

THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

# Towards sustainable shipping: Evaluating the environmental impact of electrofuels

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environmental impact of electrofuels  
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# ABSTRACT

The global, local, and regional environment is under pressure from human activity. Changes in the environment can be beneficial and strived for, but environmental and health problems need to be considered when we design human activities. Shipping is a human activity causing emissions to air, water, and soil, which has direct and indirect effects on the environment. New fuels and propulsion technologies are required to lower the emissions from the shipping sector and reduce the impact on, for example, climate change. Fuels produced through electricity, water, and carbon dioxide, so-called electrofuels, is one group of fuels suggested to reduce the climate impact of shipping. This thesis focuses on the emissions from ships and their impacts on the environment when vessels move to electrofuels.

This licentiate thesis aims to study the potential impact on the natural environment from using electrofuels onboard vessels and to explore which factors act as the main influencers on the natural environment and human health. Life cycle assessment was selected to address these questions, and through case study application the first assessment of an electrofuel in the context of shipping was performed. Through a techno-environmental system approach, critical flows between the shipping fuel life cycle and the environment were identified.

The result points towards reductions of climate change impacts if renewable energy is used and CO<sub>2</sub> is captured from a source not acting as a driver of fossil fuel extraction. Potential trade-offs were identified as electrofuels could lead to higher pressure on human health than today's conventional fuels. The extent of these trade-offs is uncertain and affected by limitations in the method approach to the life cycle assessment of marine fuels. Suggestions on how to address these uncertainties, such as detailed system boundary definitions, are brought forward and analyzed based on the current state-of-the-art. The findings discussed in this licentiate thesis aim to promote further discussion around how to assess emerging fuel and propulsion technologies and the potential impact of future marine fuels.

**Keywords:** marine fuels, sustainable shipping, environmental assessment, LCA, future fuel, power-to-x, emerging technology, carbon capture, carbon utilization, human health



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*Elin Malmgren*

## APPENDED PUBLICATIONS

### **Paper A: The environmental performance of a fossil-free ship propulsion system with onboard carbon capture - a life cycle assessment of the HyMethShip concept**

Malmgren, E., Brynolf, S., Fridell, E. Grahn, M., and Andersson, K. 2021. *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, 5, 2753-2770.

Elin Malmgren is the first author of this paper and contributed with method development, data collection, modelling, academic writing, and finalization of the paper.

### **Paper B: Review of electrofuel feasibility- Part A: Cost and environmental impact.**

Grahn, M., Korberg, A. D., Malmgren, E., Taljegård, M., Anderson, J. E, Brynolf, S., Hansson, J., Ridjan Skov, I., and Wallington, T. J. 2021. *Review of electrofuel feasibility - Part A: Cost and environmental impact. Manuscript to be submitted to Progress in Energy*

Elin Malmgren is the main author of chapter five in the paper. She contributed to the paper by reviewing literature, writing the environmental chapter, conceptualizing and drafting the meta-analysis of the environmental chapter, as well as writing discussion.

### **Paper C: The feasibility of alternative fuels and propulsion concepts for various shipping segments in Sweden.**

Malmgren, E., Brynolf, S., Grahn, M., Hansson, J., Holmgren, K. 2021. *The feasibility of alternative fuels and propulsion concepts for various shipping segments in Sweden. Manuscript accepted to IAME 2021 Conference 'Accelerating Transitions'* .

Elin Malmgren is the first author of the paper. Co-authors assisted with reviewing drafts, developing the framework, and establishing concepts.

## ADDITIONAL PUBLICATIONS

Malmgren, E., Brynolf, S., Borgh, M., Ellis, J., Grahn, M., Wermunth, N., *The HyMethShip Concept: An investigation of system design choices and vessel operation characteristics influence on life cycle performance*. 2020. Conference paper presented as poster. Transport Research Arena 2020, Helsinki, Finland.

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# NOMENCLATURE AND TERMINOLOGY

The nomenclature and terminology chapter outlines the definitions and abbreviations as used in this thesis. The exact usage varies within the research community, and as such this list should be viewed as definitions as they are used here.

## NOMENCLATURE

CO <sub>2</sub>	carbon dioxide
eMeOH	electromethanol
LNG	liquified natural gas
H <sub>2</sub>	hydrogen
HFO	heavy fuel oils
LCA	life cycle assessment
NO <sub>x</sub>	nitrogen oxides
PM	particulates matter
SO <sub>x</sub>	sulfur oxides
CH <sub>4</sub>	methane
Ro-pax	roll-on/roll-off passenger vessel
GWP	global warming potential

Allocation	The distribution of flows between multiple units.
Allocation problems	Allocation problems occur in an LCA when several products (or functions) share the same processes and the environmental loads of these processes need to be expressed in terms of a single product. Allocation can be achieved using, for example, a physical relationship or the monetary value of the products. Allocation is described here as one method for solving allocation problems. Thus, allocation methods include both allocation (also called partitioning) and system expansion.
Alternative fuels	Alternative fuels are fuels not commonly used in the shipping sector today i.e., fuels which takes up a small proportion of the current market, are not available commercially in the harbors, or are only used on singular vessels.
Attributional LCA	An attributional LCA is one that strives to be as complete as possible by accounting for all environmental impacts of a product. This type addresses such questions as “What would be the overall environmental impact of marine transportation using Fuel A?”
Boil-off gas	The gas created by the surrounding heat input (while maintaining constant pressure during storage of a cryogenic liquid such as liquefied natural gas) is called boil-off gas. Boil-off gas is inherent to the storage of a cryogenic gas due to the heat input from the surroundings.
Characterization factors	Characterization factors are factors derived from a characterization model which are applied to convert an assigned life cycle inventory

analysis result to the common unit of the category indicator. This is done to assess the total impact on the category. There are characterization factors both at midpoints and endpoints.

Consequential LCA	A consequential LCA is one that compares the environmental consequences of alternative causes of actions and evaluates the effects of change on a surrounding system. This type addresses such questions as “What would be the environmental consequence of using Fuel A instead of Fuel B?”
Elemental flows	Elemental flows are the flows between the environment and the technical system associated with each process in the system.
Endpoint	The endpoint is a point of interpretation of the aggregated emission flows. It represents the end in a cause-effect chain and may be of direct relevance to society’s understanding of the final effect, such as measures of biodiversity change.
Energy carriers	Energy carriers acts as transmitters of energy between the initial primary energy source and the end-use application. Examples include solid, liquid and gaseous fuels.
Eutrophication	Eutrophication is the increased availability of one or more limiting growth factors needed for photosynthesis leading to excessive plant and algal growth. Nitrogen and phosphorus are the most common growth-limiting nutrients.
Functional unit	A functional unit is a quantitative unit representing the function of the system. The use of a functional unit enables comparisons of various products that fulfil the same function.
Goal and scope	The goal and scope is the first step in an LCA. It describes the system under study and the purpose of the study. The goal should include, for example, the intended application and reasons for the study.
Human health	Human health is an area of protection. Damage to human health is measured by mortality and morbidity over space and time.
Impact assessment	Impact assessment is the third step in an LCA. It includes classification of the elemental flows into various impact categories and the characterization of these flows, e.g., the calculated relative contributions of the emissions and resource consumptions to the impact categories.
Inventory analysis	Inventory analysis is the second step in an LCA. It consists of three parts: the construction of a flow model based on the system boundaries, the data collection and the calculation of resource use and emissions of the system in relation to the functional unit.
Life cycle inventory	The phase of LCA involving the compilation and analysis quantification of inputs and outputs for a product throughout its life cycle.
Methane slip	Methane slip is the leakage of methane from marine engines.
Midpoint	Midpoints are links in the cause-effect chain (environmental mechanism) of an impact category. Common examples of midpoint characterization factors include ozone depletion potentials and global warming potentials.
Natural environment	The natural environment is an area of protection. The impact on the natural environment is measured by the loss or disappearance of species and the loss of biotic productivity.
Natural resources	Natural resources are an area of protection. The natural resources can be divided into the following subcategories: atmospheric resources, land

