THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Life cycle navigation through future energy carriers and propulsion options for the energy transition in shipping

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Cover: Cradle-to-grave life cycle phases of ship
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Abstract

The shipping industry's heavy reliance on fossil fuels has a detrimental effect on the global climate, human health, and the natural environment. The shipping sector now relies on the use of cheap and energy-dense heavy fuel oil and is perceived as ‘difficult-to-decarbonize’. Presently the shipping sector is adopting incremental emission reduction measures related to operational and technological energy efficiency solutions. However, to meet the global climate target, the transition from fossil-based marine fuels to renewable energy carriers is needed. Electro-fuels, which are produced from low-carbon electricity, or direct use of electricity with battery storage, are two pathways for energy transition included in this thesis.

This thesis aims to assess the possible influence of the above two decarbonization paths based on energy demand, environmental performance, and economic performance across the whole life cycle of ships. The assessment is performed for hydrogen, ammonia, methanol, and battery-electric on three case study vessels using prospective life cycle assessment (pLCA) and life cycle costing (LCC). The pLCA is based on systems thinking used for environmental assessment of emerging technologies that are in an early stage of development, and the LCC is used for economic assessment of technologies over the life cycle based on the same systems thinking. To understand the environmental and economic tradeoffs for decision making an integrated assessment of pLCA and LCC is employed in the thesis. Considering the complexity and challenges of integration, a framework termed ‘integrated life cycle framework’ is developed for this thesis, allowing for consistent assessment to understand tradeoffs. This framework can be useful for other transport sectors.

The study shows that there is a substantial potential for reducing the environmental impact of shipping through the studied pathways; however, this depends on the carbon intensity of the electricity used in fuel production. Technically, not all fuels are suitable for all vessels. Their suitability is primarily determined by the amount of fuel required for bunkering and the amount of space available onboard. Reduced climate impact comes at the expense of several other impact categories, such as human toxicity, water use, and resource use (minerals and metals). For the same type of fuel, fuel cells have greater impact reduction potential than engine options; however, engines are more cost competitive. Fuel price and utilization rate also influence cost competitiveness. The total life cycle cost of all the studied options is significantly higher than the conventional diesel option, and the critical parameter is the cost of the fuel. The cost of fuel is sensitive to the price of electricity. The carbon abatement cost estimated in this study shows that policies should be designed to imply at least a cost of 250–300 €/tCO_2eq for emitting greenhouse gases to make the assessed fuel options cost competitive.

Keywords: life cycle assessment, life cycle costing, marine fuel, electro-fuel, hydrogen, ammonia, methanol, battery electric, shipping, environmental impact, carbon abatement cost, economic impact, technical feasibility, fuel cells, engines, carbon captur

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List of publications

Paper I

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Paper II

Kanchiralla, F. M., Brynolf, S., Olsson, T., Ellis, J., Hansson, J., & Grahn, M. , How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? a life cycle study (Manuscript under 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, "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.

Life Cycle Assessment of Marine Fuels in the Nordic Region; Selma Brynolf, Julia Hansson, Fayas Malik Kanchiralla, Elin Malmgren, Erik Fridell, Håkan Stripple, Pavinee Nojpanya; 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

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Contents

Abbreviations, Acronyms, and Terminology

Abbreviations and acronyms

2SICE	2 Stroke Internal Combustion Engine
4SICE	4 Stroke Internal Combustion Engine
NH_3	Ammonia
AEC	Alkaline Electrolyser
ASU	Air separation unit
BE	Battery-Electric
CO_2	Carbon Dioxide
CAC	Carbon Emission Abatement Cost
CII	Carbon Intensity Indicator
CCS	Carbon dioxide Capture and Storage
CH2	Compressed Hydrogen (700 Bar)
cLCC	Conventional Life Cycle Costing
DWT	Dead Weight Tonnage
DAC	Direct Air Capture
ET	Emerging Technology
ECA	Emission Control Area
EOL	End Of Life
EEXI	Energy Efficiency Existing Ship Index
EF	Environmental Footprint
eLCC	Environmental Life Cycle Costing
EU	European Union
FC	Fuel Cell
FU	Functional Unit
GWP	Global Warming Potential
GHG	Greenhouse Gas
GT	Gross Tonnage
HFO	Heavy Fuel Oil
H_2	Hydrogen
ILCF	Integrated Life Cycle Framework
IPCC	Intergovernmental Panel on Climate Change
ICE	Internal Combustion Engine
IMO	International Maritime Organization
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LH2	Liquefied Hydrogen
MRL	Manufacturing Readiness Level
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
PSM	Powertrain and Fuel Storage Mass
MeOH	Methanol
NOx	Nitrogen Oxides
N_2O	Nitrous Oxide
NV	Normalized Value
NF	Normalization Factors
PM	Particulate Matter
PostCC	Post Combustion Carbon Capture

pLCA	Prospective Life Cycle Assessment
PEMEC	Proton-Exchange Membrane Electrolyzer
PEMFC	Proton-Exchange Membrane Fuel Cell
RoPax	Roll-On/Roll-off Passenger Ferry
SCR	Selective Catalytic Reduction
SEEMP	Ship Energy Efficiency Management Plan
sLCC	Societal Life Cycle Costing
SETAC	Society Of Environmental Toxicology and Chemistry
SOEC	Solid Oxide Electrolyser
SOFC	Solid Oxide Fuel Cell
SIICE	Spark Ignition Internal Combustion Engine
SOx	Sulphur Oxides
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 assigning the inputs and outputs of each part are to its corresponding impact categories. Division of flows can be done using different criteria such as physical relationship or economic value.

Biofuels: 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.

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-fuel are synthetic fuels made from electricity preferably generated from renewable energy sources such as solar or wind.

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.

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 as a result of nitrogen fertilization.

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.

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 create 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 can be expanded as 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 system 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

The maritime sector is critical for international trade because ships transport over 90% of the world's trade [1]. It is also projected that global transportation work would increase by at least 57% and as much as 126% compared to 2018 based on different shared socio-economic pathways [1]. Presently most ships run on highly polluting fossil fuels like heavy fuel oil (HFO) and marine gas oil (MGO), which result in emissions corresponding to 3% of total global anthropogenic carbon dioxide (CO_2) emissions [1]. In addition to the climate impact from the shipping sector, air emissions like nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM), and hydrocarbons from ships have a negative impact on human health and the natural environment [2]. If the shipping industry continues to use fossil fuels, these emissions would keep going up, especially since the amount of transportation work is expected to grow.

To reduce greenhouse gas (GHG) emissions from shipping, the International Maritime Organization (IMO) adopted a GHG strategy in 2018 with the goal of reducing shipping's carbon intensity by at least 40% by 2030 and total annual GHG emissions by at least 50% by 2050, compared to 2008 [3]. In the MEPC 79th session held in December 2022, it was discussed to strengthen the level of GHG reduction ambition to be decided during 2023 [4]. Furthermore, the IMO has created several regulatory frameworks for reducing GHG emissions from shipping, including Carbon Intensity Indicator (CII), Energy Efficiency Existing Ship Index (EEXI), and Ship Energy Efficiency Management Plan (SEEMP) [4]. The CII rating scheme addresses actual carbon intensity, calling for operational energy efficiency measures, whereas EEXI addresses technical energy efficiency measures, and SEEMP deals with energy management systems. In the Fit for 55 legislative packages, the EU also proposed a FuelEU maritime regulation, which aims to increase the use of renewable and low-carbon fuels in the maritime sector and also proposed to include the shipping sector in the EU emission trading scheme [5].

GHG emissions can be reduced by implementing operational and technical energy efficiency measures, abatement technologies, shifting to climate-neutral fuels, and/or developing new propulsion technologies [6-9]. Considering the increased demand for transport work by 2050, a reduction of 75–85% in GHG emission intensity per transport work would be required to meet the ambition of the IMO GHG strategy [10]. Irrespective of the GHG reduction that can be achieved through energy efficiency measures, transitioning towards climate-neutral energy carriers with appropriate powertrain technologies would be required to meet GHG targets [11].

The previous transitions from wind to coal and then to oil as the energy source for propulsion were uniform for all ships. Future energy transition in shipping would be complex because of the different challenges and barriers of each decarbonization pathway. For example, each energy carrier (e.g., hydrogen, ammonia, and methanol) has different properties like energy densities (volumetric and gravimetric), toxicity, flammability, storage requirement, safety, etc. Also, the technical design and operation of vessels differ depending on the transport work or function they are performing. IMO has categorized the entire fleet into nineteen ship types based on functionality, and further, these ship types are categorized based on capacity into 'size bins' [1]. Further, each vessel of the same type in the same size bin will have different technical, functional, and operational parameters depending on voyage length, design speed, bunkering frequency, and operating route. This variation in parameters may have different implications for each energy carrier, with different properties, and the suitability of the decarbonization solution may vary for each vessel.

Also, the production pathway of the alternate energy carriers is important for a transition toward climate neutrality. Climate-neutral energy carriers can be primarily derived from three main energy sources: 1) Biomass (biofuels): Biomass-based fuels can be considered carbon-neutral as natural or biogenic carbon is released from these sources when combusted; 2) Renewable electricity (e-fuels/battery-electric): E-fuel are synthetic fuels made from electricity generated from preferable renewable energy sources such as solar or wind; 3) Fossil fuels with CCS (blue-fuels): These are fuels synthesized using the hydrogen produced by removing carbon from the fossil fuel and storing the carbon permanently to prevent its release into the atmosphere.

1.1. Motivation and aim

The transition towards climate neutrality is complex and is accompanied by changes in the fuel supply chain, propulsion system configuration, and infrastructure. These changes may lead to shifting emissions to other sectors or impact the environmental assimilative capacity, creating other environmental problems. Also, the direction of transition for each vessel would be based on several parameters, including GHG reduction potential, economic performance, other environmental impacts, stakeholder expectations, availability of fuel and technology, access to capital, policies or regulations, and risk management. A system-level assessment with regard to both fuel and vessel is necessary to understand any transition from the status quo. A system-level assessment helps in identifying underlying factors that influence the choice of different transition pathways and the operational, functional, and technical features of the vessel.

The aim of this thesis is to evaluate the potential impact of various decarbonization pathways for shipping on the energy demand, environmental performance, and economic performance of ships throughout their life cycles. Each decarbonization pathway includes changes in energy carrier and powertrain from the current system. The energy carrier and powertrain together act as a technological system comprising various processes, technologies, and interactions. Since many technologies/processes within this technological system are at early stages of development, the technological system itself can be considered as emerging. By understanding the implications of these technological systems during the early stages of development, it is possible to identify potential environmental burdens or costs and provide decision-making support for stakeholders [12]. This approach allows actors to get involved early in the design process. This way, unnecessary environmental burdens can be avoided, costs can be cut, and the effects of future environmental rules can be predicted. The cost of making changes at this early stage could be low [13], enabling informed investment decisions and avoiding the adoption of technologies that may have a higher environmental impact in the long term.

The environmental performance of products and services can be evaluated over their lifecycle using the life cycle assessment (LCA) method, which is a well-established quantitative method for this purpose [14]. The economic performance can be evaluated using life cycle costing (LCC) or techno-economic assessment (TEA) methodologies. LCC is gaining importance considering the life cycle perspective and easier integration with the LCA in terms of methodology [15]. Integration of the TEA with LCA is often difficult due to differences in methodology and scope [16].

However, most LCA and LCC studies are done independently because of differences in terms of decision making perspective, goal and scope, and inventories considered [17]. Assessing the environmental, economic, and energy performance of complex emerging technological systems can be challenging due to the lack of harmonization between these life cycle methods. Additionally, the integration of technology factors into the assessment is also challenging, as it requires modeling future scenarios for emerging technologies, which are not yet fully developed or mature on the market [13]. The lack of integration between the methods can lead to inconsistent or conflicting results, making it difficult to compare different performances in a consistent and transparent manner. This is the first research question that is addressed in this thesis:

RQ1: How can the environmental, economic, and energy performance of different potential decarbonization pathways in the shipping sector be evaluated in a consistent way using an integrated LCA-LCC approach?

The decarbonization pathways assessed involve new technologies and infrastructure, particularly in the fuel supply chain and onboard ship. LCA studies in the transport sector often evaluate the environmental impact on the well-to-tank (WTT) and tank-to-wake (TTW) stages, and do not consider the environmental impact of the materials and energy required to produce capital equipment (components and machinery onboard ship) and infrastructure requirements [18, 19]. This lack of comprehensive evaluation can result in a shifting of environmental burden or cost, as the changes in different stages of the total system are not considered. This problem is considered in the second research question addressed in this thesis.

RQ2: How do the environmental impacts of various decarbonization technologies used in the shipping industry compare across the entire life cycle of ships from cradle to grave taking into account the production of capital equipment and infrastructure requirements, which are often excluded in traditional LCA studies in the transport sector?

Different vessels have different fuel consumption, power capacity, and storage space availability depending on function, voyage length, fuel consumption, operation style, and design. Also, the technological systems assessed are diverse, as the power conversion technologies have different power densities and efficiencies in addition to the differences in the properties of fuels (like energy densities, storage parameters, flammability, and toxicity). 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 third research question, addressing this, is:

RQ3: How do variations in ship type and operation impact the feasibility of onboard decarbonization options, and to what extent do these variations affect the environmental and economic performance of different decarbonization pathways?

The main target audiences for this thesis are researchers, policymakers, and stakeholders in the maritime industry, including shipbuilders, ship operators, and regulators. It could also be of interest to environmental organizations and academics working in the fields of energy and environmental management. The knowledge could be important when modeling decarbonization scenarios for fleets and formulating overarching policies and strategies for accelerating the decarbonization of the shipping sector.

1.2. Scope and delimitation

This thesis focuses on direct electrification and e-fuels (also called electro-fuels, power to fuels, power to X, PTX, etc.). These energy carriers have high availability of feedstock compared to biofuels (which depend on biomass availability, which in turn is limited by the availability of land and water) and blue fuels (which depend on fossil fuel availability). Apart from the feedstock availability, biofuels further face challenges related to that an upscaling may cause socio-economical issues including increased food prices [20-22], and have a negative effect on biodiversity as well as other land-use related issues like land-use change (direct and indirect), soil carbon content, the time between vegetation replacements, and biofuel supply chains globally [20]. In this study, neither blue fuels nor biomass-based energy carriers are included.

