differently and not included within the framework is one of the limitations of ILCF. How such factors can be integrated is not analyzed and needs to be studied further. Another limitation is that the study has not considered how the characterization factors would change in the future and the possibility of other environmental problems not known today is not considered. One such indicator may be marine ecotoxicity, similar to freshwater ecotoxicity, which would be relevant for ships.

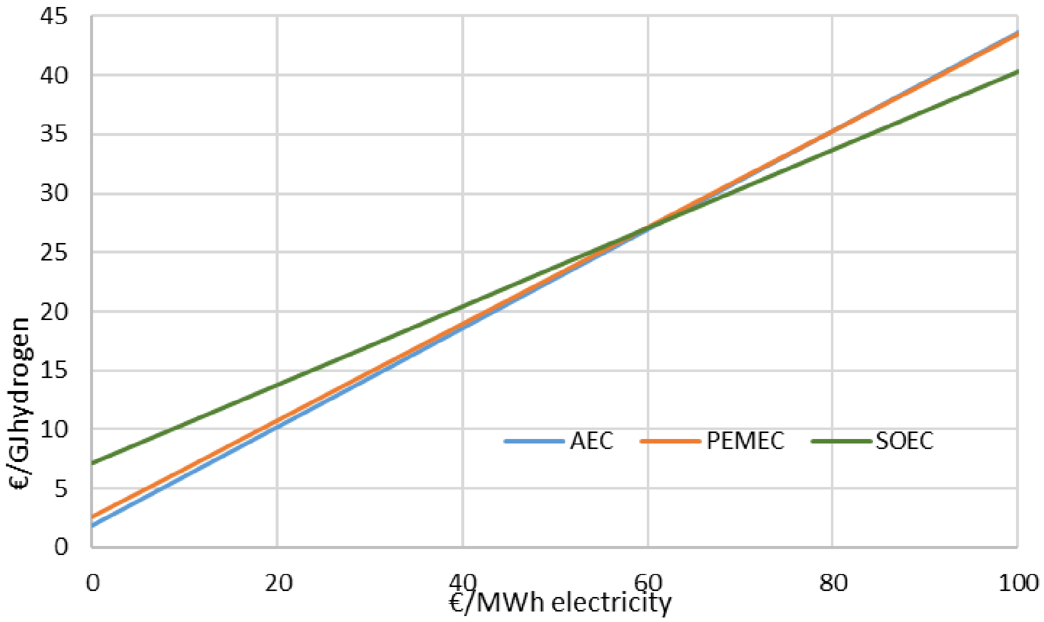

Figure 33: The influence of electricity prices in the selection of electrolyzer, expressed as €/GJ hydrogen produced.

7.1.2. Integration of LCA and GET

Another methodological contribution from this thesis is integrating LCA with the energy systems model GET. This integrated approach is used to answer RQ3 and enables an extension of the scope of energy systems analysis. The LCA models and the GET model have similar structures when considering the processes, but GET has parameters on a macro level (like efficiency, life time, cost, capacity factor) while LCI usually being micro (energy flows, material flows, process emissions, life time etc.). In LCA, the LCI is usually treated in a static setting while the actual impact of the technology will depend on the temporal and spatial changes in the energy and technology. Due to the different nature of the methods, linking them would be challenging. One of the challenges is that key parameters of processes are modeled differently. This is the case for the efficiency as in the energy system model and energy flows in the process-specific LCA. In the integration, a harmonization of these parameters is made for the parameters to be consistent with each other. The GET model also has a limitation with accounting for multiple input energy flows e.g. electricity, hydrogen, and nitrogen for the Haber-Bosch process. These are used for estimating the environmental impact in the post-processing. However, in this study, no feedback from LCA to the optimization process is performed after post-processing. The difference in the energy flows before and after post-processing is shown in the Sankey diagram in Figure 34. This shows that there is a higher demand for electricity and a lower demand for biomass when considering details in the LCI for the processes.