	resources, water resources, mineral resources, metal ores, nuclear energy, fossil fuels and renewable resources
Photochemical ozone	Photochemical ozone is an impact category that accounts for the formation of ozone at the ground level of the troposphere. Ozone formation is complex and depends on several factors, e.g., the concentrations of NO, NO <sub>2</sub> and VOC and on the level of ultraviolet radiation.
Prospective	This term, meaning forward looking, is used to denote LCAs looking at future systems.
Renewable fuels	Renewable fuels are fuels produced from renewable energy sources, where renewable energy sources refer to energy which is generated from natural processes and are constantly regenerated.
Retrospective	This term, meaning backward looking, is used to denote historic perspectives on LCA.
Ro-pax ferry	A ro-pax ferry is a roll-on/roll-off ship with high freight capacity and limited passenger facilities.
System	Connected objects, concepts, functions, etc. how they interact and their purpose, goal, or effects make up a system.
System expansion	System expansion is an allocation model in an LCA. It implies the expansion of the system to include affected processes outside the cradle-to-grave system, or to include multiple functions into the system boundary.
Tank-to-propeller	In this study, this term is used for the part of a marine fuel's life cycle beginning when the fuel is delivered to the vessel's onboard tank and ending when it is combusted for transportation of goods and/or passengers.
Well-to-propeller	Used to describe the part of a marine fuel's life cycle from the acquisition of the raw material to when the fuel is combusted for transportation of goods and/or passengers.
Well-to-tank	Used to describe for the part of a marine fuel's life cycle from the acquisition of the raw material to the delivery to the vessel's tank.
Well-to-wheel	Well-to-wheel is a term commonly used in LCAs of road fuels. These studies usually consider only energy use and climate impact.

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*“The greatest enemy of knowledge is not ignorance, it is the illusion of knowledge.”*

*– Stephen Hawking*

# INTRODUCTION

Since the start of the modern environmental movement, environmental issues are becoming better understood, but most issues are not yet solved. The transport sector is a major contributor to the global greenhouse gas emissions, and it has during recent years become heavily regulated, however the same is not true for all segments of the transport sector. Emissions from international shipping cannot be attributed to any one national economy due to its global nature and complex operation which also have shown to obstruct attempts to regulate this sector (Smith, 2015). First in April 2018 did the international maritime organization (IMO) adopt a strategy meant to reduce total annual greenhouse gas emissions by at least 50% by 2050, compared with 2008 (IMO, 2018). The shipping sector is currently contributing significantly to climate change, and legislations as well as regulations have also been put on sulfur and nitrogen oxides (NO<sub>x</sub>) emissions from the tail pipe of the vessels, as well as energy efficiency requirements for newbuilt vessels. By extension, environmental impacts and performance are taking more space in the discourse around shipping. An estimated 3.1% of the world's total greenhouse gas emissions originate from shipping (Smith, 2020), and together with emissions of sulfur oxides (SO<sub>x</sub>), NO<sub>x</sub> and particulates matter (PM) shipping have a negative impact on human health and the environment (Andersson, 2016).

## 1.1 THE SHIPPING SECTOR

The history of shipping is directly linked to economy (Stopford, 2009). Vessels have been a tool for trade for more than 10,000 years, and was a key component of various historic periods, from the European-African-American slave trade to the Byzantine trade on the Mediterranean to today's petroleum-based economy; Transporting people and goods. For the first 9750 years the main

propulsion methods were wind through sails and manpower through rowing. Then steam engines changed the industry and made it possible to travel in a safer manner, with more control, at greater speeds. After the steam engine, diesel fuel entered the market and revolutionized how we transport goods and people (Stopford, 2009). Different forms of crude oil based fuels are still the main propulsion method onboard vessels today (Smith, 2020). The sector is dominated by four-stroke and two-stroke engines, which are run continuously over long periods of time. The engines are large and run at relatively low speeds compared to other transport modes. Most vessels have 1-4 engines depending on their commercial functions, and at long-distance travels can operate for weeks or months before entering a harbor.

If we are to maintain large scale productions and globalization, shipping is likely essential, and energy to provide for this activity is therefore needed. Harnessing wind could be a solution for some transport applications, but this would require a major shift in how we use our vessel fleet and how the vessels are built. It has been predicted that the fuel demand from the shipping industry will keep growing for the next decades to come, despite expectations on more energy efficient ships (e.g. larger ships, improved hull forms and propellers and more fuel efficient engines) (Smith, 2020, Smith, 2015). Transitioning the sector to other fuels are therefore one potential route to meet the implemented legislations and reduce the pressure from the sector on the environment (Andersson et al., 2020, Smith, 2020, Balcombe et al., 2019). Most fuels used in the shipping sector today are fossil (Smith, 2020), but other fuels are entering the market. Biogenic fuels have the potential to be climate neutral, but supply is limited due to lack of sustainable biomass extraction (Jeswani et al., 2020). In addition to biomass-based options, most fuels can be produced from electricity in combination with water electrolysis and additional molecules resulting in synthetic fuels often called electrofuels or power-to-x (Garcia-Garcia et al., 2021, Korberg et al., 2021, Ridjan et al., 2016).

## 1.2 PRODUCTION AND USE OF ELECTROFUELS

In this thesis, electrofuels are defined as liquid or gaseous energy carriers produced by water, electricity, and carbon dioxide (CO<sub>2</sub>). This limits the definition to carbon-based fuels produced through synthetic processes. Other research includes broader or more narrow definitions (Ridjan et al., 2016) and the definitions varies slightly between the appended papers. Two main resources are required for production of electrofuels as defined in the thesis: hydrogen (H<sub>2</sub>) and CO<sub>2</sub>. These two resources are then combined through fuel synthesis processes and treatments, which detailed set-up depends on the final fuel product. In Figure 1, a generic outline of the electrofuel production life cycle can be seen.

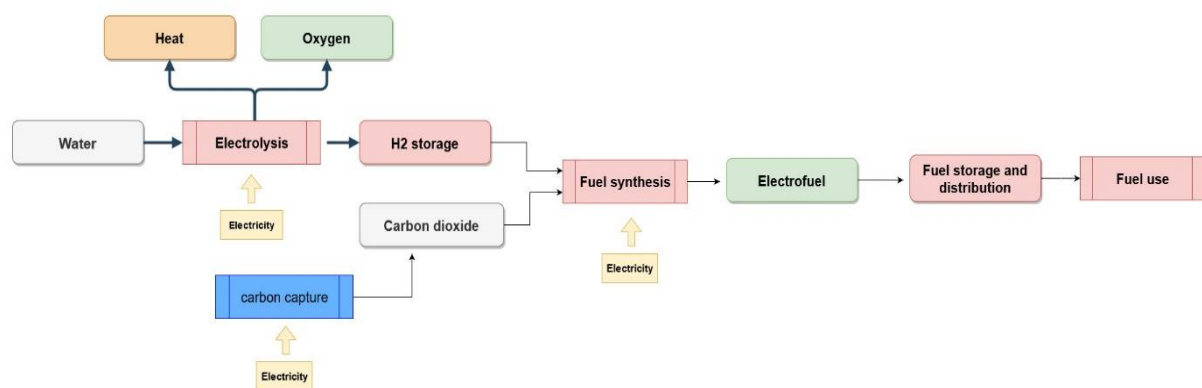


Figure 1 Generic outline of electrofuel production. Red boxes symbolize processes which are a direct part of the life cycle of the fuel and where energy is likely required. Green and orange boxes symbolizes what is sometime considered products or by-products