Several electro-fuels are investigated for application in the transport sector, like methanol, ammonia, methane, di-methyl ether diesel, hydrogen, etc. In this thesis, the following electro-fuels are compared: Hydrogen - H_2 (base electro-fuel), ammonia - NH_3 (electro-fuel with nitrogen), and methanol-MeOH (electro-fuel with a carbon atom). These fuels are investigated in different powertrain configurations, like internal combustion engines and fuel cells, in addition to battery-electric (BE) propulsion. For carbon-based electro-fuels such as methanol, it is important in LCA to consider the source of the carbon atom, that is, whether the carbon comes from a fossil or a biogenic source, because the emission of carbon need to be treated differently depending on the source [23]. This thesis considers only atmospheric CO_2 captured using direct air capture (DAC) in fuel production for a simplified assessment. This assumption avoids the impact allocation when considering CO_2 from fossil or biomass sources. 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.

Regarding the system boundary, cradle-to-grave of the entire pathway is included in the thesis, which covers direct impact during vessel operation, also called TTW, impact from fuel production and distribution, also called WTT, fuel supply chain infrastructures for electricity and supply, and ship manufacturing with end-of-life as shown in Figure 1. One of the criteria that define the system boundary is the location where the energy carrier is produced and the bunkering point. Regarding geographical scope, the thesis has assumed that energy carriers are produced locally near the bunkering port. 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.

The thesis assumes the case of only newly built ships and does not consider retrofitting existing ships. The modeling of the new built system is performed based on operation parameters, rated capacity of machinery, ship structure of the case study vessels, and assuming a change in the powertrain system.

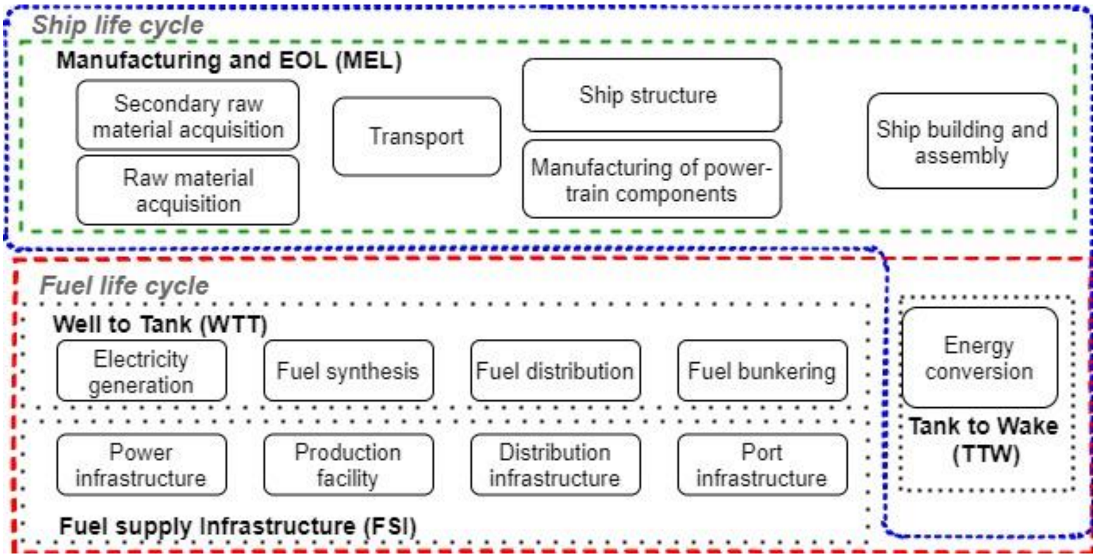


Figure 1: Illustration of the scope of the thesis in terms of various stages involved in the cradle-to-grave analysis.

1.3. Approach and outline of the thesis

Since the methodology for life cycle analysis of emerging technologies has not been consistent or standardized, especially for emerging technological systems in the transport sector, a framework combining LCA and LCC is used in the appended papers in this thesis. This framework is introduced mainly to provide guidance during the life cycle evaluation on overcoming the challenges of integrated evaluation of emerging technologies. This thesis covers two appended papers that use this integrated methodology for performing life cycle evaluation for different case study ships. Paper I investigated the overall energy efficiency, environmental performance, and economic performance using LCA and LCC of different decarbonization pathways using e-fuels and BE for a RoPax vessel. With the cradle-to-grave life cycle evaluation, this paper contributes to knowledge regarding the impact due to changes in material and energy requirements during different stages of different decarbonization pathways. Paper II analyzed the ship design feasibility, LCA, and

LCC of three case study ship types for e-fuels and BE pathways. This paper focuses mainly on the difference in impact due to differences in ship operation and function.

This thesis is broken down into six parts. Section 2 presents a review of the life cycle approaches used in different studies. This section also summarizes the challenges associated with emerging technology life cycle assessment and life cycle costing. In Section 3, the integrated framework introduced and used in the thesis is explained. In Section 4, the results from the appended papers are summarized. In Section 5, discussions regarding the thesis's results and research question are presented. The conclusions from the thesis can be found in Section 6, and Section 7 discusses the direction for future research.

2. Overview of life cycle methods

Different decarbonization pathways for shipping are associated with different technological systems. A technological system is a dynamic network of agents engaged in the production, dissemination, and consumption of technology within a certain economic/industrial domain and operating within a given set of institutions [24]. In addition to shifts in the technologies and products themselves, the technological system also undergoes shifts in the nature of the connections between them [25]. To analyze the performance of these technological systems with complex networks and interactions, systems thinking based methodologies are used. Systems thinking considers the system as a whole rather than focusing on individual parts in isolation. Environmental assessments are used to understand the interactions between different components, the environment, and the impact of human activities on those systems.

Life cycle thinking is one of the methodologies based on systems thinking where the material, energy, cost flows, and interactions between the processes and the environment during a product's life cycle (from raw material extraction to disposal) are analyzed to quantify the potential impact and resource use of the entire system [26]. 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 [27]. In this thesis, however, only the environmental and economic aspects covered by LCC and LCA are considered. Social life cycle assessment (sLCA) which is used to evaluate the social aspects of a system is not part of the 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) [26]. 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 [26] as shown in Figure 2.

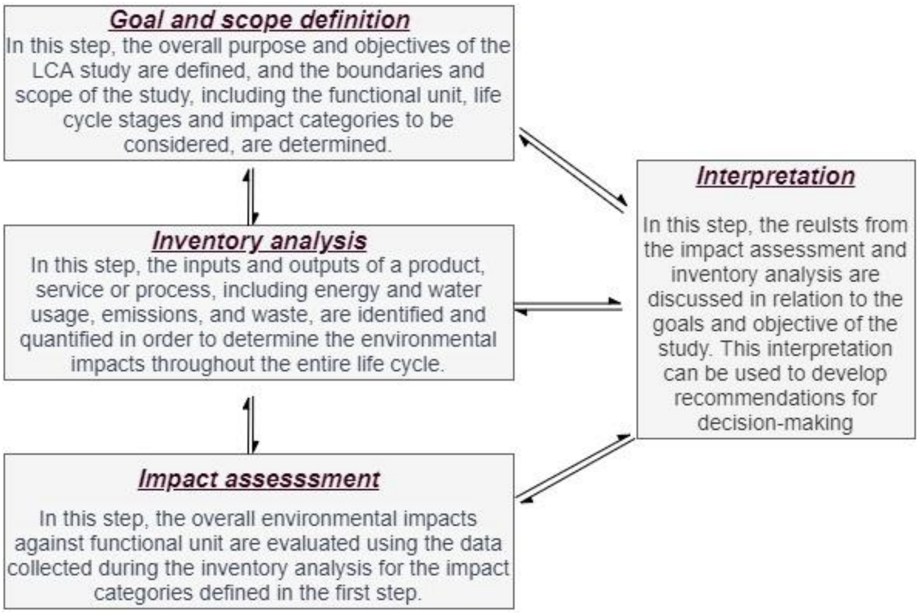


Figure 2: Four phases in the ISO framework for conducting LCA.

In this thesis, technological systems contain multiple emerging technologies calling for future-oriented LCA and future-oriented assessment 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 [28]. These different future-oriented LCAs and their approaches are summarized by Giesen et al. [28] and Cucurachi et al. [12] as shown in Table 1. 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 which are at an earlier stage of development than those technologies covered in pLCA studies [28]. In this thesis, we are assessing emerging technologies within a technological system that are in the early stages of the development phase 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 1 as used in the study by Arvidsson et al. [13].

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," and the same will be used in this thesis. 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 1: Future-oriented LCAs used in various literature, adapted from Cucurachi et al. [12] and Giesen et al. [28].

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 [12].
Dynamic LCA	This assessment emphasizes incorporating the dynamics of parameters that are anticipated to change over time and comparing various development pathways over time [28].
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 [28].
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) [13].
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 [28].

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. [29] 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. [30] 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. [13] 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. [12] 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. [28], it is shown that the challenges vary by discipline and that they are 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 [28]. 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 [28]. In impact assessment, challenges include the possibility of a new impact not being identified and changes in characterization factors over time [28]. The challenges in the interpretation stage would be uncertainty and unknowns with new technologies [28]. Another review by Moni et al. [31] 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 suggested a method for inventory modeling for upscaling emerging processes based on predictive scenarios or scenario ranges [13]. Moni et al. [31] have compiled some overarching suggestions, but do not mention how they can be integrated into LCA. Similarly, Giesen et al [28], have compiled potential remedies based on challenges specific to each phase. Thonemann et al. [30] 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

Presently 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 [32]. 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 [15]. 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 building 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."[33]. 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' [33]. Overall, the guidelines can be found to be similar to the LCA methodology.

Rödger et al. [15] distinguish LCC into conventional LCC (cLCC), environmental LCC (eLCC), and societal LCC (sLCC) depending on the purpose and target group. 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 [15]. 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 [15].

2.4. Integration of the LCA and LCC

The integration of LCA and LCC will make it easier to identify environmental and economic trade-offs while selecting the emerging technology. However, often LCA and LCC are used with little integration or done independently [34]. Franca et al. [34] 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 assessment together, differences in the scope and system boundaries, and differences in the background data. However, often LCA and LCC are used with little integration or done independently [34].

Franca et al. [34] 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 assessments together, differences in the scope and system boundaries, and differences in the background data. Miah et al. [17] also have analyzed the integrated methods for LCA and LCC and suggested a conceptual framework. In addition, there are several studies that have tried to integrate TEA and LCA for emerging technologies [14, 16, 32, 35, 36], 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.

2.5. LCA and LCC of alternative fuels in shipping

Multiple studies have conducted LCA and LCC for various marine fuel types, including fossil fuels, biofuels, electro-fuels, and electricity. However, LCA studies focusing on the prospective assessment of electro-fuels are limited, as detailed in Table 2, adopted from the study [37]. These works shed light on the challenges in the shipping sector for decarbonization pathways despite these differences and the complexity of the technological systems in the pathways. However, differences in the scope and functional unit between studies should be noted. The majority of studies found in the literature have not incorporated a prospective modeling approach for emerging pathways. Some studies have performed both the LCA and the cost assessment of the system [38-40], but it is unclear how they have integrated them in terms of inventory data. This can result in discrepancies between the material, energy, and cost inventories 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 2: 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 [41]	Hydrogen, ammonia	Global warming, ecotoxicity, ecotoxicity, acidification, ozone layer depletion, and abiotic depletion	Well to haul FU: 1tonnekm	-
Bicer and Dincer [42]	Hydrogen, ammonia	Global warming potential, abiotic depletion, acidification, stratospheric ozone layer depletion, and ecotoxicity	Cradle to grave FU: 1tonnekm	-
Fan, et al. [43]	Electricity	Global warming	Cradle to grave FU: Ship life	LCC
Fernández-Ríos, et al. [44]	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. [45]	Hydrogen, methanol	Global Warming	Well-to-Propeller FU: 1kWh	-
Ling-Chin and Roskilly [46]	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. [47]	Electricity	Global warming, acidification, eutrophication, and photochemical ozone formation	Well to wake FU: Ship life	-
Law, et al. [48]	Hydrogen, ammonia, methanol, battery	Global warming, air pollutant	Well to wake FU: 1kWh ICE out	LCC
Lindstad, et al. [49]	Hydrogen, ammonia, methanol, battery	Global warming	Well to wake FU: 1kWh ICE out	TCO
Malmgren, et al. [50]	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 [51]	Hydrogen	Global Warming	Well-to-propeller FU: daily	-
Mestemaker, et al. [52]	Hydrogen	Global Warming, acidification, eutrophication, and photochemical ozone formation	Well to wake FU: Ship life	NPV
Perčić, et al. [53]	Hydrogen, battery	Global Warming	Well to wake FU:Nautical-mile	LCC
Perčić, et al. [54]	Hydrogen, battery	Global Warming	Well to wake FU:Nautical-mile	LCC
Perčić et al. **[38]**	Hydrogen, methanol, and battery	Global Warming	Well to wake FU:Nautical-mile	LCC

2.6. Employing life cycle tools in this thesis

The decarbonization pathways contain many emerging technologies and considering the aim of this thesis, it is important to assess the environment and cost of the system at the same time. The interdependence of the parameters, like material, efficiency, emissions, and costs, should be taken into consideration. Hence, the assessment includes both the challenges mentioned in Section 2.2 and Section 2.5, which are related to RQ1. A framework is introduced in this thesis to address these challenges and to integrate the LCA and LCC. This framework formulated as 'integrated life cycle framework (ILCF)' contribute towards answering RQ1. This integrated framework is explained in detail in Section 3. ILCF is then used and tested for the life cycle analysis of the decarbonization pathways in Paper I and Paper II.

Figure 3 shows how the different RQs are connected to the papers, the ILCF is used as a method for Paper I and Paper II which has contributed towards answering the RQ2 and RQ3. Wherein ILCF itself answers RQ1. In Paper I, the assessment is performed for one case study vessel (RoPax) for the technological systems defined for the decarbonization pathways assessed. In Paper II, in addition to the first case study vessel, two other vessels (a tanker and a service ship) are also assessed. The results from Paper I also poised interest in investigating more technological systems like the possibility of using methanol in fuel cells, and the feasibility of compressed hydrogen in shipping. Hence, these technical systems were also added to Paper II for assessment. The technical feasibility of the technological options is also assessed by using a feasibility criterion developed in Paper II.