Considering the temporal and spatial differentiation in LCA is another challenge in the integration of the methods [156]. By considering the different electricity mixes for various regions and periods in the LCI inventory in the framework some of these temporal and spatial differentiations are addressed. In addition, the time evolution of the efficiency considered in the GET model is also considered when calculating LCI inventory for specific technology during the specific period. This is done during the harmonization step in the framework. However, no temporal and spatial differentiation is made in the material flows and required infrastructure. Another issue widely discussed in the scientific community regarding integration is double counting [41, 154, 156]. The issue is primarily due to the consideration of energy demand as the energy demand for upstream processes may already be part of the final energy demand of the model. In the framework, this is primarily addressed by linking the environmental impact only after post-processing, and as mentioned earlier the LCA energy flows are mapped separately after post-processing to ensure that the energy flows are not double counted. A gate-to-gate assessment is done for the impact calculation without considering energy flows.

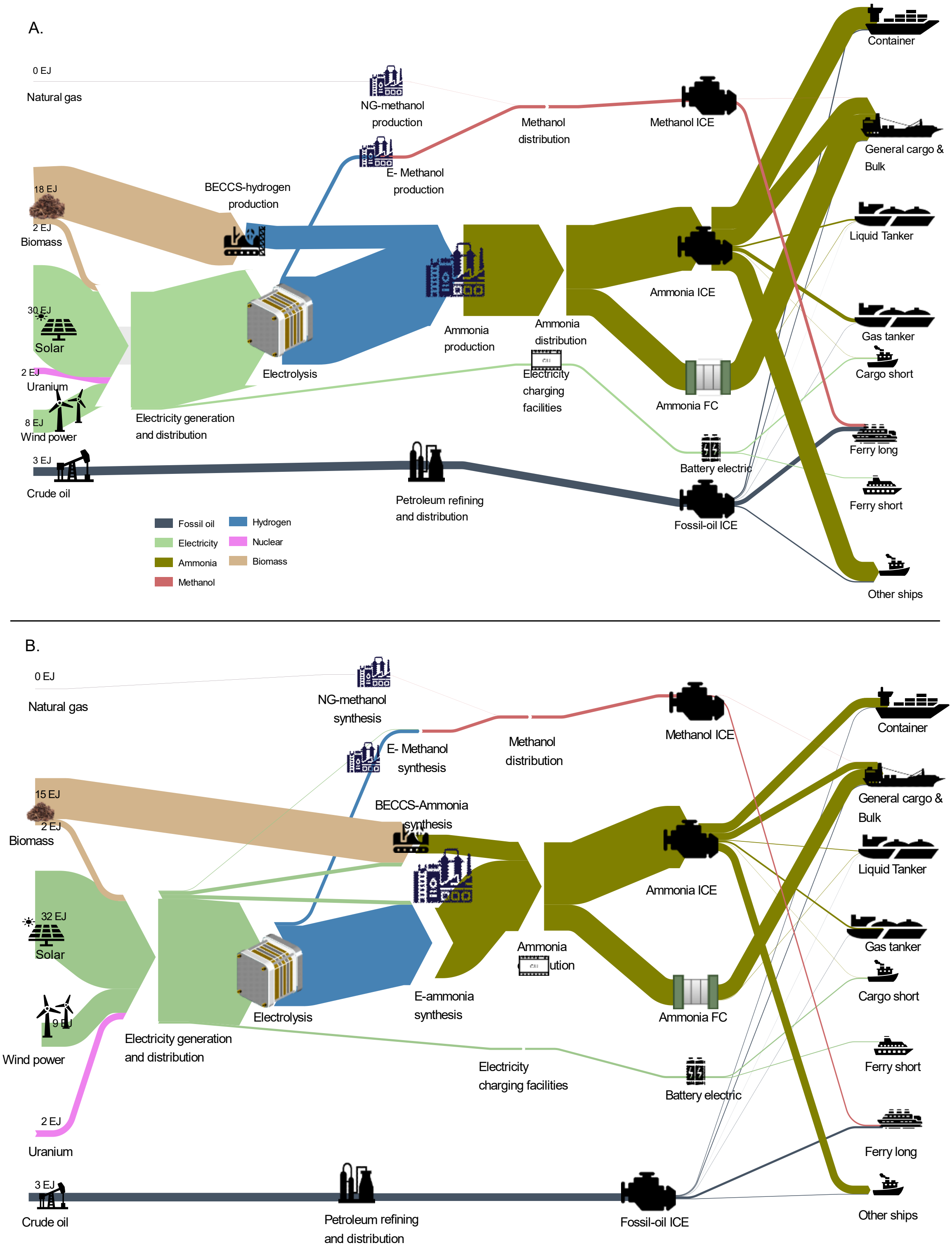

Figure 34: Sankey diagram for the energy flows specific to shipping in the scenario Levy with global climate target for year 2080. A) Result from GET. B) Result after the post-processing with LCI data

The integration done in this thesis also has several limitations including not considering the present age of the fleet, only WtW is considered (not including cradle to grave of ships), the end-of-life treatment of fuel production facilities are neither included, no allocations are performed for multi-functional processes (rather all the impacts are allocated to the technology as such).