*Hydrogen:* With varying definitions of electrofuel the definition of the required H<sub>2</sub> source also varies. H<sub>2</sub> can, and might, be produced from many different sources: natural gas reforming (fossil with and without carbon capture, biomass gasification, coal gasification (fossil) with and without carbon capture, electrolysis etc. (Abad and Dodds, 2020). Various grades of H<sub>2</sub> have been introduced in recent years. The grades are commonly referred to using a color scale including colors such as green, blue, grey, brown, and black. The exact definition still varies between sources, but green H<sub>2</sub> is mainly referred to as H<sub>2</sub> produced from renewable sources. In this thesis electricity is considered as the main energy input to the final fuel, requiring the H<sub>2</sub> to be produced from electricity. If other H<sub>2</sub> sources are used, the electrofuel should not be considered part of the electricity production pathway, nor renewable depending on the H<sub>2</sub> source. The main technology used for producing hydrogen from electricity is electrolysis (Valente et al., 2017).

*Carbon:* As with H<sub>2</sub> what is considered alternatives for the carbon supply varies between paper and research questions (Garcia-Garcia et al., 2021, Thonemann, 2020). The technologies for carbon capture are still under development, but include options such as membrane carbon capture, direct air capture, and flue stack cleaning (Al-Mamoori et al., 2017, Gibbins and Chalmers, 2008, Cuéllar-Franca and Azapagic, 2015, Cormos et al., 2018). Carbon can be captured from various sources, which can be derived into three main categories: point sources, diffuse sources, and ambient air (Koytsoumpa et al., 2018). Point sources include tail pipes, industrial smokestacks and other streams which have a high degree of carbon content. Diffuse sources have a lower degree of carbon concentration than point sources, but higher than the level in ambient air.

In this thesis several carbon sources are considered and the choice of carbon source, both for theoretical method applications and in real life assessment, is discussed.

*Fuel synthesis:* The fuel synthesis refers in this thesis to all processes going from H<sub>2</sub> and CO<sub>2</sub> to fuel product. This is boarder than the actual fuel synthesis in which the chemical reaction occurs to form the fuel and should therefore not be viewed as equivalent to the optimal chemical process. Many fuels can be produced as electrofuels, and the exact set-up of processes included in the fuel synthesis therefore varies.

Electrofuels could be an environmentally sound option, and assessments for other transport modes have indicated electrofuels to offer climate emission reductions if produced from low-carbon renewable electricity (Goh and Lee, 2010, Bongartz et al., 2018, Hoppe et al., 2018, Liu et al., 2020, Bokinge et al., 2020, Sternberg and Bardow, 2016, Uusitalo et al., 2017, Artz et al., 2018, Koj et al., 2019). However, full systemic assessments of the environmental effects of using electrofuels in shipping have earlier been lacking from the literature.

### 1.3 ASSESSING EFFECTS ON THE ENVIRONMENT

Environmental effects from human activity have from a human perspective led to both positive and negative effects on the environment. From introduction of farming, which meant adaption of the surrounding environment for production, to emission of freons to the atmosphere damaging the ozone layer, humans have affected their surroundings. In the ongoing anthropogenic age, the scale of these effects is increasing, with the current climate change being an example of human's interaction with the environment on a global scale. The best action to take or decision to make for us humans and/or other agents are not always apparent (Baumann, 2004), as for example reduction of tail pipe emissions in a car by increasing the fuel efficiency might lead to lower costs for driving and by extension



increased use of the vehicle. Specific knowledge, of the environmental problem and driving forces, is therefore required when discussing environmental problems and the possible solutions (Sanden and Karlstrom, 2007).

To assess the impacts on the environment several methods and framework have been developed over the past 50 years. The start of looking at environmental impacts from a systems perspective is commonly credited to the (Meadows and Meadows, 1975), where large scale models were constructed to investigate the future impact of economic growth, but the scientific field has grown and developed rapidly. For assessing the environmental effects of technologies and products a framework was developed in the early 1990's which relies on systemic investigation of all energy and material components needed to produce said product or technology called life cycle analysis/assessment (LCA) (Curran et al., 1993). LCA aims at assessing not only what happens when we directly use a product or technology, but also how the environment is impacted by the production of the raw materials required, production steps, recycling, or end-of-life treatment etc. Once the impacts are known or estimated, measures can then be taken to avoid damaging the environment (including the livelihoods of people living in that environment) and enhance benefits.

#### **I.4 IDENTIFIED RESEARCH GAP**

Previous research in the maritime sector has assessed the environmental performance of marine fuels from a life cycle perspective and described their life cycle, leading to improved theoretical developments in environmental assessment (Al-Breiki and Bicer, 2021, Bengtsson et al., 2011b, Bilgili, 2021b, Bilgili, 2021a, Brynolf et al., 2014a, Brynolf et al., 2014b, Gilbert et al., 2018). Researchers have also investigated the environmental effects of using electrofuels in other segments of the transport sector (Schemme et al., 2020, Albrecht and Nguyen, 2020, McDonagh et al., 2019a, Koj et al., 2019, Deutz et al., 2018, Artz et al., 2018) as well as in energy storage (Quarton and Samsatli, 2020, McDonagh et al., 2019b). The assessments of electrofuels environmental performance are acknowledged to be in the early methodically development stage (Garcia-Garcia et al., 2021, Koj et al., 2019, Thonemann, 2020, Artz et al., 2018, Muller et al., 2020, Kleinekorte et al., 2020), but some progresses have been made. However, the knowledge gap exists in the environmental performance of using electrofuels in the maritime sector. As the maritime vessels travels large distances over a long time and has a life span of 20-50 years the functionality of this assessment case differs significantly from the vehicle sector, and the theoretical framework for assessing electrofuels needs to be adapted for this use case.

## I.5 AIM AND RESEARCH QUESTIONS

The research circles around the shipping industry, the transport system in large and environmental assessment of future fuel and propulsion technologies. The aim of this thesis is to contribute to a life cycle perspective on the potential environmental performance of electrofuels within the maritime sector and provides insight to under what circumstances they might be beneficial. The aim of the thesis is investigated through three research questions (RQ:s).

RQ1: What is the potential environmental performance of using electro-methanol onboard vessels, from a life cycle perspective?

RQ2: Which factors in the electrofuel life cycle are most important to their systemic environmental performance?

RQ3: What are the main challenges of current methods and practices in life cycle assessment of carbon-based electrofuels?

## I.6 APPENDED PAPERS

Three appended papers were used to answer the above stated research questions:

**A: E. MALMGREN, S. BRYNOLF, E. FRIDELL, M. GRAHN and K. ANDERSSON. 2021. 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*, 5, 2753-2770.**

Paper A is a life cycle assessment, LCA, of an emerging marine propulsion concept called *HyMethShip* (The Hydrogen-Methanol Ship propulsion system using on-board pre-combustion carbon capture). In the paper, methanol from three different production pathways is investigated, both with and without use of an onboard carbon capture system. The production pathways are:

- i) fossil methanol from natural gas
- ii) biogenic methanol from willow
- iii) electricity based methanol, i.e. electromethanol

This is the first peer reviewed paper assessing electrofuels used in maritime transport. The purpose of the paper is to exemplify how LCA can be used to assess the use of electrofuels in shipping and establish its impact regarding electrofuels and emissions to air. The data was collected in the EU HORIZON project HyMethShip.