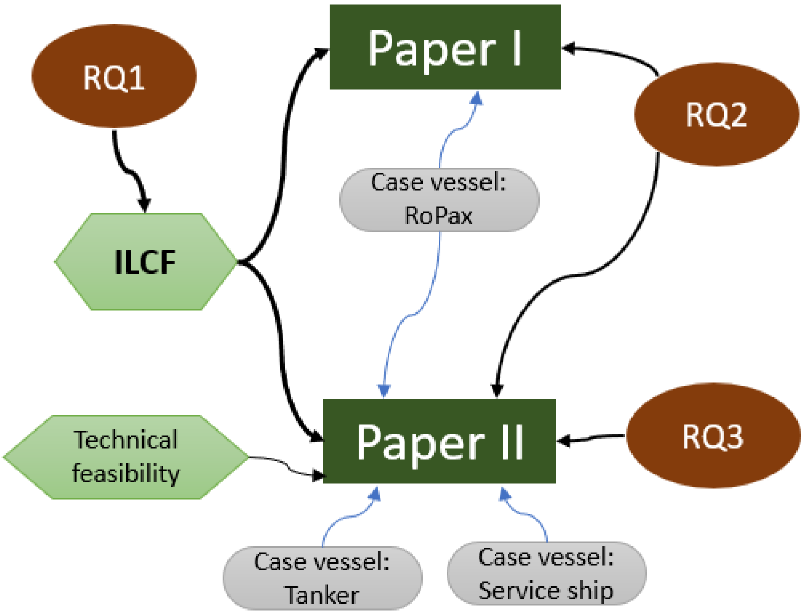


Figure 3: Overview of how the research questions are connected to the appended papers.

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 in four steps by adding different methods and approaches for integrated assessment of emerging technological systems. In the first step, the relevant challenges specific to the thesis associated with the pLCA and integration of LCC are identified from the method and review literature as discussed in Section 2. In the second step, the LCA steps suggested in the ISO 14044 guideline 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 literatures to overcome the challenge 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). There are also some common challenges associated with both for example data availability and quality. The challenges identified from the literature for methodology studies of pLCA [12, 13, 28-31] and of LCC integration [14, 16, 17, 32, 34-36] are summarized in Table 3.

Table 3: Challenges identified for pLCA and LCC integration that need to be addressed in the methodology.

Challenge	LCA phase
▪ Which functional unit should be used for comparison? ▪ What are the changes associated with technological system change? ▪ 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? ▪ When multiple emerging technologies are there for the process? e.g: PEMEC, SOEC, AEC for electrolysis. ▪ 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 tool for simultaneous assessment capturing same inventory. ▪ Whether present characterization is relevant over time?	**Impact assessment**
▪ How the uncertainty in the development can be addressed? ▪ If different technology is selected for the foreground process how would it impact the result?	**Interpretation**

The integrated framework proposed in this thesis is shown in Figure 4. The red texts are the challenges identified in Table 3, and the blue boxes are approaches integrated to the framework that is used in this thesis to address some challenges while performing life cycle analysis. As described in the second and third steps, the challenges and approaches are mapped to the four phases specified in ISO 14040/44.

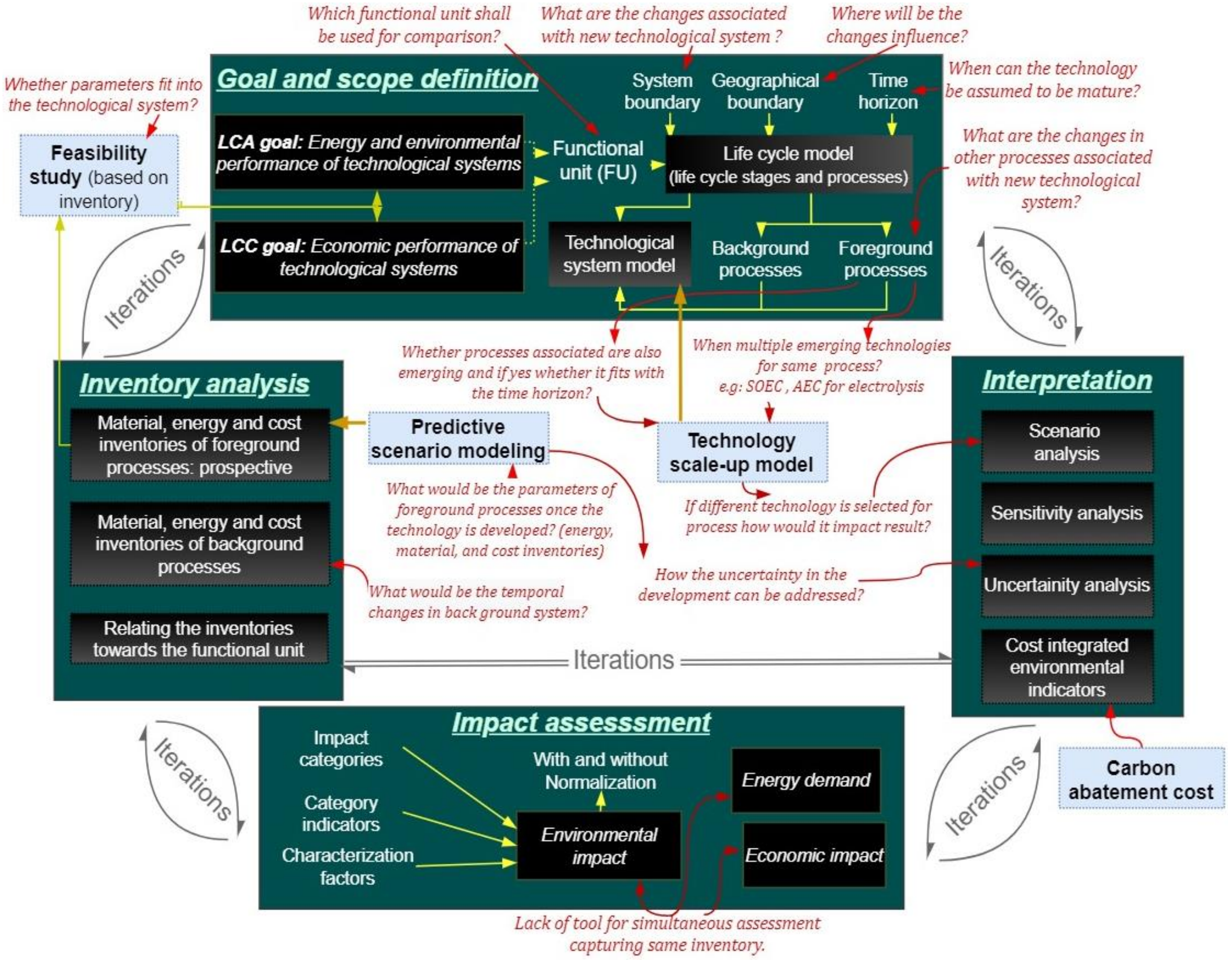


Figure 4: Integrated framework used in this thesis for the life cycle analysis of alternative fuel in the shipping sector.

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 goals in either an individual or combined fashion. 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 LCI and LCIA [55]. The goal defined as per ILCF in the appended papers is to assess environmental and economic performance over the entire life cycle of a ship fitted with a new technological system operated with electro-fuels. The goal of Paper I is to investigate the different overall energy conversion, environmental performance, and economic conditions over the entire life cycle of eight decarbonization solutions on a RoPax vessel. The goal of Paper II is to investigate the different environmental and economic performance of nine decarbonization pathways, varied for different ship types, including ferries, tankers, and service vessels. Paper II also adds the goal to analyze the ship design feasibility. The intended audience are the same for both papers as in this thesis (read more in Section 1.1).

In the scope definition phase, the LCC/LCA study's object 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 to ensure all technological systems can be compared based on the same function, both in terms of impact and cost (Figure 4). One of the common functional units in LCA studies of marine fuels, as noted in Table 2, is engine or fuel cell output. While using such functional units will not always give a fair relative comparison as the output energy form is different 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. The functional units selected in Paper I and Paper II are round-trip and annual ship operations, respectively. 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 also includes an additional functional unit that represents specific ship parameters that is GT-km (RoPax and service vessel) and DWT-km (Tanker).

The main challenge in defining system boundaries is to capture all relevant changes in the life cycle stages and process while establishing a new technological system (Figure 4). Considering the complexity of the technological system, it is difficult to identify all the processes (within the technological system and also in the related supply chain) that would be subjected to change or are influenced by the change. These changes would be different for different 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. A life cycle model should be built based on the system boundaries, life cycle stages, and processes under consideration. It is also important to show relevant activities not included within the system boundary for clear communication. While conducting pLCA, it is also important to differentiate the foreground system process from the background processes. In conventional LCA, the foreground processes are considered processes that are the focus of the study. In pLCA, since the change in the future is considered, 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 foreground processes and background processes defined for Paper I and Paper II are shown in Figure 5. Ship structure is not included in Paper I but in Paper II.

	Paper I	Paper II
Functional unit	Round trip	Annual / DWT-km(tanker) & GT-km(other)
Time horizon	2030	2030
Cost flows	Euros (€) Discount rate: 3%. Base year: 2021	Euros (€) Discount rate: 5%. Base year: 2021
Geographical boundaries	Components and ships are assumed to be produced in Europe. The fuel production facilities are assumed to be located near the port of bunkering.	

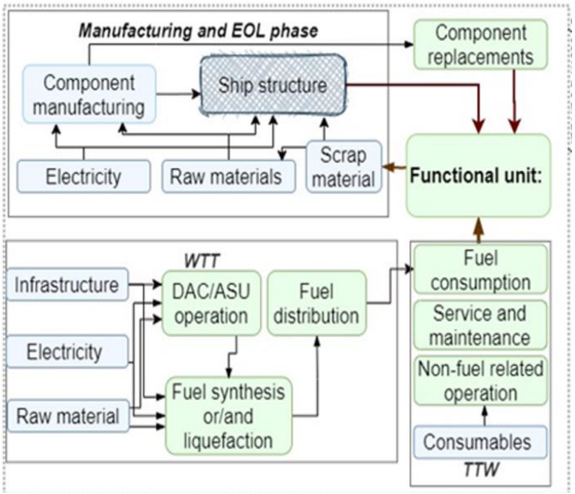


Figure 5: Goal and scope defined in both papers. The right side of the figure shows the system boundary used in both papers. Green represents the foreground processes and blue represents the background processes. Ship structure (cross-hatched) is included only in Paper II.

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 4). These changes also should be identified and evaluated before completing the technological system modeling. The time horizon and geographical boundaries considered in Paper I and Paper II are shown in Figure 5. The summary of the goal and scope defined in the appended papers is also shown in Figure 5. A technological system model is defined in this goal and scope definition phase taking into consideration of all the above parameters. The technological system model includes the entire technological system (powertrain components and energy carrier), supply chain (fuel production pathway and component production), and ship structure. 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 used in a specific process for the time horizon of the study, a technology scale-up model can be used. For technological scale-up for identifying emerging technology for the processes in the foreground system, the level of maturity of different emerging technology 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 in the x-axis of Figure 6. Figure 6 also shows the technology scale-up model used in this thesis adapted from Thonemann et al. [30]. 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 (also refer to Section 4.1.2). This modeling makes use of inputs like interviewing experts, analyzing TEA literature, other literature reviews, etc. As shown in Figure 6, 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 system modeling. In addition, it is important to check whether the given technology is compatible with other processes in the technological system. 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 both papers.

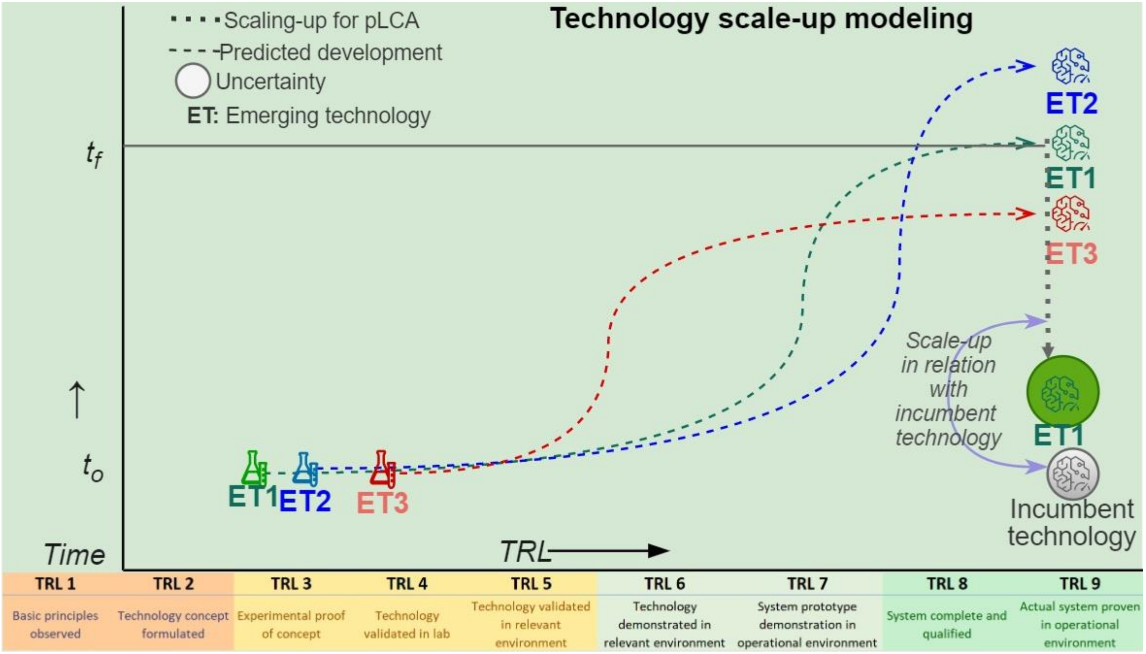


Figure 6: Technical readiness level definition and technological scale-up model used in this thesis (adapted from the Thonemann et al. [30])

In addition to defining the technological systems and the 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. In both papers, the technological system model includes both the technological system and the entire supply chain selected based on the scale-up modeling. That is, it includes all processes in the fuel pathway and propulsion system technology used onboard within the defined system boundary. The technological system models are developed after several iterations and the technological systems defined for the papers are given in Section 4.

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 looked into the additional volume and mass that may be required at the existing condition with the current ship structure.

In this thesis, the challenges of space available for energy carriers in the existing ship structure of case study vessels are addressed in Paper II using a simple screening. The space and weight needed to store energy carriers onboard, which should be sufficient for the voyage expected to use the most energy are analyzed. The space and weight of the powertrain units are also included in the assessment. In summary, 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. For mass feasibility, the design is considered infeasible only if the PSM/DWT ratio of the propulsion system is more than 3 times the PSM/DWT ratio of the reference fuel. PSM is the total weight of the propulsion system machinery and fuel storage tank. For volume constraint, the ratio of the total volume of powertrain and fuel storage tanks (PSV) and GT that is PSV/GT is calculated. The design is considered infeasible only if the PSV/GT of the new technological system is more than 2 times the reference system. The mass constraint is used for the tanker, and the volume constraint is used for the RoPax and the service vessel. In addition, safety risk associated with the handling of fuels such as ammonia and hydrogen onboard was also checked as ammonia is toxic to human health and hydrogen is explosive in nature. A risk assessment workshop was conducted to analyze the safety risk associated with these fuels.