7.2. Contribution to the knowledge on sustainable shipping

This thesis makes a major contribution by expanding the research frontier around the knowledge of life cycle impacts and costs for shipping energy transition by including the role of different energy carriers and related feedstocks, fuel supply infrastructure, ship design, and fuel properties. In this section, the discussion is made around RQ2: '*How can integrated assessment of environmental, economic, and energy performance improve the understanding of different potential energy carriers derived from various feedstocks for different ship types?*'. The discussion is divided into 1) Role of different energy carriers, 2) Role of feedstock in fuel production, and 3) Role of ship characteristics.

7.2.1. Role of different energy carriers

Different energy carriers have different production routes and combustion properties resulting in different environmental impacts. When using energy carriers produced from renewable sources (renewable electricity or sustainable biomass), the assessed options have lower climate impact and reduce other environmental impacts such as particulate matter, acidification, photochemical ozone formation, resource use-fossil, and ozone depletion. One of the exceptions is when using ammonia-fueled engines, which have a significant impact on categories like acidification, and marine eutrophication due to the tailpipe emissions of N_2O, NOx, and ammonia. It may be noted that there is significant uncertainty regarding the emission of N_2O (a much stronger GHG than CH_4 and CO_2) originating from the nitrogen atoms in the fuel itself. Monitoring and mitigating N_2O and NOx emissions from ammonia engines are important, and the potential after-treatment methods, such as selective catalytic reduction with specialized catalysts, needs to be studied. The production route e-ammonia is one of the cheapest e-fuels to produce. However, bio-ammonia is less promising than the other assessed biomass-based fuels due to its high cost and energy demand. This is due to the high energy use in the production process linked to efficiency losses and the energy required for pressure swing adsorption for separating hydrogen. However, using carbon capture and storage in the production of bio-hydrogen and bio-ammonia could potentially change this result by possibly achieving negative GWP and hence reducing CAC further [125, 159].

"The shift towards ammonia-based engines can potentially increase environmental impacts like eutrophication and acidification and may limit GWP reduction. More assessment on the emissions of nitrogen-based compounds and effectiveness of possible abatement technologies needs to be done before more firm conclusions about the potential of ammonia as fuel can be made."

Methane has the highest GWP among all energy carriers due to the methane slip from the engine and fugitive emissions of methane during liquefaction and distribution. As GWP reduction is limited, it would be challenging for stakeholders who have already invested in ships that run on LNG to meet the long-term IMO GHG targets. Also, e-methane is a more expensive fuel to produce compared to other methane-based fuel options. It may be noted that a major portion of the order book of new ships is designed for the use of LNG [1]. After-treatment technologies such as methane oxidation catalysts after-treatment or plasma reduction technology can potentially be used to reduce onboard methane emissions. These are under development and have currently low service life [160].

“The stakeholders investing in LNG ships may encounter challenges in meeting the long-term GHG targets, as e-methane and bio-methane that could replace LNG fuel without retrofitting have higher GWP than most other decarbonization options.”

For methane and also for methanol production, the source of carbon in the fuel is important while assessing environmental impact. It is recommended that the CO_2 used is of biogenic origin or is from DAC [9]. If the carbon used has fossil origin, the carbon emissions, to the atmosphere, are only delayed [59]. Considering that CO_2 is sourced from DAC in this thesis, e-methanol and e-methane turn out to be both energy intensive and costly, compared to other fuels. Using CO_2 from biomass and waste instead of DAC and matching it with local or regional sources is another option to reduce the cost. Korberg, et al. [8] considered point source biomass-based CO_2 and found e-methanol to be cheaper than e-ammonia. However, this needs to be treated with caution because when CO_2 comes from a carbon capture process that delivers other products such as bioenergy, the impact from the process needs to be appropriately allocated between all products including CO_2, unlike in a mono-functional system such as direct air capture [161] so that double counting is avoided. Bio-methanol and bio-methane from gasification do not need a sub-system for CO_2 supply, instead uses the carbon in the syngas produced during the gasification. This renders both bio-methanol and bio-methane more economical and energy-efficient in comparison to bio-ammonia and bio-hydrogen. One of the environmental impacts that stands out for methanol is higher human toxicity. This can be linked to the possible formaldehyde emissions from methanol engines due to incomplete combustion. The use of an exhaust after-treatment system with suitable catalysts may be able to control formaldehyde emissions [10].