**B: M. GRAHN, A. D. KORBERG, E. MALMGREN, M. TALJEGÅRD, J. E. ANDERSON, S. BRYNOLF, J. HANSSON, I. RIDJAN SKOV, and T. J. WALLINGTON. 2021. Review of electrofuel feasibility- Part A: Cost and environmental impact. *Manuscript to be submitted to Progress in Energy*,**

Paper B reviews the current state-of-the-art of electrofuels. The main relevant chapter for the aim of this thesis is “5. Environmental performance”. Here scientific literature has been reviewed based on quantitative and qualitative insights to key issues for the sustainability for electrofuels. The review discussed how some fuels are more investigated than others and identifies where more research is still needed. The state of art in literature was used to identify methodology issues with LCA of

electrofuels, and in combination with the case study in paper A, some main insights to methodology issues, was established.

**C: E. MALMGREN, S. BRYNOLF, M. GRAHN, J. HANSSON, K. HOLMGREN. The feasibility of alternative fuels and propulsion concepts for various shipping segments in Sweden. *Manuscript accepted to IAME 2021 Conference 'Accelerating Transitions'* .**

The third and final paper summaries alternative fuels currently discussed for the Swedish shipping industry. It is mainly based on available literature and data from governmental databases focused on the Swedish vessel fleet. For the work in this thesis, it acts as a foundation to the current situation for alternative shipping. It identifies which electrofuel alternatives might be relevant for the shipping sector, as well as what would be feasible alternative scenarios to use in future comparisons.

## 1.7 DELIMITATIONS

The work of this thesis is limited to assessing electrofuels in the context of today's conventional fuel options. The results are limited to identifying main issues and does not reflect assessment of the preferred future low-emission technology. Impact on the environmental system is analyzed from an anthropogenic perspective, with the humans best in center of the assessment. The types of environmental impacts investigated are limited to the main categories commonly used in environmental LCA, but further implications are discussed in the discussion chapter. This thesis is limited to the current stage of technology development within the technical framework of the project. The primary time frame is developments and process applicable for the next 30 years, focused on the merchant vessel application. For a transition of the entire industry refitting or rebuilding more than 50,000 vessels would be required and adjust the industry entirely will have environmental impacts outside the scope of this thesis.

# 2

*“Science is a way of talking about the universe in words that bind it to a common reality.”*

*– Neil Gaiman*

## THEORETICAL FRAMEWORK

This thesis lies in the intersection between technology research and environmental science. The work is meant to inform on potential consequences to, and interactions between, technical innovations and the natural environment. As such, the specific theoretical framework applied in this thesis needs to be outlined to establish the specific scientific context.

### 2.1 SYSTEMS THINKING

The scientific principles found in this thesis has its origination in systems thinking. Systems thinking, also called systems theory, has its roots in general systems theory developed by Boulding (1956) among other, and has over the past 70 years developed into a wide research field with multiple applications. Systems thinking is the act of describing how different objects, concepts, functions, etc. interact and what purpose, goal, or effects they have. A system consists of several components and the interactions between them. Together, these components and interactions form a whole. When objects, factors, and their relationships are dependent on how they interact, and that interaction affects further consequences, it is not always given how the system looks in a given moment (Meadows and Meadows, 1975). The relationship between the individual objects will influence each other, and knowledge of the relationships are therefore required. Drivers and dampeners, positive and negative feedback, creates a need for systems thinking (Sanden and Hillman, 2011). Understanding these links and collecting knowledge on how they interact might not lead to explicit solution, but systems thinking will make it possible to acknowledge trade-offs and connections between different linked components. The system's boundaries set the system's limits to the rest of the world, called the

surroundings or environment. Interactions with the surroundings occur through input or output to the system. A system can usually be divided into sub-systems. The sub-systems are considered part of the larger system but do themselves involve several objects and the interactions between them. There are thus many systems levels and the viewpoint from which you look at a system is central to the applied research questions.

## 2.2 MODELLING REAL SYSTEMS

One approach to investigate systems dynamics and the links between objects, factors, and relationships is through establishing models of reality. Descriptions of the individual objects and their interactions is what is known as models and the broad definition of modelling includes developing physical, conceptual, or computer-based representations of systems. Epstein in his 2008 lecture on “Why model” talks about how a model is a way of structuring the world. He does not distinguish between conceptual models, systems models, or simple mathematical facts. A model is anything consisting of different parts and their interactions, portrayed in a way that creates an image for the beholder. It can be a physical image, an equation, or a story. When investigating complex decision-making situations with direct applications in the real-world models are often needed as experimental research in a real system is not feasible. A model is thereby something that strives to be an image of reality and then attempts to reflect the impact of a shift in either guiding principles, behaviors within the systems, or influence from outside of it. Scientific modelling in general is a scientific activity with the aim to make part of the world, or a feature in it, easier to understand or analyze by describing an observed phenomenon.

The real world in which we all interact consists of endless combinations of objects, factors, and relationships, where the effect of different decisions is not always given. The construction of models depicting reality is therefore inherit simplifications of more complex or even wicked scenarios. Problems which are difficult or impossible to solve are often defined as wicked. Where wickedness means problems which are incomplete, contradictory, ever changing, or ungraspable. When first introducing wickedness Rittel and Webber (1973) argued wickedness was a new challenge facing decision makers, where now that the basic needs of the people had been met the more complex, less clear, issues were raised. In his review “Wicked problems revisited” Coyne (2005) did a retake on this assumption and instead states that it is not the wicked that is abnormal but the formal rules and calculations. Wickedness is the most common thing there is. As soon as you have the possibility of a diverse group of decision makers (divers as in different values, mindset, or opinions) you have the potential of a wicked problem. The democratization of society forces us to address this, it is only now that the decision makers around the table are diverse enough for everyone to be forced to realize that there are few if any correct decisions. An essential part of the research presented in this thesis is the undefined goal of the main system of “lower environmental impact” or “better environmental performance”. This goal does not mean the same thing for all, if any, individuals. The results of this thesis therefore need to be viewed from a wicked problem view-point, which entails acknowledging the limitations of the results.

## 2.3 THE TECHNO-ENVIRONMENTAL SYSTEM

There are various systems types, including machinery systems, biological systems, social systems, socio-technical systems, and nature-society-technology systems (Ingelstam, 2002). This work focuses on the interaction between technology and nature but involves society; thus, nature-society-technology systems exist in this thesis. The main terminology used for this systems interaction

throughout the work is techno-environmental systems. The natural, or environmental, systems may be understood in an ecological sense as the set of interactions between the elements of the biosphere. A technology system may be understood as the interactions between elements of technical components, or the full technological system. Techno-environmental systems are systems consisting of both environmental systems components and technical systems, with the connected objects, factors, and relationships. Interactions between technical systems constructed by humans and the environment have occurred for centuries, as pointed out in the introduction of this thesis, but to understand these more complex systems interactions modelling and analysis is required. Technologies does not only interact with the environment in one point, but throughout the entire life cycle links occur between a technology, the user, and the environment through energy extraction, material use and emissions (Baumann, 2004).

## 2.4 ENVIRONMENTAL PROBLEMS

Environmental problems can be defined as harmful effects on the biophysical environment developed because of human interference or mistreatment of the planet. They can range from local issues, such as water shortage due to over-extraction (Harto et al., 2010), regional issues, such as eutrophication and acidification, and global issues, such as climate change (Stocker et al., 2013). The problems are often caused by conflicting interests regarding natural resources and the preservation of the environment (Ostrom, 1990). Environmental problems are often wicked, as competing interests are an inherit part of the cause of the issue (Maron et al., 2016, Turnpenny et al., 2009).