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 technology (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 likely performance at full operational scale [12, 13]. For modeling parameters for the processes in the foreground system, two approaches were suggested by Arvidsson et al. [13]. The first approach includes the use of predictive scenarios, which are essentially 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. Paper I and Paper II 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 7. The data for the prediction of parameters are collected from expert interviews, comparing different techno-economic and life cycle literatures. Three predictive pathways (highly optimistic, present status, and less optimistic values) are analyzed to select three different values. Here, less optimistic value is taken for the base calculation. And the other values are used in the interpretation phase for uncertainty analysis.

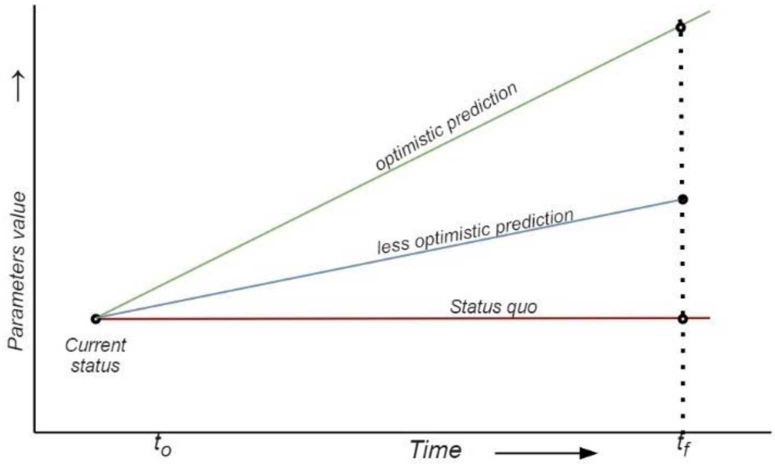


Figure 7: Predictive scenario modeling used in the thesis adapted from Arvidsson et al [13].

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 [16]. For the background system, while choosing the parameters of the process based on existing data, temporal mismatch with the foreground system should be avoided [13]. One example of adjusting temporal change of the background information used in both papers is the electricity mix of the grid. For data consistency, in both papers, the mixes are adjusted to the scenario projection for the year 2030 based on different forecasts. In this thesis, the forecasts of electricity mixes are taken from IEA for global mixes [56], and EU and Swedish grid mixes from EU Commission based on the reference year 2020 [57]. However, the cost inventory should be 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 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 to each other. In this thesis, the fuel costs are calculated from the electricity cost and consider the electricity required in each stages of the life cycle and investment cost of the same technology under consideration. Also, the parameters are selected based on same prospective pathway as in inventory of technological parameters.

A challenge here is that available background data, like the LCI database, often are outdated [28]. This is clearly visible in the papers, Paper I used the electricity from the wind power dataset from Ecoinvent 3.7 [58] whereas Sphera (GaBi) dataset [59] was used in Paper II. A wide difference can be seen between the datasets (e.g., GWP100 of around 25gCO_2eq in Ecoinvent and 9gCO_2eq in the Sphera dataset). The datasets not only need to be compared with temporal changes but also with the latest life cycle studies. For a fair comparison, if the updated data is not available it would be better to use the same background dataset uniformly for different technological systems. However, this reduces comparability between different studies, this is also visible in this thesis. Comparing values for the same technological option between Paper I and Paper II shows that they have different GHG reduction potentials for same given functional unit.

3.3. Impact assessment

For assessing the environmental impact the main challenge is regarding the 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 at once towards the functional unit. To accomplish this, all parameters are listed in an Excel spreadsheet from where the values are captured simultaneously for the LCA and the LCC assessments performed using openLCA and Python, respectively.

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 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 both papers 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 [55] as shown in Figure 8. Again for both papers, the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) for calculating GWP20 and GWP100 [60].The midpoint level is used in both papers 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 [55] as shown in Figure 8. Again for both papers, the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) is used for calculating GWP20 and GWP100 [60]. The other impact categories are assessed according to Environmental Footprint (EF) 3.0 LCIA method recommended by the European Commission's Joint Research Centre [61].

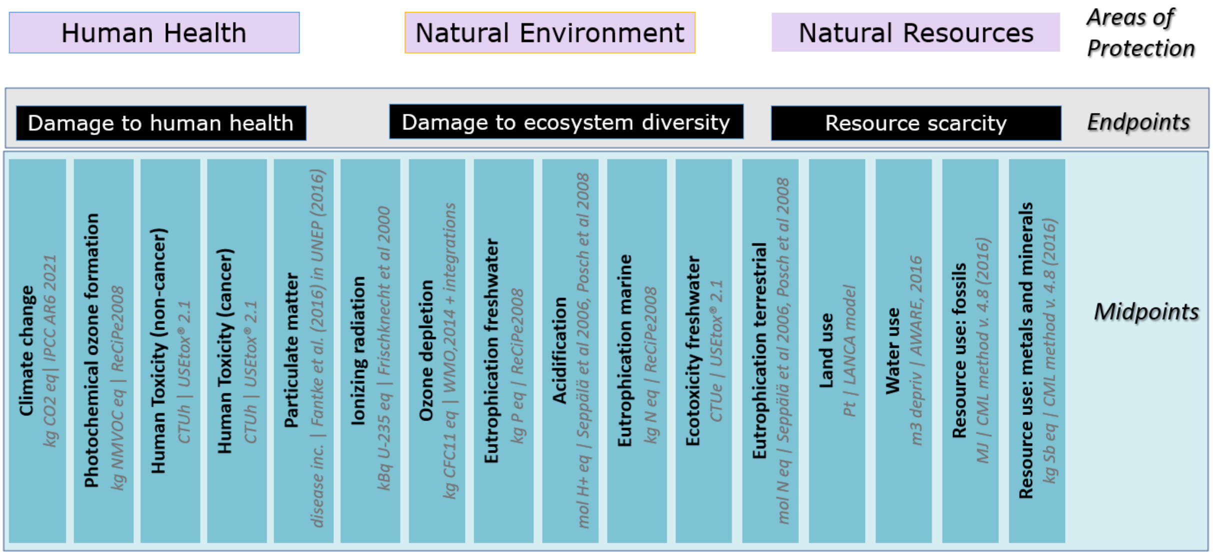


Figure 8: Life cycle impact assessment showing the midpoints, endpoints, and areas of protection. The midpoint indicator shown is used in this thesis for impact assessment.

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. [62]. Even though normalization is optional as per ISO 14044 [26], normalization provides a reference situation for the environmental pressures [63]. In both papers, the global normalization factors (NFs) are taken from EF 3.0 [64]. Global NFs represent the relevance of the total environmental impact in a certain category in a global context [64]. 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 and none of the alternatives is clearly better than the other, 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 tool is not used in the appended papers. Even though weighing helps to identify the most relevant impact categories, present results in an aggregated manner for better communication, and guide decision-makers [65], weighing is based on value choices and not scientifically based [26]. 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 [65].

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

The total energy demand for the technological system can also be calculated from energy quantified in the inventory analysis phase along with the environmental impact. However, integrated assessment of the cost along with the environmental cost is challenging due to the lack of tools. A combination of openLCA, Excel and Python software is used for simultaneous assessment where the customized codes were developed in Python that captures the same parameters for life cycle costing as in the LCA. Discounting the results of the LCC is often debated as it is inconsistent with the steady-state assumption of LCA [15]. However, for both papers a discount rate was 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.

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

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

As it is necessary to make assumptions and there are a lot of uncertainties about the modeling choices that must be made, the results of a pLCA study shouldn't be seen as a definite result. Instead, they should be seen as a possible effect that a technology could have under a certain set of assumptions. There are two main sets of challenges that should be addressed in the interpretation phase as shown in Figure 4. First, if different emerging technology for the foreground process is used what would be the new environmental and cost impact? and secondly, uncertainty associated with the parameters while scaling up emerging technologies. The first challenge can be addressed by scenario analysis by modeling technological systems with different emerging technology and following the steps again. Scenario analysis can also be performed for different strategies that may define technological systems differently. An example of different strategy scenarios is charging strategies for the BE option assessed in Paper I. Two scenario analyses are performed in Paper I and one scenario analysis in Paper II.

The second challenge regarding uncertainties in parameters for the processes is assessed in both studies including all major parameters within ranges using uncertainty analysis. Since uncertainties of several parameters are assessed, a statistical method called Monte Carlo analysis is used. It uses 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 uniform distribution of the range of parameters with 10,000 iterations to generate a distribution of possible outcomes for the system. The results of the simulations are then analyzed to understand the likely environmental impact and the cost of the system. In addition, sensitivity analysis can be used to understand the impact of a certain parameter on the results of the study, where for example the sensitivity of the carbon intensity of the electricity mix was evaluated in Paper I.

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' [66]*. 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.

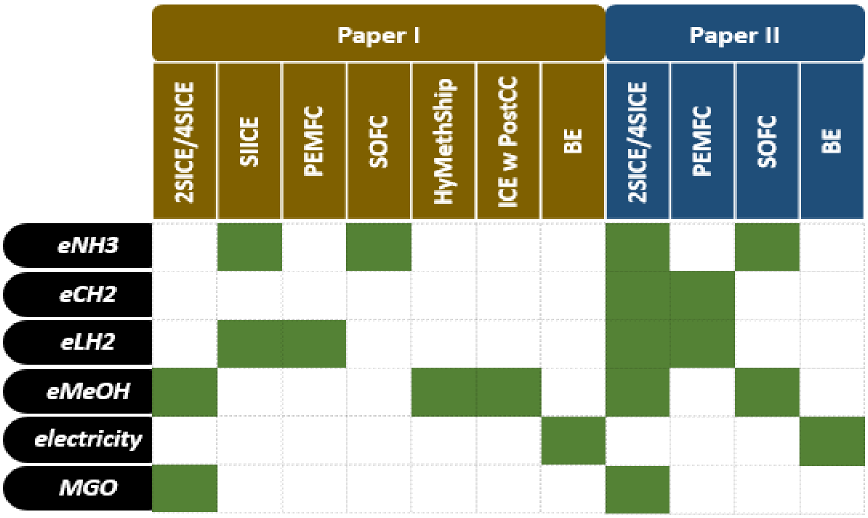
$$CAC(€/tCO_2eq) = \frac{LCC\ \ relative\ to\ reference\ (€/kWhprop)}{GWP100\ relative\ to\ reference\ (tCO_2eq/kWhprop)} \qquad (5)$$

4. Results from appended papers

This chapter covers the result from two appended papers that have contributed to answering RQ2 and RQ3 and in which the framework developed for RQ1 is tested/used. Results from Paper I and Paper II contribute to knowledge regarding the energy, environmental, and cost impacts from different technically suitable decarbonization pathways from cradle to grave for shipping. In addition, paper II considers technical viability and analyzes the difference in environmental, and cost impacts between ship types. Life cycle results depend on the technological systems defined for the decarbonization pathway. The technological system defined in the appended papers, including powertrain configuration and supply chain of energy carrier, is summarized below.

4.1. Technological system model

Figure 9 shows all technological systems comprising of energy carrier supply chains and powertrain technologies assessed in Paper I and Paper II. The description of technologies selected for the powertrain units and energy carriers are described below.



	Paper I							Paper II			
	2SICE/4SICE	SIICE	PEMFC	SOFC	HyMethShip	ICE w PostCC	BE	2SICE/4SICE	PEMFC	SOFC	BE
eNH3		🟩		🟩				🟩		🟩	
eCH2								🟩	🟩		
eLH2		🟩	🟩					🟩	🟩		
eMeOH	🟩				🟩	🟩		🟩		🟩	
electricity							🟩				🟩
MGO	🟩							🟩			

Figure 9: Summary of technological systems assessed in two papers.

4.1.1. Powertrain configuration

Transition to different energy carriers will need changes in the onboard fuel 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 the alternate fuels are in early TRL and need a technological scale-up model. In both papers, the energy converters included are spark ignition ICE (SIICE), 2-stroke ICE (2SICE), 4-stroke ICE (4SICE), proton exchange membrane (PEMFC), and solid oxide (SOFC), and BE.

In combination with onboard carbon capture systems, Paper I investigated eight different powertrain configurations and Paper II investigated nine different powertrain configurations as shown in Figure 10. It can be noted that Paper I investigated SIICE configuration for ammonia, and hydrogen fuels, whereas 4SICE and 2SICE configuration, are considered in Paper II. This variation is done considering recent progress on hydrogen and ammonia-based dual-fuel ICEs (e.g., engine manufacturer Wärtsilä is developing 4SICE for ammonia [67] and MAN Energy Solutions is also developing 2SICE for using ammonia as fuel [68]). Likely efficiencies of these emerging ICEs were compared with the incumbent technology during the prediction modeling after deducing heat of vaporization. Emission parameters are developed based on stoichiometric ratio, comparing with gas engine emissions based on natural gas, and the amount of pilot fuel. Paper II have investigated the powertrain for three vessels, and based on current engine configuration 2SICE is assumed for the tanker, and 4SICE for both the RoPax and the service vessel.

In Paper I, two carbon abatement technologies are assessed: methanol-powered 4SICE with postCC and HyMethShip concept which combines an onboard membrane reactor to split methanol into H_2 and CO_2 with H_2-powered SIICE (pre-combustion CC). Considering the challenges in the supply chain related to CO_2 onboard to the fuel production facility, these options are not assessed in Paper II. In Paper II, the possibility of eCH2 in the ships was additionally investigated as it is considered a potential choice in trucks.

A wide variety of FCs depending upon electrolyte membranes is available such as (SOFC), molten carbonate, proton exchange membrane (PEMFC), phosphoric acid, and alkaline fuel cells. In the papers, PEMFC is considered for hydrogen and SOFC is considered for ammonia and methanol. In Paper I, the eMeOH in SOFC was not investigated due to the lack of data during the assessment. However, after preliminary modeling based on stoichiometric ratios and reviewing literatures, this option was later added in Paper II.