“The source of carbon in the production of methane and methanol is important. CO2 from DAC ensures that fuels are carbon-neutral (assuming carbon-neutral input energy), but the process is energy intensive and results in higher costs. When using the CO2 from other sources it must be ensured that appropriate allocation or system boundary expansion is done when assessing.”

Even though the share of climate impact of various infrastructures in the fuel supply chain is relatively low, its contribution to other impacts is high especially associated with the metals and minerals used in the construction of the infrastructure. The main impact can be associated with freshwater ecotoxicity, and resource use (metals and minerals). These can be improved with better recycling and stricter environmental regulations on primary material extraction [162]. All options except the blue fuel and OCC have a lower impact on the impact category resource use-fossil. For fossil fuel use along with onboard carbon capture, all impacts are higher compared to direct use of fossil fuel except for the climate impact, and this can be directly attributed to the energy penalty associated with these options which is required for capturing and storage of the CO_2. However, these options have one of the lowest CAC.

“Both blue fuel and OCC can reduce the climate impacts but won’t be an environmentally sustainable solution from life cycle perspective and perhaps be considered only for short-term solutions .”

7.2.2. Role of feedstock in fuel production

For all pathways, the impact and cost associated with fuel production significantly contribute to the overall impact and total cost, respectively. Also, the primary energy demand for decarbonization pathways related to e-fuels and bio-fuels (based on gasification) is high, indicating that the source of feedstock in the production of these fuels plays an important role. The sensitivity analysis conducted in this study indicates that it is important that electricity with a low carbon intensity is accessible for e-fuel production and charging (for BE). Not all regions have access to low climate-impact electricity; investments in renewable electricity sources are critical for increasing the potential use of e-fuels in the shipping sector. On the downside, e-fuels produced using electricity from wind power will have an increased impact on human toxicity and resource use due to materials such as copper, zinc, and rare earth elements, in addition to steel in wind power infrastructure and electrolyzers. The environmental burden from the materials used in wind power infrastructure and electrolyzers can be reduced by recycling or reusing the materials and also by using materials produced from cleaner technologies, like fossil-free steel [10]. The possibility of reducing such impacts may be investigated further. Future studies should specifically analyze the availability of critical raw materials, which are necessary for understanding material constraints for the fleet-level transition toward decarbonization pathways.

"Source of electricity for e-fuel production and charging is critical, it is important to ensure that cheap and clean electricity is available to support the energy transition of shipping and also have lower environmental concerns."

The result shows that bio-methanol has the lowest CAC. But similar to e-fuels, the bio-fuel cost is influenced by biomass costs, and the GWP is affected by the availability of sustainable biomass resources, biomass collection, and gasification efficiency. The use of bio-fuels (through gasification and hydrotreated vegetable oil) will create an additional environmental burden on acidification potential, land use, and eutrophication (terrestrial and freshwater). The acidification and eutrophication are due to the use of fertilizers and NOx emissions during gasification; this has also been observed in earlier studies [163, 164]. The high land use means that more land cover is required for producing biomass in comparison with other fuel production pathways. The availability of feedstock like biomass also depends on the geographical distribution, which will also affect WtT emissions, and it is particularly important to consider the limited availability of biomass from sustainably managed forests [165]. Also, higher demand for bio-fuels can result in the expansion of biomass production, which can result in the emission of GHGs due to direct and indirect land use due to changes in soil carbon content and other environmental consequences like loss of biodiversity, nutrient depletion, and water consumption [104]. Using biomass from non-sustainable sources will not benefit climate mitigation and will also be environmentally problematic. However, the availability of biomass from sustainable sources is limited [104]. Additionally, competition from other sectors demanding bio-fuels could significantly impact biomass prices. Moreover, the implementation of agricultural regulations and practices is also required to ensure the mobilization of sustainable biomass.