Which environmental problems to consider is not an arbitrary choice, nor is which things are considered to be environmental problems in a society. Eutrophication is an example of an environmental problem which occurs only if specific regional and/or local criteria are met. The problem occurs when substances limiting growth are supplied in abundance and as such the growth of algae etc. spurs extreme oxygen requirements suffocating the surrounding flora and fauna. This is an environmental problem considered highly important in northern Europe, as the Baltic sea is directly affected by Eutrophication.

Climate change is currently one of the mainly discussed environmental issues (Stocker et al., 2013). For the context of electrofuels the fundamental principles behind this issue are central to investigate if the fuels can decrease the impact on climate change. Increased concentrations of greenhouse gases in the atmosphere are the triggering effect for climate change, which puts the flow of greenhouse gases to and from the atmosphere as a central keystone to deal with this issue (Tanzer and Ramirez, 2019). When determining how the Technosphere affects the global, regional, and local ecosystems how material and energy flows to and from the environment becomes essential. In most cases, such as for burning of fossil fuels, this flow is linear; as crude oil is removed from the ground, treated, and eventually burnt the carbon is added to the atmosphere (Cuéllar-Franca et al., 2015). The use of biogenic fuels is a more complex issue regarding climate change and has been debated intensely in the research community (Jeswani et al., 2020), as this is more of a circular system. Plants are removing carbon from the air, the plant is then treated and processed into a fuel, which is then released to the atmosphere when the fuel is burnt. Therefore, no carbon is added to the atmosphere over time. However, this requires the same plant to be cultivated on the same piece of land again for the ecosystems to not be altered in any other ways (Ho et al., 2014), such as transformation of land or just a one-way pit stop. The problem with defining the emissions therefore lead to an expansion of the methodology of assessing the climate change effects of fuel usage to include effects such as land

use change (Cherubini et al., 2009).

Electrofuels creates a third potential flow of materials, where carbon flows can be reused or captured or manufactured to then be put into a fuel. The process of capturing carbon from sources and using it in products is commonly referred to as carbon capture and utilization (Baena-Moreno et al., 2018) (Gabrielli et al., 2020). How this mitigation of carbon from the atmosphere should be treated in environmental assessments is not yet fully established (Garcia-Garcia et al., 2021, Muller et al., 2020). This thesis highlights the impact of different possible methodology decisions in relation to these synthetic fuels and the accompanying carbon capture technologies.

This thesis addresses the impact from flows of emissions from technical systems to the surrounding environment on ecosystems as well as health. Exposure to emissions of pollutants is known to cause negative health effects such as respiratory deceases (Brunekreef and Holgate, 2002, Manisalidis et al., 2020), and along with local, regional, and global issues investigation is needed to identify trade-offs and quantify the impact in terms which can be incorporated into decision making.

## 2.5 ENERGY CARRIERS AND PRIMARY ENERGY

Fuel is primarily an energy carrier, where the fuel is used to carry energy from the extraction source to the use point. There are many potential pathways to produce energy carriers, and various types of primary energy sources can be used. Some fuels are produced solely through natural processes without human interaction, others range from cultivation of natural resources to synthetic production. Electrofuels are synthetic fuels produced though human activities from the energy source (merged with carbon) to the energy carrier. The choice of primary energy sources therefore affects if the electrofuel can be categorizes as renewable.

There are both renewable and non-renewable primary energy sources. A renewable resource is a resource that can be regenerated in a timeframe (from hours to a hundred years). Non-renewable resources are of essentially fixed quantity, or stock, in the Earth's crust, with a renewable time on the scale of geological processes. The energy sources primarily used in the shipping sector today are non-renewable fossil-fuels. One of the main energy sources to Earth is the sun, with an annual input of 3,900,000 EJ. The energy from the sun can be used directly after conversion to heat and electricity or be used after its natural conversion to flowing water, wind, waves, and biomass. These energy sources are all considered renewable if they meet the regeneration requirement in praxis.

Biomass was the primary energy source used by humans before the nineteenth century and is considered a potential renewable energy source for fuel production. Biomass is biological material gathered from agricultural crops, forest products, aquatic plants, crop residue, animal manure and waste. Estimates of the global supply potential varies based on perspectives e.g., its theoretical potential, technical potential, market potential, and sustainable potential. Different studies present vast differences on global biomass supply potential, e.g., in the range 10-245 EJ/yr (Creutzig et al., 2014) as well as in the range 1135-1550 EJ/yr (Ladanai and Vinterbäck, 2009). Many of the authors claim up to 100 EJ of bioenergy can be produced in a sustainable way and that 300–500 EJ/yr may be technically possible, but that such expansion might challenge sustainability criteria. As such, the global biomass supply potential is limited and that harvesting large fractions of the available biomass would result in severe adverse impacts on the natural environment.

# 3

## LIFE CYCLE ASSESSMENT

Life cycle thinking and life cycle perspective are broad concepts with roots in systems thinking. Life Cycle Assessment, LCA, is a tool used to assess the environmental impact of a product or technology by mapping all material and energy flows from each process in the life cycle (Curran et al., 1993). These flows are then linked to impacts on the environment. In this way the environmental impact of similar options can be quantified and compared, which in turn gives information on how the environment will be affected by the choices made. The life cycle model in LCA is a typical example of a system that consists of several processes connected by a flow of goods, material, and energy. LCA belongs to the family of systematic environmental assessment. The method is useful when trying to avoid shifting problem from e.g., one phase of the life-cycle to another, from one region to another, or from one environmental problem to another (Baumann, 2004).

LCA considers a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste (Curran et al., 1993). When using a technology or product not only the direct usage, commonly referred to as the use phase in LCA, has an impact on the environment. The energy and materials required also comes from somewhere. The processes required to produce that energy and refine those materials also emits emissions and changes landscape. Maybe something has been transported, requiring fuel and a car, or perhaps water was used to wash of parts before they were assembled in a factory? The environmental effects from these additional energy and materials are defined as derived demands. All these derived demands, and demands derived after the use such as waste management, are together with the use phase, called the life cycle of the technology or product.

LCA includes four main irritative steps according to the ISO 14040 standard: goal and scope definition, inventory analysis, impact assessment and interpretation (Heinrich, 2010). First goal and scope are identified, which sets the stage for the assessment. Here what to compare is established, both in terms of which unit that is directly compared and the systems surrounding it. The aim of this step is to describe the studied system as well as the purpose of the study and includes for example reasons for carrying out the study and the boundaries of it (Ekvall et al., 2016). To compare different options a quantitative unit called the functional unit is defined in detail (Curran et al., 1993). This unit represents the function of the system i.e., what specifically



that is compared, and this unit should be deemed as being the same throughout all the different options.

Secondly, all emissions, energy and material required for one functional unit are outlined and added to a life cycle inventory. This inventory is the basis for the calculations and acts as an outline of the investigated unit and the surrounding. Here resources and emissions related to the functional unit is calculated, a model for materials and energy flows within and over the system boundaries are mapped and data is collected.

Thirdly, an assessment on how these emissions, energy extractions and material usages affect the environment (land used, carbon emitted, power used) (Curran et al., 1993). These impacts are categorized based on what they are affecting in the environment and varies depending on which type of LCA methodology is used. However, the basic principle is the same: everything crossing the system boundary (emissions, energy, materials) is added together based on how much they affect a specific category of impact compared to a reference emission/substance (Baumann, 2004). The different categories are referred to as “impact categories”. This way the result is a total amount of the reference emission/substance which can be compared between different technology options etc. The number converting emission from the system to reference emission/substance is called the characterization factor.