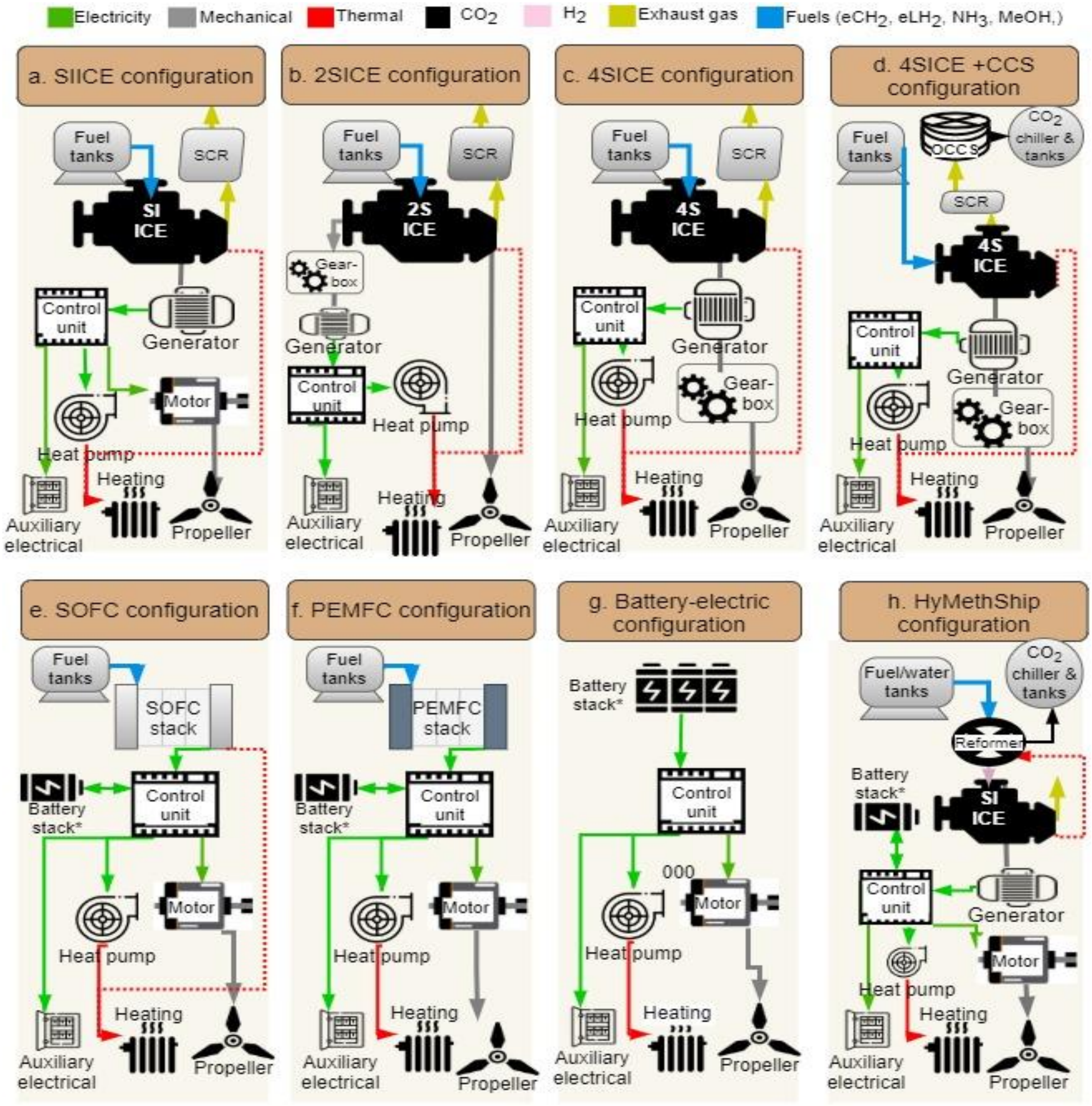


Figure 10: Onboard powertrain configurations covered in Paper I and Paper II for different energy carriers.

4.1.2. Supply chain of energy carrier

The reference fuel used in the assessment is fossil-based MGO which contains less than 0.1 percent sulfur by mass. The fuel supply chain for the energy carriers used in the assessed technological system is shown in Figure 11. Electricity is considered the base energy for the assessment of all fuels except for MGO. Electricity is used for four stages in the technological system: i) fuel production/liquefaction, ii) component production, iii) charging batteries for BE case, and iv) direct consumption while the vessel is docked. Several electricity scenarios are considered in the thesis. Electricity from wind power is considered a base case in Paper I and Paper II. Other cases include the electricity mixes considering 2030 as the time horizon. In Paper I, the sensitivity of electricity towards total impact due to different carbon intensities of electricity used is assessed. In Paper II, a scenario analysis with global build electricity margin is considered.

In both papers, E-hydrogen is considered to be produced by the electrolysis of water using electricity based on alkaline electrolysis (AEC). AEC is considered based on the technological scale-up model performed with literature data. Other emerging technologies for electrolysis are proton exchange membrane electrolysis (PEMEC), solid oxide electrolysis (SOEC), and anion exchange membrane. E-hydrogen is used directly as fuel and for feedstock for the production of eNH3 and eMeOH. The gaseous hydrogen which has a very low density and volumetric energy density is difficult to use due to supply chain issues and hence needed to compress (refers to compressed hydrogen (eCH2)) or liquefy it (refers to liquefied hydrogen (eLH2)).

E-ammonia (eNH3) can be produced using multiple pathways such as the Haber Bosch process, electrochemical process, photocatalytic, biological, and non-thermal plasma [69]. In both papers, it is considered that eNH_3 is produced using the Haber Bosch process using eH_2 and nitrogen. In both papers, it is considered that eMeOH is produced by CO_2 hydrogenation using catalytic conversion. E-methanol (eMeOH) can also be produced by using different process approaches such as catalytic conversion, thermo-chemical conversion, electrochemical, and photocatalysis [70]. Another important factor is the source of CO_2 in methanol production. Out of different possible technologies and sources of CO_2, the direct air capture technology by cyclic temperature-vacuum swing adsorption is considered in this thesis. DAC is considered as the source of carbon, and thus not based on fossil carbon. Another source of climate-neutral carbon would be from biogenic sources whose availability near the port where the production is assumed need to be assessed case to case basis. The CO_2 recirculation using an onboard carbon capture is assessed in Paper I as detailed in 4.1.1.

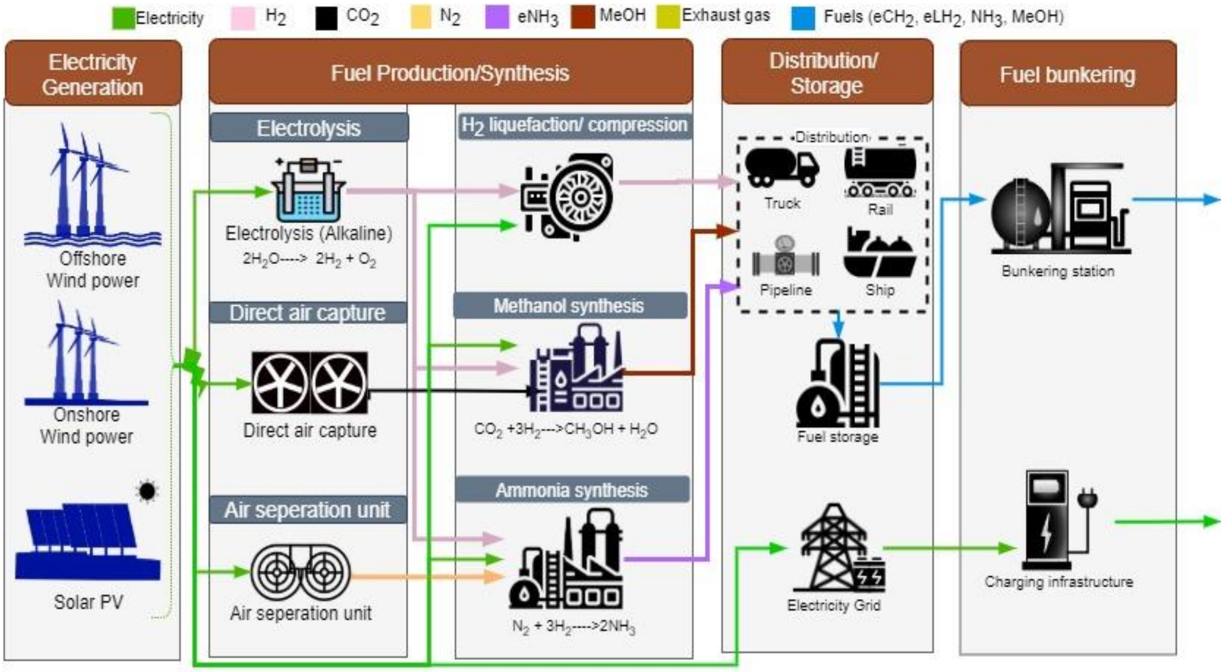
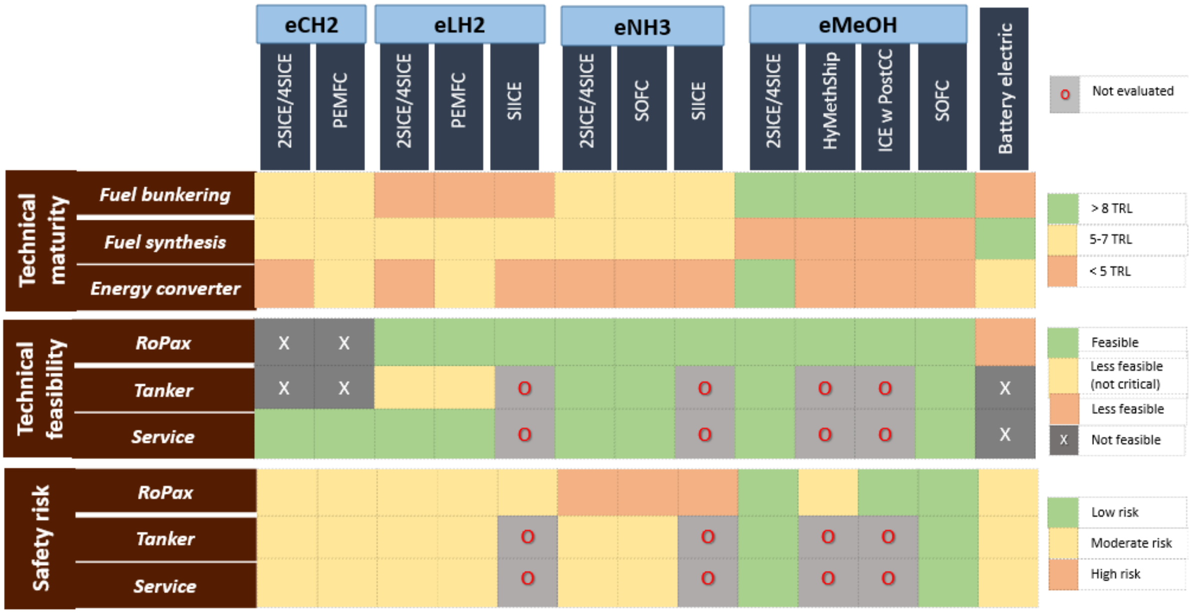


Figure 11: Fuel supply chain for the assessed technological system from electricity generation to fuel bunkering/charging.

4.1.3. Technical viability result

During the goal and scope definition, the emerging technologies within each technological system need to be assessed for the level of maturity for the scaling-up. Also, the technical viability of technological systems is assessed in Paper II for the case study vessels. The summary of the assessment of TRLs of different technologies, the technical feasibility of the system in vessels, and the risk assessment of safety evaluated in the appended papers is shown in Figure 12. It can be noted that these are summarized results where TRL of the least matured emerging technology in the supply chain is only shown (e.g., fuel synthesis category for methanol production includes several emerging technologies including electrolysis, methanol synthesis, and DAC).



		eCH2		eLH2			eNH3			eMeOH				
		2SICE/4SICE	PEMFC	2SICE/4SICE	PEMFC	SIICE	2SICE/4SICE	SOFC	SIICE	2SICE/4SICE	HyMethShip	ICE w PostCC	SOFC	Battery electric
Technical maturity	Fuel bunkering	🟨	🟨	🟧	🟧	🟧	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟧
	Fuel synthesis	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟩
	Energy converter	🟧	🟨	🟧	🟨	🟧	🟧	🟧	🟧	🟩	🟧	🟧	🟧	🟨
Technical feasibility	RoPax	X	X	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧
	Tanker	X	X	🟨	🟨	o	🟩	🟩	o	🟩	o	o	🟩	X
	Service	🟩	🟩	🟩	🟩	o	🟩	🟩	o	🟩	o	o	🟩	X
Safety risk	RoPax	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟩	🟨	🟩	🟩	🟨
	Tanker	🟨	🟨	🟨	🟨	o	🟨	🟨	o	🟩	o	o	🟩	🟨
	Service	🟨	🟨	🟨	🟨	o	🟨	🟨	o	🟩	o	o	🟩	🟨

o Not evaluated

🟩 > 8 TRL
🟨 5-7 TRL
🟧 < 5 TRL

🟩 Feasible
🟨 Less feasible (not critical)
🟧 Less feasible
X Not feasible

🟩 Low risk
🟨 Moderate risk
🟧 High risk

Figure 12: Technical assessment in terms of maturity of technologies, feasibility in vessels, and safety onboard.

For the feasibility assessment, the mass and volume of different components onboard in each technological system are compared with the reference technological system as described in Section 3.1.2. Different vessels have different levels of dimensional constraints, the tanker is more constrained on the mass whereas it is the volume that is critical for the RoPax and the service vessel.

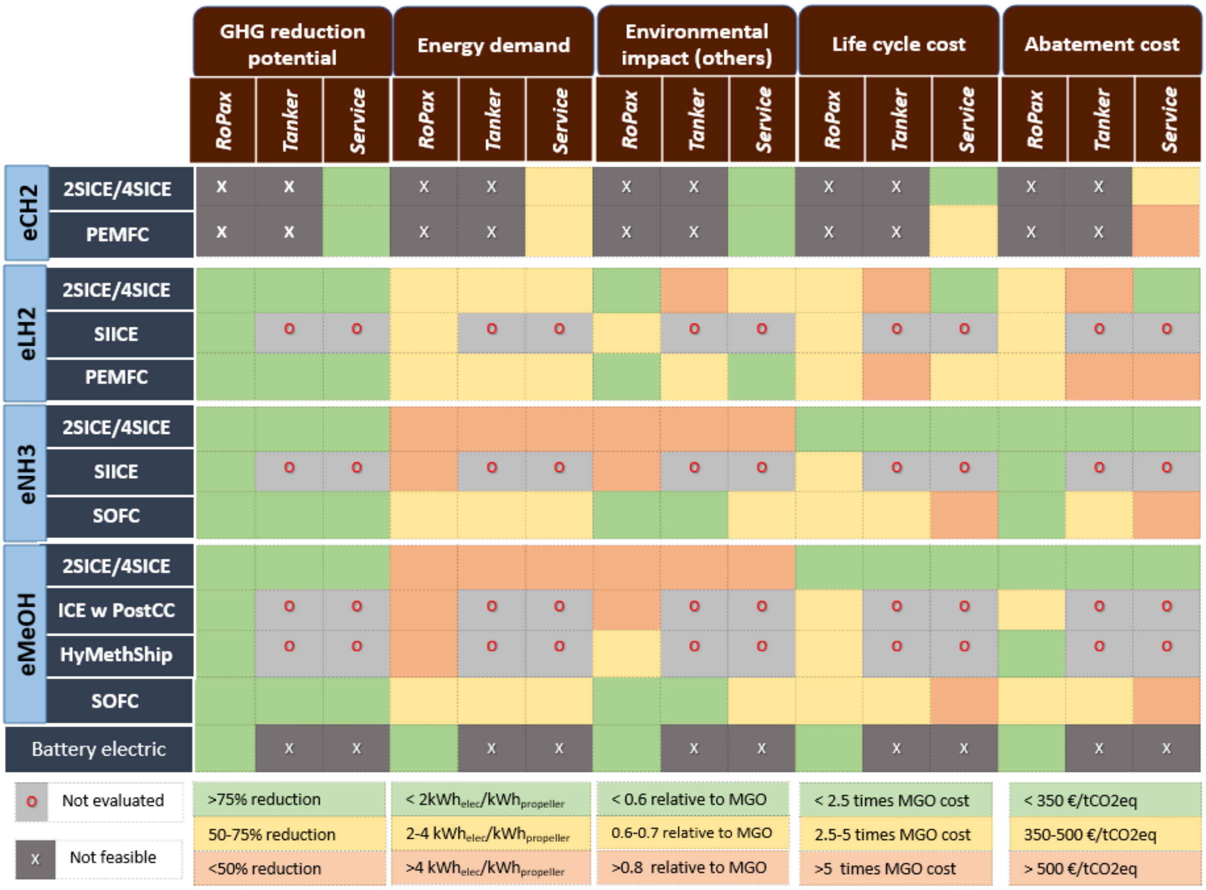
Regarding the safety assessment performed in Paper II, the concepts are deemed feasible with additional safety measures, such as gas detection, adaptations to fire detection and suppression, double-walled piping, ventilation in general, determination of safety distances for any venting in the case of 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. In the case of RoPax, the risk would be higher considering the possibility of NH_3 exposure to passengers.