"Bio-methanol may be among the most promising options for energy transition considering the carbon abatement cost, but largely depends on the availability of biomass from sustainable sources."

7.2.3. Role of ship characteristics

From the results of the thesis, it can be noted that the choice of the decarbonization pathway differs between the vessel types and operation profiles making it evident that the decarbonization strategies should be different for different vessels. These differences can be linked to different ship characteristics, as 1) the energy required for the design range of the ship (also depends on many factors like speed, distance, installed power, etc.), 2) the power and type of engine installed (different engine type have different emissions and efficiencies), 3) utilization rate (can be referred to as the annual energy use per installed capacity), and 4) total fuel consumption (the energy required will influence the amount of fuel burned).

The energy required for the design range can also be represented by the need for onboard energy storage. This usually determines the maximum distance that the ship can operate between each bunkering. Results show that low volumetric energy storage options like liquid hydrogen and batteries will be less feasible for long-range ships. Also, these options have a higher impact on both the cost and environmental performance due to the enormous size of the storage required (loss of capacity and more material required). The capacity loss for OCC options is also high for a long-range vessel, as the space for storage of captured CO_2 is proportional to the amount of energy used onboard for the design range, this is in addition to the size of the carbon capture system itself. The availability of a port reception facility (to off-load and handle CO_2) and CO_2 transport, as well as the proximity to the permanent storage site, is another significant challenge that should be addressed for the OCC [166, 167]. Also, the operation of OCC reduces the availability of heat for other purposes on-board ships, like space heating, which will have a greater effect on passenger ships traveling longer routes like cruise vessels, as more fuel will be needed for space heating, as shown in Paper III. Currently, fuel storage on-board ships are not designed considering these limitations, and storage size is usually oversized. The feasibility rate can be increased with several strategies: 1) the design of the fuel storage tanks aligned with the transport missions (based on major routes the ship will likely operate), 2) adjusting transport schedules to fit the range of ships, 3) adding more bunkering/refueling stops, and 4) reducing the cargo space. All the strategies will influence environmental impacts and cost. One of the challenges associated with charging batteries or bunkering hydrogen is that these processes are time-consuming and complex.

“Ships performance can significantly improve if the ships are specifically designed focusing on transportation work or changing the operational strategies, e.g. opportunity charging for battery electric ferries.”

Another parameter affecting the result is the power and type of engine installed. As noted in the analysis different powertrain configurations have different emissions and efficiencies, resulting in different environmental impacts and costs. One example is that low-pressure dual-fuel 4S engines for LNG have higher methane slip compared to 2S engines resulting in higher climate impact. For ICE, fossil-based diesel as pilot fuel has a major share of GHG emissions for all options. Substituting fossil-based diesel with bio-based diesel as a pilot fuel may be a good option to reduce the GHG emissions from ICEs. The total cost of fuel cell options is higher for all types of ships because of the higher investment cost and the shorter life of fuel cells. Installed capacity is important while assessing FC options because the higher installation capacity means more fuel cells need to be installed onboard. The cost of fuel cells is a significant part of the total life cycle cost.

The utilization rate also needs to be analyzed when considering the total power. It may be noted that the utilization rate is not a well-defined term. In this thesis, utilization rate refers to the amount of energy consumed annually per kW of installed capacity. Fuel cell options can have a lower CAC than ICE options for the same fuel when the utilization rate is high, which refers to higher annual energy use per installed capacity, as mentioned also in earlier studies [8, 10]. Such formulation helps to understand how effectively the installed energy converter capacity is used. For example, for cruise ships fuel cell options have a lower CAC than ICE options for the same fuel. For fuel cell systems, a higher utilization rate would offset the higher cost of the propulsion system by lower fuel consumption due to higher efficiencies of fuel cells. Also, if the fuel cost is higher than a threshold value lower fuel consumption can compensate for the higher cost of investment for fuel cells. The high investment cost and limited lifespan of fuel cells pose significant limitations when considering the adoption of fuel cell technology. However, improvements in these key elements can make a significant change in competitiveness due to the higher efficiency and cleaner combustion that fuel cells offer.