These three steps are done iteratively, going back and forth, while interpreting the results to make sure that everything is coherent and to create depth to the study. In LCA the impact from method choices on the results is acknowledged. What you do, and do not, include is always important in scientific settings, but for LCA how to make this choice and what to look into can directly affect your end recommendation (Curran 1993). When conducted, an LCA includes many assumptions of the context investigated and the technologies used. The result can appear as a singular number for a specific impact category, but the model as such contains more information.

### 3.1 LIFE CYCLE TERMINOLOGY AND SPECIFIC METHOD CHOICES

The main parameters to consider when setting the scope of the assessment are the functional unit/units, processes included (the system boundary of main study object and alternative concepts), data quality, emission and material flow inventory, and characterization method/methods. There are several types of LCA, where the methodological choices are derived from a specific purpose or framework. *Attributional LCA* is commonly referred to as LCAs which try to assess how much environmental impact/burdens which can be attributed to a specific product in a system. This includes assessments where the questions are specified as” how much is the climate change effect from buying this product?”. *Consequential LCA* is commonly referred to as an LCA which looks at how the assessed system interacts and changes the surrounding system. This includes assessments where the addressed questions are “how much is the climate change effect from using an additional product?” and “What would be the difference if we used product A or B?”. The view of the differences between the types and how they interact are still being discussed, and additional types of assessments are being proposed. One such example is ex-ante LCA, which is defined by Cucurachi et al. (2018) as a broad type where future assessment of emerging technologies and systems are assessed, and consequential LCA could be viewed as a subset (Cucurachi et al., 2018, Villares et al., 2017).

As there are different types of LCAs there are also different ways to set-up the life cycle

inventory data. In this thesis the bottom-up approach process-based LCA was used. This method models the LCI using knowledge about industrial processes within the life cycle of a product, and the physical flows connecting them. To define the function of the system and the system boundaries knowledge of how the product or technology will be/are used is required (Curran et al., 1993). As the goal often is to assess the impacts of a real systems this requires modelling and thereby simplifications and assumptions of how the systems look. The design of the life cycle model sets the scope of the assessment.

The distinction between what is inside and outside the system boundary can be derived in many ways and formed on several basis, but a main definition of interest for this thesis is the definition of products, by-products, and waste flows. A product is something produced on purpose and acts as a driver to why the human activities are occurring. A product should therefore be attributed environmental burdens, as it is the driver of those emissions. By-products can be defined as additional products which occurs due to the main product. In some assessments several by-products are viewed as together acting as the main product of the system, and by-products are in most assessments attributed i.e., allocated, environmental burdens. A waste flow is by definition an unwanted by-product where the environmental burden is allocated to the initial main product. If a system has several products, or multiple functions can be identified, a choice have to been made in how to solve this multifunctionality issue.

Solving for multifunctionality can be done through several different methods, where the main tools are called “system expansion” and “allocation”. System expansion is the process of expanding the function of the system to include the full set of functionalities, or to subtract the function which would be replaced by a by-product on the market. Allocation is defined as separating the input and output from a process, or separating the inputs and outputs of a product systems between product systems (Hermansson et al., 2020). The choice of how to solve for multifunctionality does affect the results of an LCA, and despite a recommended hierarchy in the ISO standard discrepancies occur depending on research question and feasibility.

For the assessments in this thesis, the new maritime propulsion technologies need to be competitive in an unknown future system. The consideration of what will be the actual functionality of the system in a future system, as well as knowledge on how the system will interact with its surroundings therefore becomes essential. As this thesis assess future technologies, not yet existing on a market, future development has be considered, and the type of LCA used here could be viewed as a prospective LCA. As such, prospective LCA involves aspects of incorporating unknown information (Arvidsson et al., 2018). The LCA methodology is thereby based on limitations and context, which in large parts are managed though delimitations and uncertainty analysis (Finnveden et al., 2009). Three approaches to address uncertainty were proposed in Finnveden et al. (2009), the “scientific way”, the “social way” and the “statistical way”. The scientific way includes further developing the scientific approach by for example identify better data and develop better models. The social way limits uncertainties by discussions with stakeholders, with the aim to reach consensus on the methodology choices and data used. The statistical way looks at way to incorporate uncertainties into the analysis.

### 3.2 LIFE CYCLE ASSESSMENT OF MARINE FUELS

LCA of marine fuels have been conducted for a multitude of different fuels. From competing fossil-fuel options (Balcombe et al., 2021, Bengtsson et al., 2011a, Bilgili, 2021b, Corbett and Winebrake, 2008, Cucinotta et al., 2021, Gilbert et al., 2018, Hwang et al., 2019, Manouchehrinia et al., 2020, Thomson et al., 2015), to biofuel alternatives, (Kesieme et al., 2019, Tan et al., 2021, Tanzer et al., 2019, Brynolf et al., 2014a, Gilbert et al., 2018) and future options such as hydrogen (Olindo and Vogtländer, 2019, Trillos et al., 2021, Jeong et al., 2018, Gilbert et al., 2018, Baldi et al., 2019, Bicer and Dincer, 2018a, Bicer and Dincer, 2018b) or electricity (Jeong et al., 2020). Most of the papers are limited to climate change impact, but some look at a wider scope of impacts (Al-Breiki and Bicer, 2021, Bengtsson et al., 2011b, Bilgili, 2021b, Bilgili, 2021a, Brynolf et al., 2014a, Brynolf et al., 2014b, Gilbert et al., 2018, Malmgren et al., 2021).

Eyring et al. (2005) established emissions to air as the main source of emissions from shipping to the environment. The use phase of LCA on marine fuels is mainly modelled in today's literature through emissions factors based on a few vessel measurements or test-beds from onshore tests on marine engines (Agrawal et al., 2008, Comer, 2017, Cooper, 2004, Corbett and Koehler, 2003, Corbett and Koehler, 2004, Endresen et al., 2004, Eyring et al., 2005, Goldsworthy and Goldsworthy, 2015, Jalkanen et al., 2016, Merien-Paul et al., 2018, Sofiev et al., 2018). The exact combustion properties are not established for most alternative fuels. Instead, pragmatic parameters based on physical relations are used for the emissions where this relationship is established. These primarily include sulphur emissions and carbon dioxide emissions, which are calculated based on the chemical content of the fuel minus other known emissions containing the concerned molecule. Measuring the content of exhaust gas is limited by economic and practical reasons, and knowledge on which emissions occur is still being established (Lunde Hermansson et al., 2021).

# 4

*“Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less.”*

– Marie Curie

## METHOD

Several methodologies were used to answer the aim of the thesis through three appended papers. They are presented in this chapter. The primary methodology used in the work of this thesis was LCA. This systemic assessment method was combined with literature reviews to capture the current state of the art of both alternative fuels in shipping as well as the environmental performance of electrofuels. The data collected in paper A, B, and C include secondary data from literature based in other scientific fields, where knowledge from the different scientific fields have been gathered, connected, and further analyzed. LCA aims to analyze the links between the environmental and the socio-technical systems and connects various fields. This thesis can therefore be seen as having an interdisciplinary approach.

### METHODOLOGICAL TOOLS

The following methodological tools were used to answer the research questions.

**Literature review** is a survey of scholarly sources on a specific topic. The aim of a conducted review is to give an overview of the state-of-the-art knowledge for the subject, to identify relevant theories, methods, and gaps in the existing research (Paul and Criado, 2020, Snyder, 2019). It is performed through literature search in databases and/or snowballing methodologies where known sources are used to identify referenced or referencing literature.