4.2. Life cycle results

Life cycle results from Paper I and Paper II are summarized in Figure 13 showing the GHG reduction potential, energy demand, other environmental impacts (such as acidification, eutrophication, etc.), LCC, and CAC. The results from Paper I and Paper II are categorized into three scales based on relative values. The GWP100 values are compared using the percentage GHG reduction from the reference case. The results from the papers show that even considering GHG emissions from various phases from cradle to grave, all technological systems still have high GHG reduction potential. Except for the BE, for all other technological systems, the major factor that affects impact is the carbon intensity of electricity. For BE and FC options, manufacturing of battery stacks and FC stacks have relatively higher contributions towards total emissions. In Paper I, for SIICEs the GHG emissions are lesser compared to 4SICE/2SICE in Paper II as the emissions from fossil-based pilot fuel used in the latter has a significant contribution towards total emissions. However, due to the lower efficiency of SIICE, the impact related to fuel production is higher for this configuration. The scenario analysis performed in Paper II and sensitivity analysis in Paper I show that the GHG potential is highly dependent on the carbon intensity of the electricity mix used in the production.

The life cycle electricity demand for decarbonization pathways based on e-fuels is significantly high. This is due to energy losses linked with conversion during upstream (production of fuel) and downstream (conversion to work) steps. Among all options, eMeOH powered in the ICE pathway has the lowest energy conversion efficiency followed by the eNH3 powered in the ICE pathway. This makes eMeOH options more sensitive to the impacts of electricity than other options. This shows that a shift towards the e-fuels requires 2.5 to 3 times as much electricity as BE. This electricity demand is primarily driven by electrolysis. Hence, an energy transition of the shipping sector towards e-fuels will result in higher electricity demand and requires higher electricity generation capacity as well as infrastructure requirement for electricity transmissions.

It was also found from the LCA result that all assessed systems significantly reduce the impacts of acidification, ecotoxicity, eutrophication (except for NH_3 options), ionizing radiation, land use, ozone depletion, particulate matter, photochemical ozone formation, and resource consumption (fossil). Nonetheless, a number of impact categories, including human toxicity (cancer and non-cancer), water use, and resource use (minerals and metals), are negatively affected, more than for MGO. All the environmental impacts are converted to normalized values using normalization factors in the papers. To compare the environmental impacts (results from Paper I and Paper II) between options the normalized result is converted into an aggregated single score relative to the reference case (MGO powered in ICE). It can be noted that the major impacts are linked to electricity from wind power and are associated with the metals and minerals required for wind power infrastructure. FCs have better environmental performance compared to ICEs as they require less fuel for operation and clean electrochemical combustion. In ICEs, H_2 has a better performance compared to other e-fuels and eNH3 poses the highest risk followed by eMeOH. The results of Paper II show that the choice of fuel and propulsion technologies will be different for each vessel if the decision is taken in terms of total environmental impacts.



		GHG reduction potential			Energy demand			Environmental impact (others)			Life cycle cost			Abatement cost		
		RoPax	Tanker	Service	RoPax	Tanker	Service	RoPax	Tanker	Service	RoPax	Tanker	Service	RoPax	Tanker	Service
eCH2	2SICE/4SICE	x	x	🟩	x	x	🟨	x	x	🟩	x	x	🟩	x	x	🟨
	PEMFC	x	x	🟩	x	x	🟨	x	x	🟩	x	x	🟨	x	x	🟧
eLH2	2SICE/4SICE	🟩	🟩	🟩	🟨	🟨	🟨	🟩	🟧	🟨	🟨	🟧	🟩	🟨	🟧	🟩
	SIICE	🟩	o	o	🟨	o	o	🟨	o	o	🟨	o	o	🟨	o	o
	PEMFC	🟩	🟩	🟩	🟨	🟨	🟨	🟩	🟨	🟩	🟨	🟧	🟨	🟨	🟧	🟧
eNH3	2SICE/4SICE	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩
	SIICE	🟩	o	o	🟧	o	o	🟧	o	o	🟨	o	o	🟩	o	o
	SOFC	🟩	🟩	🟩	🟨	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟧	🟩	🟨	🟧
eMeOH	2SICE/4SICE	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩
	ICE w PostCC	🟩	o	o	🟧	o	o	🟧	o	o	🟨	o	o	🟨	o	o
	HyMethShip	🟩	o	o	🟧	o	o	🟨	o	o	🟨	o	o	🟩	o	o
	SOFC	🟩	🟩	🟩	🟨	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟧	🟨	🟨	🟧
Battery electric		🟩	x	x	🟩	x	x	🟩	x	x	🟩	x	x	🟩	x	x

		GHG reduction potential	Energy demand	Environmental impact (others)	Life cycle cost	Abatement cost
o	Not evaluated	🟩 >75% reduction	🟩 < 2kWh$_{elec}$/kWh$_{propeller}$	🟩 < 0.6 relative to MGO	🟩 < 2.5 times MGO cost	🟩 < 350 €/tCO2eq
		🟨 50-75% reduction	🟨 2-4 kWh$_{elec}$/kWh$_{propeller}$	🟨 0.6-0.7 relative to MGO	🟨 2.5-5 times MGO cost	🟨 350-500 €/tCO2eq
x	Not feasible	🟧 <50% reduction	🟧 >4 kWh$_{elec}$/kWh$_{propeller}$	🟧 >0.8 relative to MGO	🟧 >5 times MGO cost	🟧 > 500 €/tCO2eq

Figure 13: Summary of results from pLCA and LCC detailed in Paper I and Paper II in relation to the reference MGO case.

Regarding LCC results, the LCC shows that the major cost is associated with the fuel price for all technological systems except for batteries. The fuel cost is calculated along with LCA assessment considering interdependencies between inventory parameters and electricity price. For batteries, the major cost is associated with the investment cost related to the battery system and the replacement required during the vessel's service life. Fuel cost is sensitive to electricity cost, hence the LCC cost will depend on the overall electricity demand (i.e., when the electricity cost increases, eMeOH in ICE will have a higher increase in cost than other options). Distribution and bunkering cost is high for the hydrogen option and BE as the infrastructure required is complex for these energy carriers. At higher electricity costs, FCs would be more competitive than ICEs. In Paper II, among decarbonization options for different ship types, eNH3 followed by eMeOH when used in the ICE has the lowest cost. Cost between different technological systems varies drastically between the ship types, this is mainly associated with the annual energy consumption, installed capacity, and utilization rates. The effect of utilization rate can be observed clearly in the results of service vessels, where the capital cost related to the component is prominent resulting in a higher cost for fuel cell and battery options. The same trend can be observed in the CAC results from both papers.

5. Discussion

The aim of this thesis has been to increase life cycle knowledge of decarbonization pathways for shipping from an energy, environmental, and cost perspective. The earlier life cycle studies (mentioned in Table 2) have not considered the prospective modeling approach for the emerging pathways and used different system boundaries. In previous studies, LCA and LCC are evaluated independently making it difficult to compare the results. This chapter begins with a discussion regarding the method developed and used in this thesis for answering RQ1. The discussion then proceeds with examining the results of the papers critical to answering RQ2 and RQ3. The discussion concludes with the learnings from this thesis.

5.1. RQ1: Integrated cost and environmental assessment.

RQ1 is intended to describe and clarify the method used for the life cycle evaluation of the decarbonization pathways in the shipping sector integrating LCA and LCC. The ILCF (Integrated life cycle framework) was developed and used in this thesis by integrating LCA and LCC along with other tools to ensure the life cycle evaluation of energy, environmental, and economic performance in a consistent way. The ILCF introduced in this thesis contributes to the knowledge of life cycle methodology to better comprehend evaluating emerging technologies in the transportation sector. The ILCF gives a methodological guideline on how and where different external approaches can be used so that specific challenges are addressed. By offering guidance on the assessment process, ILCF helps to overcome challenges for performing LCA of complex emerging technological systems and also overcome the methodological challenges of integrated evaluation of cost and environmental impacts. 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 establishing the entire set of assumptions at once. Any inconsistencies and discrepancies can be noted in the early stage of evaluation. Defining the technological system at the goal and scope definition stage ensures same processes/technologies are used in the selection of energy, material, and cost inventories. The ILCF is applied in both Paper I and Paper II.

The selection of functional units poses a challenge for 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 the vessel that is transporting the cargo or passengers. This makes it difficult to assess the impact on the function of the vessel during the transition toward the decarbonization pathway. Some of the technological options would occupy more space from cargo or passengers for the same trip length than others, which results in a reduction of transport work that can be performed with the vessel (indicating less cargo/passenger can be moved). In Paper II, the functional unit was selected in terms of transport work in addition to the annual operation. However, the reduction in the transport work was not performed in the paper as data on the weight and space of cargo/passenger is required for detailed assessment. Instead, technical feasibility was performed thereby restricting the choice of technological option depending on the space available for powertrain components.

Defining the system boundary is another challenge in comparability. Paper I and Paper II were consistent in the definition of system boundaries for both LCA and LCC, however, the approach while assessing parameters of foreground and background systems differs between methods. This difference is mainly because of the difference in the properties of inventory/flow. In cost inventories, the final cost flow represents all the upstream flow 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 need not be aggregated. However, for material and energy flows, all upstream flows need to be aggregated while evaluating the environmental impact. Similarly, both papers have considered discount rates for capital equipment considering the owners' perspective that the time of investment is important. This is a challenge in the integration, as the life cycle evaluation follows a steady state process, and including a discount rate only for the cost can cause discrepancies while interpreting both results together.

In the inventory assessment phase, consistency in selecting parameters like efficiencies, energy use, and material consumption for each technology/process is important for both LCC and LCA evaluation without discrepancies. However, 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 [34]. Hence, the scale-up of the environmental parameters and cost parameters need not be in relation to each other during the scenario modeling in the inventory assessment phase. In the two papers, predicting scenario method is used for the scale-up. One of the key challenges in predictive scenario modeling is the availability and quality of data. In the appended papers of this thesis, data is collected by conducting expert interviews, literature reviews, and modeling. Technical parameters of new technologies that will fit into the background system also need to be checked. These technical aspects are not integrated into the ILCF and have to be performed separately. The LCA and LCC results won’t provide information on the technological feasibility for the decision maker. As mentioned before, the technical viability tool in Paper II is used to check the feasibility of the technological system in case study ships.

In the impact assessment and interpretation phase, the integrated evaluation and integrated indicator of the environmental and economic results would make it easier to find the trade-offs between them. In this thesis and appended papers, CAC is used as an integrated indicator that compares the cost of technical options with the climate impact. This indicator helps the decision maker to understand the economic trade-offs of different options in relation to climate impact reduction. For example, it helps to quantify the extent of policy measures like a carbon tax to compete with fossil fuel options. In this thesis, the framework is used for ships that can be extended to other transport sectors without hassle.

During interpretation, 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 14, with higher electricity prices, SOECs are preferred. In this thesis, the influence of external parameters during scale-up is not included. How such factors can be integrated is not very clear and need to be studied further. Furthermore, the following difficulties are not currently being addressed by the ILCF but need to be looked at, as e.g.,:

1) In case of an allocation issue where the activities or flows are shared between different product systems, as integration assessment of both cost and impacts are considered whether the economic allocation principle should be used or whether other allocation principles would fit in the integrated assessment?

2) How the characterization factors would change in the future?

3) The dynamic changes in the technological system over time as the technological system would be in operation for decades, and

4) The possibility of a new environmental problem is not known now. One such indicator may be marine ecotoxicity similar to freshwater ecotoxicity which would be relevant for ships.

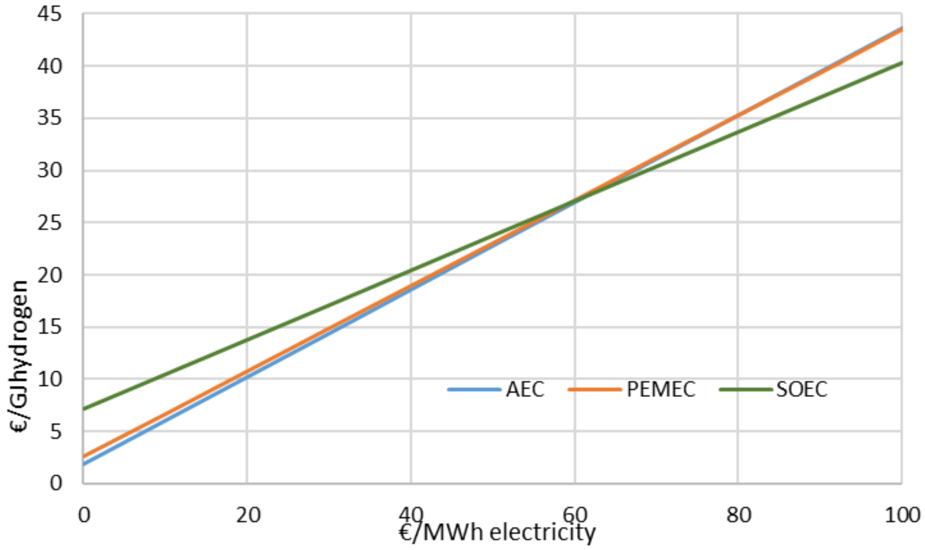


Figure 14: The influence of electricity price in the selection of electrolyzer, expressed as €/GJ hydrogen produced.