“Fuel cell technology may not be a cost-effective option for the majority of ship types; however, it offers one of the most environmentally sustainable solutions for long-range vessels.”

An additional parameter considers the total energy use over the vessel’s life cycle, encompassing the fuel’s overall environmental impact, cost, and bunkering requirements. In scenarios with low fuel consumption, the installation of high-cost or high-impact powertrain options may not be advantageous. For example in the case of service vessel, battery electric and fuel cell options have higher impact and cost. This also affects the environmental impacts linked with the manufacturing and replacement of fuel cells or batteries.

Regarding safety, the hazards associated with the new fuels and systems need to be properly contained and managed. Regulations for the use of ammonia and hydrogen onboard vessels are not yet mature but are under development by the International Maritime Organization and will be part of the International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code) [168]. Draft interim guidelines for ships using hydrogen as fuel were agreed on at the IMO’s Sub-Committee on Carriage of Cargoes and Containers (CCC7) [169]. Work is underway to develop guidelines for the safety of ships using ammonia as fuel, with initial work on the collection of safety information reported in 2022 by Japan [170]. Ship classification society guidance documents on the use of hydrogen [171, 172] and ammonia [173, 174] were considered during this study. Considering the additional safety measures that need to be taken for ammonia, the use of ammonia in passenger ships may be avoided.

Paper IV specifically evaluates battery electric ferries, which offer emission-free operation in urban areas and significantly reduce environmental impacts related to particulate matter, resource use-fossil, acidification, eutrophication, and photochemical oxidation. However, BEFs also present trade-offs in terms of resource use and freshwater ecotoxicity, largely due to metals such as copper, zinc, cobalt, nickel, lithium, and rare earth elements (REEs) found in battery packs and in the infrastructure required for electricity generation and distribution. The results indicate that, unlike long-range vessels, ferries on shorter routes with the potential for frequent bunkering and high utilization rates are particularly suited to battery electric systems, as their lower on-board energy storage needs favor this technology. Furthermore, the scenario assessment in Paper IV reveals that lower interest rates on installation costs can make battery electric ferries highly competitive with fossil-fueled alternatives.

“Low interest rates or subsidies for batteries can benefit battery-electric ferries significantly in terms of cost competitiveness.”

One limitation of this thesis is that it does not assess the geographical locations of ports for long-range vessels, which could influence both the cost and availability of feedstock for fuel production. Feedstock availability directly impacts fuel supply and demand, affecting the accessibility of alternative fuels at the ship’s operating ports—an essential factor for successful implementation.

7.3. Energy system model including shipping

Achieving net-zero emissions by 2050, as set by the IMO, presents a formidable challenge due to the high level of technological inertia [175] and the substantial carbon abatement costs within the sector [176]. Large-scale deployment of alternative fuels will necessitate trillions of dollars in investment for land-side infrastructure [6], making the decarbonization of the entire sector across all regions exceptionally difficult [177]. Despite these challenges, our results indicate that policies can play a role in accelerating the energy transition of the shipping sector.

This thesis captures the complexity of the transition for different ship categories, given the diversity of alternative energy carriers. For ship categories operating over shorter distances, such as ferries and other vessels on fixed routes with frequent charging opportunities, the transition is primarily driven by electrification. However, this short distance sector represents a minimal portion of the overall energy requirement of the shipping industry. Ferries and cruise ships on long routes face the most significant delays in energy transition, compared to the other ship categories, due to the risks posed by ammonia to passengers and the higher costs associated with other alternative fuels like liquid hydrogen and methanol. For other ship categories, the transition is mainly driven by the adoption of ammonia.

Our study demonstrates the significance of using a more comprehensive representation of shipping as this allows to capture the intricate interactions of energy carriers, ship types, and other energy systems with different global climate targets.

The use of ammonia also increases the energy demand in the shipping sector since ammonia engines are likely to have lower efficiencies, as ammonia is difficult to combust [37, 178]. Even after considering the increased energy demand, the production and distribution of ammonia are more economical than other alternatives like liquid hydrogen. The reason that a switch to carbon-based fuels like methanol and methane is not considered more cost-effective in the case of ship specific policies is that the levy applies to all CO_2 being released during combustion regardless of the production route. This underscores the need to include a WtW perspective in policy considerations. Previous studies have shown that carbon-based fuels are not cost-effective in the transport sector when long-term carbon storage is viable [142]. Our GET results show that carbon-based fuels are found cost-effective primarily in sectors where carbon capture is an option like process industries. In this thesis, even though OCC is assessed in Paper I and Paper III, the GET model does not include OCC, it could be incorporated in future studies and may serve as an interim solution.