**Case study** can be defined as an exhaustive study of a person, a group of people or a unit, with the aim to produce knowledge which can be generalized over several people, contexts, or units (Meyer, 2001). Case studies are used to describe, compare, evaluate, and understand different

aspects of a research problem or application scenario. This thesis views a case study as the specific application of life cycle methodology to an application scenario, where the specific case can be described, compared, evaluated, and understood within the stated framework.

**Life cycle assessment** is a method used to evaluate the impact from a technology or product on the environment (mainly). The method is a quantitative research method often aimed at informing decision makers.

**Life cycle inventory data collection** is the process of gathering, analyzing and summarizing data. This is a central part of the LCA methodology. A detailed LCA requires large amounts of data which is not always available nor practical to use, thus simplified or average data is commonly applied.

**Sensitivity analysis** is a way to predict the outcome of a decision given a certain range of variables. In the context of LCA, the aim of a sensitivity analysis is to determine the robustness of the assessment and identify assumptions, or unknown variables, which may change the results of the study (Curran et al., 1993). The method is commonly used by establishing the range of uncertainty in the input data and analyze how the result shifts over the uncertainty range.

**Monte-Carlo analysis** is a form of uncertainty analysis. Monte Carlo provides a range of possible outcomes and probabilities to allow for analysis of the likelihood of different outcomes (Heijungs, 2019). This is done by randomized input variables given an uncertainty range for all/any factor which has an inherent uncertainty.

The **Multi-criteria approach** provides a systematic approach for supporting complex decisions according to pre-determined criteria and objectives. The criteria and objectives important to the decision maker is developed, and then feasible options are evaluated against the stated criteria.

*Table 1 The distribution of methodological tools used in the appended papers.*

	PAPER A	PAPER B	PAPER C
LITERATURE REVIEW	✓	✓	✓
CASE STUDY	✓		✓
LIFE CYCLE ASSESSMENT	✓	✓	
LIFE CYCLE INVENTORY DATA COLLECTION	✓		
SENSITIVITY ANALYSIS	✓	✓	
MONTE-CARLO ANALYSIS	✓		
MULTI-CRITERIA APPROACH			✓

## 4.2 METHOD FOR APPENDED PAPERS

A summary of the methodological tools used in the three appended papers can be viewed in Table 1. All appended papers include narrative literature reviews, where scientific literature has been included to establish the research scope and the current state of knowledge for the topics addressed (Snyder, 2019). A main component in the shaping of research questions and factual context has been networking within the scientific community, and in the prolongation inclusion

of relevant papers and reports for discussed topics. The work included in this licentiate thesis was carried out during 2018-2021 mainly within the *HyMethShip* (The Hydrogen-Methanol Ship propulsion system using on-board pre-combustion carbon capture) project. The project is funded by the European Union's Horizon 2020 research and innovation program.

#### 4.2.1 Paper A

Paper A presents an attributional LCA, where electrofuel production and use is investigated to find the main influencing design factors, processes, and emission types. The LCA is designed around use of direct carbon capture and water electrolysis used to produce electromethanol in harbor. The electrofuel is then used onboard the vessel. The electromethanol is when needed for propulsion split to hydrogen and carbon dioxide in a reformer. The hydrogen is used in an internal combustion engine and the carbon dioxide is stored onboard before it is brought back to shore. As such, the full concept revolves around using electromethanol as storage of energy. The case study application is focusing on the a Ro-pax vessel travelling from Gothenburg to Kiel. The assessment also includes a concept where electromethanol is used directly in an internal combustion engine. The data used in Paper A was collected through the research and development of an onshore prototype system within the HyMethShip project and has been gathered through the collaborative partners, which include Graz University of Technology.

The life cycle inventory model and the impact assessment were modelled using the software tool openLCA. The influence of the uncertainties around the potential future technology development in the main life cycle was investigated using Monte-Carlo analysis. The uncertainty ranges were estimated by experts within the projects, as well as through literature data on expected future energy usage and material requirements within electrolysis and direct carbon capture. Several fuel and propulsion concepts were investigated to establish when the electrofuel pathways is the main driver of environmental impact and how different concept set-ups might compare. The results were analyzed using several sets of LCA methods, such as impact category sets, characterization factors, and normalization factors.

#### 4.2.2 Paper B

In paper B a secondary data analysis was performed based on the system boundaries and data inventories presented and discussed in literature. The research questions identified was mapped against the scope investigated in the reviewed papers, and a generic model for the life cycles of electrofuels was created. The concluding qualitative model is used as a life cycle outline to establish the context for the various quantitative and qualitative conclusions presented in the literature. A structured literature review was performed using the database Scopus. The aim of this literature review was to identify all relevant publications for electrofuels up to end of 2020. Since a wide range of terms for e-fuels is used in the scientific literature (e.g., electrofuels, e-fuels, and power-to-fuels), several search term options were analyzed. In the search 77 publications was identified, published between 2006 and 2020. In addition to these publications snowballing was used to identify further relevant papers which were addressing the topic. An additional 33 papers were identified.

The finalized search term used to identify environmental analysis of electrofuels was:

*(electrofuel\* OR "electro-fuel\*" OR efuel\* OR "e-fuel\*" OR "e-gas" OR "e-methane" OR "e-methanol" OR "e-gasoline" OR "e-diesel" OR "e-kerosene" OR "e-ammonia" OR "e-liquid\*" OR "electro-methane" OR "electro-methanol" OR "electro-gasoline" OR "electro-diesel" OR*

*“electro-kerosene” OR “electro-ammonia” OR “electro-liquid\*” OR electromethane OR electromethanol OR electrogasoline OR electrodiesel OR electrokerosene OR electroammonia OR electroliquid\* OR powerfuel\* OR “power-fuel\*” OR ((PTX OR PTL OR PTG OR “power-to-\*)” AND (methane OR methanol OR gasoline OR diesel OR ammonia OR fuel\* OR liquid\*)) AND (“carbon recycling” OR “carbon conversion” OR “carbon capture” OR “carbon capture and utilization” OR “carbon capture and utilisation” OR ccu OR “direct air capture”) AND NOT \*cigar\* AND NOT “power fuel cell\*” AND (“environmental impact\*” OR “climate impact\*” OR LCA OR “Life cycle assessment\*” OR “CO2 emission\*” OR “carbon dioxide emission\*” OR “carbon emission\*” OR “GHG emission\*” OR “greenhouse gas emission\*”)*

A meta-analysis was then performed on the identified papers, based on the type of fuels investigated, scope, type of assessment, investigated environmental impacts, main identified hot-spots and quantitative impact results.

### 4.2.3 Paper C

Paper C outlines the current uptake of alternative fuels in the Swedish vessel fleet. Its main purpose in this thesis is to provide context for which fuels are currently discussed as potential future fuel and propulsion options for the maritime industry and to establish factors with a significant influence on the choice of marine fuel. First, ship categories were identified, and their operational characteristics were analyzed based on critical parameters such as function, typical route length, bunkering time requirements, energy requirements, and vessel age. A multi-functionality approach was then used to map the identified characteristics against the performance profile of selected alternative propulsion technologies and fuels. Through this, constraints for the fuel and propulsion alternatives were identified and discussed according to technical, environmental, and economic performance aspects. The main information sources were expert input from project partners and literature review.

# 5

## RESULTS

This section summarizes the results from paper A-C. For a full understanding of the results, a review of the individual papers is recommended. The results are presented based on their connection to the stated research questions.