5.2. RQ2: life cycle environmental impacts

In this section, the RQ2 regarding the environmental impacts of different decarbonization pathways is discussed. The technological system defined for the different decarbonization pathways is assessed from cradle to grave in Paper I and Paper II. There is potential for all technological systems to decarbonize the shipping sector from a life cycle perspective.

However, this reduction potential is highly sensitive to the carbon intensity of the electricity used for fuel production. So, it is important to ensure that the electricity used in e-fuel production has low carbon intensity for reducing the climate impact of shipping. This sensitivity is inversely proportional to the energy conversion efficiency of the given pathway. That is the increase in the total GWP with GHG intensity of the electricity mix will be higher for the pathway with lower energy conversion efficiency. Based on the assumptions used in our thesis, all assessed methanol options have the lowest conversion efficiency.

The variation between decarbonization pathways depends on several factors. For the BE option, together the manufacturing and replacement of batteries contribute more to the impact than the energy carrier itself. For FC the impact from the manufacturing and replacement is lower than for the BE case, however, these emissions cannot be avoided. This shows the importance of choosing the system boundary from cradle to grave rather than WTW. As most of the studies performed have system boundaries, comparing the results of studies are different. For ICE, fossil-based diesel as pilot fuel is having 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. In addition, the combustion properties of different fuels also influence the reduction potential, among assessed fuels formation of N_2O is highly likely while combusting eNH3 due to the presence of nitrogen atoms in the fuel. As N_2O is a stronger GHG than methane and CO_2. Hence, it is important to regulate the emission of N_2O from the engine using some abatement method like SCR. Presently, more knowledge is required on the amount of N_2O emissions from NH_3 ICEs (emerging technology) and how it can be abated using SCR. Both shifting the fossil-based pilot fuel to bio-based and abatement technologies come with some cost that should be included in integrated assessments.

Although switching to e-fuel from MGO has many positive environmental effects (less acidification, less PM, etc.), there are tradeoffs in other environmental impacts (human toxicity, resource use, etc.). These impacts mainly come due to the materials used in wind farms, electrolyzers, fuel cells, or batteries. The possibility of reducing such impacts may be investigated further e.g., how a higher share of recycled materials in the infrastructure and components can reduce such impacts. Another example is the impacts related to the use of eNH3ICE that results in higher eutrophication potential, which may require special attention for ships operating in emission control areas like the Baltic Sea. 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.

5.3. RQ3: Life cycle evaluation of different vessels

In RQ2 the main discussion was regarding the environmental impacts pertaining to the different decarbonization pathways, in RQ3 the discussion focused on changes in environmental impact and cost of decarbonization pathways with the vessel type and their operation. 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. This difference is mainly due to the energy conversion efficiencies, electricity cost, complexity in bunkering, propulsion system utilization rate, installed capacity, and fuel required between bunkering. Hence it is important with ship specific LCAs and LCCs.

Energy conversion efficiency upstream along with the infrastructure cost determines the cost of the fuel which is the main element for all e-fuel-based decarbonization pathways. The fuel cost is sensitive to the electricity cost and the sensitivity depends on the energy conversion efficiency. On the other hand, the bunkering cost is higher for the electricity and hydrogen options (which have higher upstream efficiency) which depends on the property of the energy carrier.

The onboard system in the vessel depends on three parameters:
1) Installed capacity determines the size of the energy converter required onboard.
2) energy between bunkering which determines the size of the storage tanks/batteries onboard, and
3) utilization rate which represents the amount of energy that is consumed during the operation.

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 FC is a significant part of the total life cycle cost. This also affects the environmental impacts linked with the manufacturing and replacement of fuel cells. The second parameter regarding the energy between bunkering is important for hydrogen and BE due to lower energy density and higher cost of storage (i.e., higher energy required between bunkering means larger energy storage is required). Both hydrogen storage and batteries have a higher impact on cost and environmental impact compared to other options.

The utilization rate is not a well-defined term. In Paper II, it is suggested to formulate the utilization rate as the amount of energy consumed annually per kW of installed capacity. Such formulation helps to understand how effectively the installed energy converter capacity is used. In an earlier study [71], utilization rate considered only the time at sea, this won't specify the engine loads during the operation. 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 FCs. Also, if the fuel cost is higher then again lower fuel consumption can compensate for the higher cost of investment for fuel cells. Hence, the choice of the propulsion system and the fuel may be analyzed individually for each vessel would be ideal before making a choice of decarbonization pathway. It can be noted that the above-mentioned scenarios favor BE more than FC as the overall energy demand is least for BE provided it is technically feasible. Utilization rates can be increased using a hybrid configuration between FCs and batteries as proposed in long-distance trucks [72].

The vessels operating on shorter routes with the possibility of frequent bunkering and higher utilization rates favor battery and hydrogen due to lower energy storage requirements onboard. One of the challenges associated with charging batteries or bunkering hydrogen is that these processes are time-consuming and complex.

5.4. Learning outcomes

Life cycle analysis at an early stage of transition gives an understanding of the bottlenecks in the decarbonization pathways, parameters that are sensitive to the performance, and the factors that can influence the decision in the future. Identifying such parameters and factors increases the knowledge of the system as well as developing tools and approaches for monitoring it. For example, CAC was added to the assessment to understand the tradeoffs between climate impact and cost which was used as a combined indicator and can help with decision-making.

Another insight is the importance of integrated assessment starting from the first phase (goal and scope definition). In Paper I, the cost and environment assessments were not integrated from the first stage during the initial assessment which resulted in discrepancies in the data and results. That is, the cost of fuels is adopted from other studies that used different system boundaries. Then the integration was performed during the second iteration. During iterations, the system boundaries were further developed. This helped in a better choice of technology and also integrating calculation of fuel costs along with the calculation of impact from fuel production. Often such changes in the later stages are difficult as the assessments are data and time intensive. In Paper II, the initial choices are made based on these insights which reduced the number of iterations required.

The most important part of the LCA and LCC methodology is the choice of functional unit, system boundary, transparency and consistency in the data inventory, and choice of impact categories. The choice of the functional unit is important to capture the actual function of the system under assessment. For ships, the functions vary between types but may be generalized based on the weight (DWT) or volume (GT) available for performing the function. Choosing another functional unit such as engine output won't be representative as neither the downstream efficiencies are captured in the assessment nor the variation in the function. In Paper I, functional unit round trip was considered which was not capturing the actual function of the RoPax which is the passenger and vehicle carrying capacity. Considering this in Paper II functional unit per GT-km was also added. However, due to the unavailability of details like loading capacity and ballast water level during operation, the effect of volume and weight changes was not included in the assessment.

The choice of system boundary can give a different indication of results, as highlighted in the earlier section. The WTW analysis of the options does not reflect the complexities and impacts involved in the storage tanks and conversion technologies onboard. Also, a cradle-to-grave analysis gives better insight into the burden-shifting, e.g., the use of FCs and batteries results in more resource use (minerals and metals) than other options. Differences in the system boundaries between studies also make it difficult to compare the results.

The life cycle results depend on the data used and underlying assumptions. This can be clearly visible in the results of Paper I and Paper II where the difference in two assumptions changed the results. The first change is the selection of the dataset for energy, Paper I used the Ecoinvent dataset for the carbon intensity of wind power (assumed 25gCO_2eq/kWh), whereas Paper II used the Sphera dataset (around 9 gCO_2eq/kWh). Second, an engine configuration that does not require pilot fuel was not considered in Paper I, whereas fossil-based pilot fuel was considered in Paper II. So, transparency in the underlying dataset is important while publishing a life cycle study. The consistency between the cost and other parameters also should be in line with understanding actual tradeoffs. Choice of impact categories, again in Paper I, fewer impact categories were considered, e.g., impact category resource use (minerals and metals) which was found to be important in Paper II was not considered in Paper I.

Three approaches are used to assess the robustness of the results and consider the impact of possible future development, i.e., sensitivity analysis, scenario analysis, and uncertainty analysis. The uncertainty analysis was performed using Monte-Carlo simulation with uniform distribution of the range of parameters predicted in different development pathways. Sensitivity analysis is performed to evaluate the relevance of the electricity mix in LCA results. The scenario analysis on various charging strategies for BE was assessed in Paper I. Several other possibilities could be checked but only selected parameters are considered because of the lack of data. This analysis to check the robustness of the result also helps to identify parameters that can have a significant effect on the result (e.g., N_2O emission for NH_3 engines has a higher impact on climate change and NH_3 slip has a higher impact on eutrophication)

6. Conclusion

This thesis has evaluated different decarbonization pathways and a framework is formulated in order to perform a combined economic and environmental assessment.

The main conclusions related to this integrated life cycle framework are:

- To include the interdependencies between the cost and environment parameters, the use of an integrated life cycle framework similar to what was developed during the thesis is important.
- Such frameworks can provide practitioners with step-by-step guidance through the four phases of LCA methodology in order to overcome the difficulties associated with evaluating emerging technologies.
- Integration of the method may include defining functional units, setting up system boundaries, modeling foreground and background processes, scaling up emerging technologies, checking the robustness of results, and finally including integrated indicators like carbon emission abatement cost.

Using the framework, the thesis has performed detailed environmental and economic assessments of different decarbonization pathways based on e-fuels and direct electrification using batteries from a life cycle perspective. The main conclusions regarding the environmental impact are:

- All the options have a high potential for reducing GHG emissions if the electricity comes from wind or low-carbon-intensity energy sources. Also, fuel cells have the highest reduction potential if the same energy carrier is considered.
- In addition to the climate impact, these options also seem to reduce several other environmental impacts like acidification, ecotoxicity, eutrophication (except for NH_3 options), ionizing radiation, land use, ozone depletion, particulate matter, photochemical ozone formation, and resource use (fossil).
- The above benefits come with a tradeoff, i.e., it can lead to an increase in some other impact categories including human toxicity (cancer, non-cancer), water use, and resource use (minerals and metals).
- To use ammonia in engines, it is critical to control the leakage/slip of the ammonia, and the emissions of nitrogen oxides which contribute to eutrophication and emission of nitrous oxides which have a high impact on climate.

This thesis has also analyzed the environmental and economic impacts from a life cycle perspective for the different ship types. The main conclusion from the results is as follows:

- Feasibility of the decarbonization pathways varies with the ship type and major factor being the volumetric and gravimetric energy density of the fuel along with the energy needed between bunkering and the installed capacity of energy carriers.

- For all ship types, ammonia in dual-fuel engines followed by methanol in dual-fuel engines seem to have the lowest life cycle cost. However, these systems have higher energy conversion losses making them more sensitive to the electricity cost. Also, these options have higher environmental impacts on most of the categories other than climate impact compared to other assessed pathways.
- The higher capital cost and shorter lifetime for fuel cells and batteries have a significant effect on the cost competitiveness of these technologies. However, if the utilization rate and cost of fuels are high, these choices may become more cost-competitive than engines.

7. Future work

There are additional questions and directions that this thesis can lead to, which could be investigated in subsequent research, including but not limited to the following:

- One of the alternative fuels discussed as a possibility of transition fuels is blue fuels. It would be important to conduct a similar evaluation for blue fuels in relation to the shipping industry with the help of the integrated life cycle assessment framework. This will make it possible to increase our knowledge about using blue fuels in the shipping sector and allows for decision-making that can avoid unnecessary environmental burdens and cut costs.

- As shown in this thesis, the transition towards the decarbonization of the shipping sector won't be uniform for all ships. Hence, the proportion of each fuel used in a fleet will be different and depends on vessel operation and types in the fleet. For understanding the requirements of the supply chain, port infrastructure, etc., knowledge about how different fuels will develop and be introduced is required. Integrating additional tools such as modeling global energy systems with life cycle framework may allow drawing future scenarios of energy carriers for fleets level transition.

- With the use of e-fuels in future transformation scenarios for shipping, there would be a higher demand for electricity and natural resources including critical materials in the fuel supply chain which need to compete with other sectors. In future work, it would be interesting to anticipate how the future transition of shipping will affect the demand for electricity and essential raw materials.

- The transition towards decarbonization comes with additional costs. It is required to investigate how various policies and market-based measures will affect the transition in the shipping sector toward decarbonization.

References

[1] International Maritime Organization, "Reduction of GHG emissions from Ships: Fourth IMO GHG Study 2020," International Maritime Organization, London, 2021.

[2] K. Andersson, S. Brynolf, F. Lindgren, and M. Wilewska-Bien, *Shipping and the Environment : Improving Environmental Performance in Marine Transportation*, 1st ed. Berlin, Heidelberg: Springer Berlin Heidelberg : Imprint: Springer,, 2016, pp. 1 online resource (XXIII, 426 pages 77 illustrations, 49 illustrations in color.

[3] I. M. Organization. "IMO: Nitrogen Oxides (NOx) – Regulation 13." https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx (accessed 22 October, 2021).

[4] M. E. P. C. (MEPC). "Marine Environment Protection Committee (MEPC) - 79th session, 12-16 December 2022." IMO. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-79th-session.aspx (accessed 02 Jan, 2023).

[5] C. o. t. EU;, "Fit for 55 package: Council adopts its position on three texts relating to the transport sector," D. Mammonas, Ed., ed: The European Council, 2022.

[6] I. M. Organization;. "IMO action to reduce greenhouse gas emissions from international shipping." https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/IMO%20ACTION%20TO%20REDUCE%20GHG%20EMISSIONS%20FROM%20INTERNATIONAL%20SHIPPING.pdf (accessed 18 May, 2021).

[7] Z. Wan, A. El Makhloufi, Y. Chen, and J. Tang, "Decarbonizing the international shipping industry: Solutions and policy recommendations," *Mar Pollut Bull,* vol. 126, pp. 428-435, Jan 2018, doi: 10.1016/j.marpolbul.2017.11.064.

[8] S. Bullock, J. Mason, J. Broderick, and A. Larkin, "Shipping and the Paris climate agreement: a focus on committed emissions," *BMC Energy,* vol. 2, no. 1, 2020, doi: 10.1186/s42500-020-00015-2.