“From a cost optimization perspective, ammonia is anticipated as an important energy carrier for shipping, particularly for ships operating on extended routes. Electrification will be the most economical option for ships operating in shorter and regular routes.”

Another aspect highlighted in this thesis is the role of global climate targets in the transition towards low carbon intensity production pathways. This is particularly important since different regions will likely exhibit varying rates of energy transition, with those having less stringent climate targets likely to drive the transition towards ammonia produced from natural gas. Global climate targets prioritize low-carbon intensity ammonia production pathways including BECCS-ammonia, NGCCS-ammonia, and e-ammonia. Under global constraints, the transition is initially driven by bio, however, this needs infrastructure development, technology scalability, availability of sustainable biomass, and advancements in carbon dioxide removal technologies [179, 180]. The model also finds e-fuels to be cost-effective in the long term, this can be linked with the increased investments in renewable electricity shown in the model. This implies a need to reduce significant hurdles such as infrastructure for electrolysis, technology scalability, and investment in renewable electricity production. The GET model is only suited to identify cost-effective scenarios considering interactions between different sectors the results must not be interpreted as forecasts. The result explores the behavior of the energy system including future energy transition of shipping under different policy situations, emphasizing the opportunities and threats that may arise.

7.4. Integrated LCA and GET

This session includes a discussion around RQ3: '*How can the integration of LCA and ESM increase the understanding of well-to-wake environmental impacts linked to cost-effective fuel transition pathways for decarbonization of the global shipping sector reflecting different policy ambitions?*'.

In regions with relaxed climate targets, a shipping levy without a WtW perspective is likely to drive the transition towards ammonia produced from natural gas whereas stringent climate targets prioritize low-carbon intensity ammonia production pathways including BECCS-ammonia, NGCCS-ammonia, and e-ammonia. The integrated assessment gives insights into possible burden shifting of impacts associated with different transition routes. The results show that the transition towards ammonia produced from natural gas possesses a significantly higher WtW impact on all the assessed impact categories including climate impact. This indicates that transitions dependent on fossil fuels (without carbon capture and storage) should be avoided, as the environmental burden is not only shifted but also worsened. With a global climate target, the transition is initially driven by NGCCS-ammonia and BECCS-ammonia, and towards 2080, e-ammonia occupy a higher share. BECCS-ammonia can generate minus-emissions of CO_2, from a WtW perspective, which is good for the climate, and adoption of such fuels can be important given the revised IMO target of net-zero climate impact. However, whether the emissions could be considered negative for shipping would depend on the allocation criteria based on other potential products from the bio-refineries and the specific biofuel pathway. It should also be noted that the global supply potential of sustainably grown biomass is limited (less than approx. 200 EJ/yr) for reasons such as its demand for land and water, socioeconomic consequences, and biodiversity issues [181]. The biomass supply potential has however been considered in GET.

The adoption of BECCS-ammonia raises critical concerns about burden shifting to other environmental categories, most notably increased impacts on land use, mineral resource depletion, particulate matter, and acidification. The acidification, particulate matter, and eutrophication are due to the use of fertilizers and emissions from biorefineries [163, 164]. The high land use means that more land cover is required for producing biomass in comparison with other fuel production pathways and the mineral resource depletion is associated with the production facilities and distribution infrastructure [36]. Transitioning to e-ammonia in a later period reduces WtW impacts such as particulate matter, acidification, and land use compared to BECCS-ammonia. However, concerns about mineral resource depletion persist mainly due to infrastructure requirements associated with for example renewable electricity production [33].

"The integrated assessment shows that the transition raises concerns about the environmental burden shifting from downstream to upstream without a strong complementary global climate target while also creating other environmental concerns like land use, acidification, eutrophication, and mineral resource depletion"

7.5. Learning outcomes and Future work

This thesis provides a comprehensive understanding of the energy transition in the shipping sector by employing a bottom-up approach within a broader system perspective. It emphasizes the importance of treating shipping decarbonization as an integral part of a larger system, acknowledging the critical interactions between shipping and other sectors. Through the integration of life cycle thinking and energy system cost optimization models, the thesis highlights the value of systemic analysis in identifying cost-effective and sustainable pathways for reducing greenhouse gas emissions in the maritime industry. The findings underline that while the shipping sector is classified as 'hard-to-abate' with respect to decarbonization, overcoming the challenges is possible. The research identifies the need for innovative solutions and collaborative efforts to address technical, economic, and organizational barriers. A key insight is the necessity of involving new stakeholders, such as alternative fuel producers and the broader energy sector, to drive decarbonization. By fostering collaboration and reorganization within the industry, it is possible to overcome existing inertia and pave the way for the shipping sector to move away from fossil fuels.

Applying diverse methodological approaches, and combining different tools is one of the strengths of this thesis. Integrating interdisciplinary tools, such as cost and impact assessments, posed challenges, particularly in reconciling different perspectives and assumptions. For example, integrating cost and impact assessments was challenging, particularly in reconciling the different viewpoints of economists and environmentalists. The research highlights the importance of transparency in datasets and continuous stakeholder engagement to improve data quality and ensure consistency between costs and trade-offs. For instance, variations in data and assumptions, such as engine configurations and fuel types, significantly influenced results, as demonstrated in Papers I and II. In the same context, checking robustness of results is crucial, and employing approaches like sensitivity, scenario, and uncertainty analyses to account for future uncertainties is particularly useful.

The global energy model offers a broad perspective by encompassing multiple sectors, but significant data gaps remain, particularly in sectors with complex technologies. These gaps arise from the model's reliance on a lack of updated knowledge, as different sectors were developed at varying times. One of the main highlights is the integration of GET with LCA, this integration gives an understanding of the environmental tradeoffs associated with the transition.

The new approach allows for the identification of significant environmental trade-offs associated with the adoption of alternative fuels for shipping when going for cost-effective transition. The transition to reliance on biomass introduces challenges such as acidification, eutrophication, and extensive land use due to fertilizer application and biomass cultivation. Similarly, e-fuels produced using renewables generate environmental burdens related to mineral resource use and ecotoxicity. The use of ammonia can pose a risk to the nitrogen cycle cycles and enhance effects like eutrophication and acidification. These trade-offs underline the necessity of considering sustainable feedstock sourcing, installing emission abatement technologies, and material recycling in the pursuit of decarbonization pathways for shipping. These also necessitate future studies delving into social, ethical, and environmental aspects alongside strategies to reduce them.

Some questions and directions that could be interesting to explore in the future based on the findings of this thesis are discussed below:

Applying Integrated Life Cycle Framework to fuels produced from BECCS: The life cycle assessment and costing of Bioenergy with Carbon Capture and Storage technologies can provide critical insights into their environmental and economic implications. Such evaluations will help to understand the role of fuels from BECCS within decarbonization strategies for shipping. One major aspect to consider is the multifunctionality of bio-refineries, which necessitates addressing the allocation problem. Another important consideration is the dynamic LCA, which accounts for the timing of emissions, resource use, and associated impacts.

Extending the framework to include social sustainability: Understanding the ethical and social aspects of the transition is crucial. Extending the scope of assessment to include social life cycle assessment can provide valuable perspectives on the social implications of alternative fuels and technologies, such as crew conditions, community impacts, and equitable access to resources.

Improving the resolution of the GET: While this thesis initiates a better representation of the shipping sector, further understanding requires adding more nodes to the GET. It is also important to improve the representation of other sectors, considering region-specific climate targets. Additionally, retrofitting possibilities for ships and alternative approaches to demand calculation, such as the gravity model, should be considered.

Integration of Automatic Identification System (AIS) data in the modeling and extending scope of policy analysis: AIS data provides granular insights into ship traffic patterns, operational profiles, and voyage characteristics. This enhancement will allow for more precise assessments of energy use, emissions, and the applicability of alternative technologies under real-world conditions. Expanding the scope of policy analysis by incorporating a broader array of international and regional policies will deepen insights into the regulatory landscape, such as global fuel standards.

Assessment of green corridors: The concept of green corridors is widely discussed. Integrated LCA and energy system models may be used to understand the scaling of alternative fuels and technologies in these specific maritime routes.

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