[9] E. Lindstad, "Fuels and engine technologies with focus on GHG and Energy Utilization," Smart Maritime, Trondheim, Norway, 14 April 2020 2020. [Online]. Available: http://www.smartmaritime.no/documentation/publications/research-reports/fuels-and-engine-technologies-with-focus-on-ghg-and-energy-utilization/

[10] E. Lindstad, B. Lagemann, A. Rialland, G. M. Gamlem, and A. Valland, "Reduction of maritime GHG emissions and the potential role of E-fuels," *Transportation Research Part D: Transport and Environment,* vol. 101, 2021, doi: 10.1016/j.trd.2021.103075.

[11] B. Stolz, M. Held, G. Georges, and K. Boulouchos, "Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe," *Nature Energy,* vol. 7, no. 2, pp. 203-212, 2022, doi: 10.1038/s41560-021-00957-9.

[12] S. Cucurachi, C. van der Giesen, and J. Guinée, "Ex-ante LCA of Emerging Technologies," *Procedia CIRP,* vol. 69, pp. 463-468, 2018, doi: 10.1016/j.procir.2017.11.005.

[13] R. Arvidsson *et al.*, "Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA," *Journal of Industrial Ecology,* vol. 22, no. 6, pp. 1286-1294, 2018, doi: https://doi.org/10.1111/jiec.12690.

[14] G. Thomassen, M. Van Dael, S. Van Passel, and F. You, "How to assess the potential of emerging green technologies? Towards a prospective environmental and techno-economic assessment framework," *Green Chemistry,* vol. 21, no. 18, pp. 4868-4886, 2019, doi: 10.1039/c9gc02223f.

[15] J.-M. Rödger, L. L. Kjær, and A. Pagoropoulos, "Life Cycle Costing: An Introduction," in *Life Cycle Assessment*, 2018, ch. Chapter 15, pp. 373-399.

[16] J. Wunderlich, K. Armstrong, G. A. Buchner, P. Styring, and R. Schomäcker, "Integration of techno-economic and life cycle assessment: Defining and applying integration types for chemical technology development," *Journal of Cleaner Production,* vol. 287, 2021, doi: 10.1016/j.jclepro.2020.125021.

[17] J. H. Miah, S. C. L. Koh, and D. Stone, "A hybridised framework combining integrated methods for environmental Life Cycle Assessment and Life Cycle Costing," *Journal of Cleaner Production,* vol. 168, pp. 846-866, 2017, doi: 10.1016/j.jclepro.2017.08.187.

[18] F. M. Kanchiralla, S. Brynolf, E. Malmgren, J. Hansson, and M. Grahn, "Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping," *Environ Sci Technol,* vol. 56, no. 17, pp. 12517-12531, Sep 6 2022, doi: 10.1021/acs.est.2c03016.

[19] F. E. Ltd;, "Future Fuels: FVV Fuels Study IV," Frankfurt, 2021.

[20] H. K. Jeswani, A. Chilvers, and A. Azapagic, "Environmental sustainability of biofuels: a review," *Proc Math Phys Eng Sci,* vol. 476, no. 2243, p. 20200351, Nov 2020, doi: 10.1098/rspa.2020.0351.

[21] C. Azar, "Biomass for energy: a dream come true…or a nightmare?," *Wiley Interdisciplinary Reviews: Climate Change,* vol. 2, no. 3, pp. 309-323, 2011, doi: 10.1002/wcc.109.

[22] D. J. A. Johansson and C. Azar, "A scenario based analysis of land competition between food and bioenergy production in the US," *Climatic Change,* vol. 82, no. 3-4, pp. 267-291, 2007, doi: 10.1007/s10584-006-9208-1.

[23] E. Malmgren, "Towards sustainable shipping: Evaluating the environmental impact of electrofuels " Licentiate of Philosophy, Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden, 2021:17, 2021.

[24] B. Carlsson, S. Jacobsson, M. Holmén, and A. Rickne, "Innovation systems: analytical and methodological issues," *Research Policy,* vol. 31, pp. 233–245, 2002.

[25] A. Bergek, S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne, "Analyzing the functional dynamics of technological innovation systems: A scheme of analysis," *Research Policy,* vol. 37, no. 3, pp. 407-429, 2008, doi: 10.1016/j.respol.2007.12.003.

[26] *ISO 14044: 2006, Environmental management — Life cycle assessment,* International Organization for Standardization, 2006.

[27] S. Valdivia, C. M. L. Ugaya, J. Hildenbrand, M. Traverso, B. Mazijn, and G. Sonnemann, "A UNEP/SETAC approach towards a life cycle sustainability assessment—our contribution to Rio+20," *The International Journal of Life Cycle Assessment,* vol. 18, no. 9, pp. 1673-1685, 2012, doi: 10.1007/s11367-012-0529-1.

[28] C. van der Giesen, S. Cucurachi, J. Guinée, G. J. Kramer, and A. Tukker, "A critical view on the current application of LCA for new technologies and recommendations for improved practice," *Journal of Cleaner Production,* vol. 259, 2020, doi: 10.1016/j.jclepro.2020.120904.

[29] A. C. Hetherington, A. L. Borrion, O. G. Griffiths, and M. C. McManus, "Use of LCA as a development tool within early research: challenges and issues across different sectors," *The International Journal of Life Cycle Assessment,* vol. 19, no. 1, pp. 130-143, 2013, doi: 10.1007/s11367-013-0627-8.

[30] N. Thonemann, A. Schulte, and D. Maga, "How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance," *Sustainability,* vol. 12, no. 3, 2020, doi: 10.3390/su12031192.

[31] S. M. Moni, R. Mahmud, K. High, and M. Carbajales - Dale, "Life cycle assessment of emerging technologies: A review," *Journal of Industrial Ecology,* vol. 24, no. 1, pp. 52-63, 2019, doi: 10.1111/jiec.12965.

[32] R. Mahmud, S. M. Moni, K. High, and M. Carbajales-Dale, "Integration of techno-economic analysis and life cycle assessment for sustainable process design – A review," *Journal of Cleaner Production,* vol. 317, 2021, doi: 10.1016/j.jclepro.2021.128247.

[33] *ISO 15686-5: 2017, Buildings and constructed assets — Service life planning* International Organization for Standardization, 2017. [Online]. Available: https://www.iso.org/standard/61148.html

[34] W. T. França, M. V. Barros, R. Salvador, A. C. de Francisco, M. T. Moreira, and C. M. Piekarski, "Integrating life cycle assessment and life cycle cost: a review of environmental-economic studies," *The International Journal of Life Cycle Assessment,* vol. 26, no. 2, pp. 244-274, 2021, doi: 10.1007/s11367-020-01857-y.

[35] J. A. Bergerson *et al.*, "Life cycle assessment of emerging technologies: Evaluation techniques at different stages of market and technical maturity," *Journal of Industrial Ecology,* vol. 24, no. 1, pp. 11-25, 2019, doi: 10.1111/jiec.12954.

[36] S. Van Schoubroeck *et al.*, "An integrated techno-sustainability assessment (TSA) framework for emerging technologies," *Green Chemistry,* vol. 23, no. 4, pp. 1700-1715, 2021, doi: 10.1039/d1gc00036e.

[37] S. Brynolf *et al.*, "Nordic Roadmap Publication No.1-C/1/2022," 2022.

[38] M. Perčić, N. Vladimir, and A. Fan, "Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: A case study of Croatia," *Applied Energy,* vol. 279, 2020, doi: 10.1016/j.apenergy.2020.115848.

[39] M. Percic, I. Ancic, and N. Vladimir, "Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector," (in English), *Renew Sust Energ Rev,* vol. 131, Oct 2020. [Online]. Available: <Go to ISI>://WOS:000565621200008.

[40] L. Law, B. Foscoli, E. Mastorakos, and S. Evans, "A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost," *Energies,* vol. 14, no. 24, 2021, doi: 10.3390/en14248502.

[41] Y. Bicer and I. Dincer, "Clean fuel options with hydrogen for sea transportation: A life cycle approach," *International Journal of Hydrogen Energy,* vol. 43, no. 2, pp. 1179-1193, 2018/01/11/ 2018, doi: https://doi.org/10.1016/j.ijhydene.2017.10.157.

[42] Y. Bicer and I. Dincer, "Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: A comparative evaluation," *International Journal of Hydrogen Energy,* vol. 43, no. 9, pp. 4583-4596, 2018, doi: 10.1016/j.ijhydene.2017.07.110.

[43] A. Fan, J. Wang, Y. He, M. Perčić, N. Vladimir, and L. Yang, "Decarbonising inland ship power system: Alternative solution and assessment method," *Energy,* vol. 226, p. 120266, 2021.

[44] A. Fernández-Ríos *et al.*, "Environmental sustainability of alternative marine propulsion technologies powered by hydrogen-a life cycle assessment approach," *Science of the Total Environment,* vol. 820, p. 153189, 2022.

[45] P. Gilbert, C. Walsh, M. Traut, U. Kesieme, K. Pazouki, and A. Murphy, "Assessment of full life-cycle air emissions of alternative shipping fuels," *Journal of Cleaner Production,* vol. 172, pp. 855-866, 2018/01/20/ 2018, doi: https://doi.org/10.1016/j.jclepro.2017.10.165.

[46] J. Ling-Chin and A. P. Roskilly, "A comparative life cycle assessment of marine power systems," *Energy Conversion and Management,* vol. 127, pp. 477-493, 2016.

[47] B. Jeong, H. Jeon, S. Kim, J. Kim, and P. Zhou, "Evaluation of the lifecycle environmental benefits of full battery powered ships: Comparative analysis of marine diesel and electricity," *Journal of Marine Science and Engineering,* vol. 8, no. 8, p. 580, 2020.

[48] L. C. Law, B. Foscoli, E. Mastorakos, and S. Evans, "A comparison of alternative fuels for shipping in terms of lifecycle energy and cost," *Energies,* vol. 14, no. 24, p. 8502, 2021.

[49] E. Lindstad, B. Lagemann, A. Rialland, G. M. Gamlem, and A. Valland, "Reduction of maritime GHG emissions and the potential role of E-fuels," *Transportation Research Part D: Transport and Environment,* vol. 101, p. 103075, 2021.

[50] E. Malmgren, S. Brynolf, E. Fridell, M. Grahn, and K. Andersson, "The environmental performance of a fossil-free ship propulsion system with onboard carbon capture–a life cycle assessment of the HyMethShip concept," *Sustainable Energy & Fuels,* vol. 5, no. 10, pp. 2753-2770, 2021.

[51] N. V. Menon and S. H. Chan, "Technoeconomic and environmental assessment of HyForce, a hydrogen-fuelled harbour tug," *International Journal of Hydrogen Energy,* vol. 47, no. 10, pp. 6924-6935, 2022.

[52] B. Mestemaker, H. van den Heuvel, and B. Gonçalves Castro, "Designing the zero emission vessels of the future: Technologic, economic and environmental aspects," *International Shipbuilding Progress,* vol. 67, no. 1, pp. 5-31, 2020.

[53] M. Perčić, N. Vladimir, I. Jovanović, and M. Koričan, "Application of fuel cells with zero-carbon fuels in short-sea shipping," *Applied Energy,* vol. 309, p. 118463, 2022.

[54] M. Perčić, I. Ančić, and N. Vladimir, "Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector," *Renewable and Sustainable Energy Reviews,* vol. 131, p. 110028, 2020/10/01/ 2020, doi: https://doi.org/10.1016/j.rser.2020.110028.

[55] European Commission - Joint Research Centre, "International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance," Institute for Environment and Sustainability,, Luxembourg, 2010.

[56] IEA, "World energy outlook 2022 " 2022.

[57] European Commission, "EU Reference Scenario 2020- Energy. transport and GHG emissions trends to 2050," European Commission, Brussels, 2021.

[58] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology," *The*

International Journal of Life Cycle Assessment, vol. 21, no. 9, pp. 1218-1230, 2016/09/01 2016, doi: 10.1007/s11367-016-1087-8.
[59] Sphera, "GaBi Databases & Modelling Principles 2022," 2022.
[60] I. AR6, "Climate Change 2021: The Physical Science Basis. Sixth Assessment Report of the Intergovernmental Panel on Climate Change ", 2021.
[61] L. Zampori and P. rana, "Suggestions for updating the Product Environmental Footprint (PEF) method, EUR 29682 EN," Luxembourg, 2019.
[62] H. Baumann and A.-M. Tillman, *The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application*. Lund, Sweden: Studentlitteratur, 2004.
[63] E. Crenna, M. Secchi, L. Benini, and S. Sala, "Global environmental impacts: data sources and methodological choices for calculating normalization factors for LCA," *The International Journal of Life Cycle Assessment,* vol. 24, no. 10, pp. 1851-1877, 2019, doi: 10.1007/s11367-019-01604-y.
[64] Serenella Sala, Eleonora Crenna, Michela Secchi, and R. Pant, "Global normalisation factors for the environmental footprint and life cycle assessment," European Commission, Joint Research Centre, ISBN 978-92-79-77213-9, 2017.
[65] Serenella Sala, Alessandro Kim Cerutti, and R. Pant, "Development of a weighting approach for the Environmental Footprint," European Commission, Joint Research Centre, ISBN 978-92-79-68042-7, 2018.
[66] *ISO 14045: 2012 Environmental management — Eco-efficiency assessment of product systems — Principles, requirements and guidelines*, International Organization for Standardization, 2012. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:14045:ed-1:v2:en
[67] Wärtsilä Corporation. "World's first full scale ammonia engine test - an important step towards carbon free shipping." https://www.wartsila.com/media/news/30-06-2020-world-s-first-full-scale-ammonia-engine-test---an-important-step-towards-carbon-free-shipping-2737809 (accessed 05 May, 2021).
[68] MAN Energy Solutions. "MAN B&W two-stroke engine operating on ammonia." MAN Energy Solutions,. https://www.man-es.com/docs/default-source/marine/tools/man-b-w-two-stroke-engine-operating-on-ammonia.pdf?sfvrsn=544dc811_16 (accessed 05 May, 2021).
[69] C. Smith, A. K. Hill, and L. Torrente-Murciano, "Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape," *Energy & Environmental Science,* vol. 13, no. 2, pp. 331-344, 2020, doi: 10.1039/c9ee02873k.
[70] A. A. Kiss, J. J. Pragt, H. J. Vos, G. Bargeman, and M. T. de Groot, "Novel efficient process for methanol synthesis by CO 2 hydrogenation," *Chemical Engineering Journal,* vol. 284, pp. 260-269, 2016, doi: 10.1016/j.cej.2015.08.101.
[71] A. D. Korberg, S. Brynolf, M. Grahn, and I. R. Skov, "Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships," (in English), *Renew Sust Energ Rev,* vol. 142, May 2021, doi: 10.1016/j.rser.2021.110861.
[72] S. Ma *et al.*, "Fuel cell-battery hybrid systems for mobility and off-grid applications: A review," *Renewable and Sustainable Energy Reviews,* vol. 135, p. 110119, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.rser.2020.110119.