### 5.1 LIFE CYCLE ASSESSMENT OF ELECTROFUELS

When conducting an LCA, the function of the system is essential, as it determines the functional unit and by prolongation the absolute and relative environmental performance of the investigated product or technology (Curran et al., 1993, Baumann, 2004). A key question when determining the system function is the motivation for using the product or technology. A process on how to define the functional unit of carbon capture technologies, including electrofuels, was proposed in Muller et al. (2020). This process includes three main options for fuels. The decision tree defined in the paper establishes the function as either an energy storage unit or as fuel. As a fuel, the energy content or the quantitative function of the energy service are proposed as functional units. For many assessments, this could be the primary functionality of the product or technology, but some of the motivation for electrofuels and scientific questions lies outside this scope. One example is when a primary function of the system is the direct utilization of carbon, such as when you use LCA as a step when determining what to do with a collected carbon stream, which would require a comparison between either producing electrofuels or using, for example, carbon storage facilities. There is, therefore, a need to consider a broader scope of functions than proposed in the guideline.

Electrofuels are an interesting case study for LCA theory, as it is resting between being an energy product, material recycling, a potential carbon sink, as well as an energy storage function. One of the first meta-reviews of LCAs of carbon capture and utilization products (von der Assen et al., 2013) included method analysis for some potential pitfalls when assessing electrofuels. The main conclusions pointed to three potential pitfalls:

- i) intuitively interpreting utilized CO<sub>2</sub> as a negative greenhouse gas emission
- ii) allocating environmental burdens wrong over multiple functions (multifunctionality)
- iii) Overestimating the temporary storage aspect



The choice of carbon capture technology in fuel production and how emissions of CO<sub>2</sub> are treated in the calculations can lead to negative impacts from the technology. Negative GHG emission results mean that GHG emissions have been removed from the atmosphere through some form of capture process, i.e., DAC or biomass cultivation, and not yet been released back to the atmosphere. Cradle-to-gate assessment does not include combustion of fuel and therefore can have negative emissions. To assess if a technology could be able to be considered to have negative emissions over the full life cycle a list of minimum criteria was set up in Tanzer and Ramirez (2019). The list includes the above-stated goal of physical greenhouse gas emissions to be removed from the atmosphere, as well as a permanent storage sink, including upstream and downstream processes, and that the full life cycle results conclude in a larger removal than additional release. As electrofuels are not carbon capture and storage technologies, they fail the second criteria, and life cycle assessment results from cradle-to-wake cannot be absolute reductions. Negative results in electrofuel LCAs should not be viewed as true negative but as comparative results. In some cases, the calculations also assume emissions which should have been released to the atmosphere if these fuels were not produced, i.e., already existing fossil fuel plants or similar, as negative emissions. Results that include this assumption do not reflect absolute GHG emissions but simply a comparative result between two or more scenarios.

The choice of system boundary has also been discussed in earlier work, and the current recommendation brought forward by Muller et al. (2020) is to use cradle-to-gate assessments if the final product has the same chemical structure as the benchmark products. However, this recommendation fails to consider that it is not only the function of the product that should be identical but also the following environmental inventory calculations. If for example biogenic carbon is assumed, it is important to consider the differences in emission also in tank-to-wake if the comparison is to be valid. Multifunctionality is also an aspect discussed in several papers, and as shown in Paper B application of system expansion can lead to results which are hard to interpret. As for earlier discussion on negative emissions subtracting the environmental burdens from the product which the by-product replaces on the market might lead to negative results as a consequence of the model choices. For electrofuels the agreed perspective today, as concluded by Muller et al. (2020), is to not consider temporary CO<sub>2</sub> storage at all as the storage time can be considered small. The storage time is defined as the time it takes from capturing the carbon until it is released back to the atmosphere.

The motivation behind electrofuels brought forward in the scientific community varies (see paper B). Several papers look at electrofuels as a way to store surplus energy from the electricity grid, where, instead of a direct energy loss or storing it in buffer facilities, the surplus electricity can be used to produce fuels (Sternberg and Bardow, 2015, Daggash et al., 2018, Walker et al., 2017, Hoppe et al., 2018, Biernacki et al., 2018, Parra et al., 2017, Zhang et al., 2020). Others investigate electrofuels solely as an alternative production route for fuel production. In LCAs, the energy storage argument is sometimes coupled with modelling the electricity as a waste flow, and as such it is free from environmental burden. In paper B it is concluded that this assumption can lead to very low comparative environmental impact from the assessed fuel.

For the work in this thesis the functional units of the LCAs are therefore identified and coupled with the scope of the assessment to determine what has been assessed through the study. To be transparent with the assumptions, is crucial for the interpretation of the results.

## 5.2 THE POTENTIAL ENVIRONMENTAL PERFORMANCE OF USING ELECTRO-METHANOL ONBOARD VESSELS

The results from paper A are primarily aimed at answering this research question. The summary of the aggregated LCA results is shown in Figure 2 and Figure 3. The results establish that the environmental performance of electromethanol is at a level where utilization in the sector could lead to lower impacts compared to conventional fuels for most investigated impact types (see Figure 2). However, some potential trade-offs are identified as human health impacts appears to increase (see Figure 3). Through sensitivity analysis it is established that these results are uncertain, but that potential trade-offs between these categories cannot be ignored for future assessments of electrofuels as it is driven by the need for electricity.

## 5.3 IMPORTANT FACTORS IN THE ELECTROFUEL LIFE CYCLE

Paper B concludes emissions from electricity production or carbon supply (carbon source and capture process) as the primary contributor to climate change according to the literature. The exception is studies which have assumed the contribution of electricity production and carbon supply to be zero due to methodology related arguments, and where heating is provided by natural gas. The methodological arguments concerned are mainly assuming the carbon supply to be avoided emissions or waste streams, or assumption that electricity is excess supply. The sensitivity analysis in paper A shows a similar conclusion, where electricity source has a major influence on the climate change. The main influencing factors on the environmental performance of electrofuels are summarized in Table 2.

*Table 2 The identified main influencing factors for the systemic environmental performance of electrofuels.*

<b>FACTOR</b>	<b>DESCRIPTOR</b>	<b>INFLUENCE ON ENVIRONMENTAL PERFORMANCE</b>
<b>CHOICE OF ELECTRICITY SUPPLY SOURCE</b>	The choice of primary energy source, whether renewable, fossil, or energy mix	The emissions from the energy production have a direct impact on the environmental performance, with even low amounts of emission per produced energy unit influencing the total environmental performance of the system
<b>ELECTRICITY REQUIREMENT</b>	The absolute need for electricity in fuel production, primarily affected by energy efficiency over the life cycle	Lower energy demand correlates to less energy requirement and better environmental performance
<b>COMBUSTION PROCESS CHARACTERISTICS</b>	The emission factors when combusting fuel in the use phase of the vessel	Main influencing factor on particulate matter, combustion characteristics of other combustion processes throughout the life cycle (such as trucks used in the production facilities and power plant electricity production) also affects this when low-emitting options are considered
<b>ELECTRICITY NEEDED FOR SUPPORTING SYSTEMS</b>	Heating requirements mainly related to the fuel synthesis	High emitting heating options can directly affect the performance of the fuels
<b>CHOICE OF CARBON SOURCE</b>	The carbon source considered in the assessment, and the characterization of the associated emissions	How the carbon sources are treated varies greatly between assessments and has a direct effect on the results
<b>ALLOCATION OF UPSTREAM EMISSIONS</b>	The inclusion or exclusion of emissions connected to the by-products or waste-flows	The choice of allocation method and system boundary directly affects the results in the climate change impact category, and for some assessment set-ups can lead to presentation of negative results without the technology investigated being a net-zero emission technology

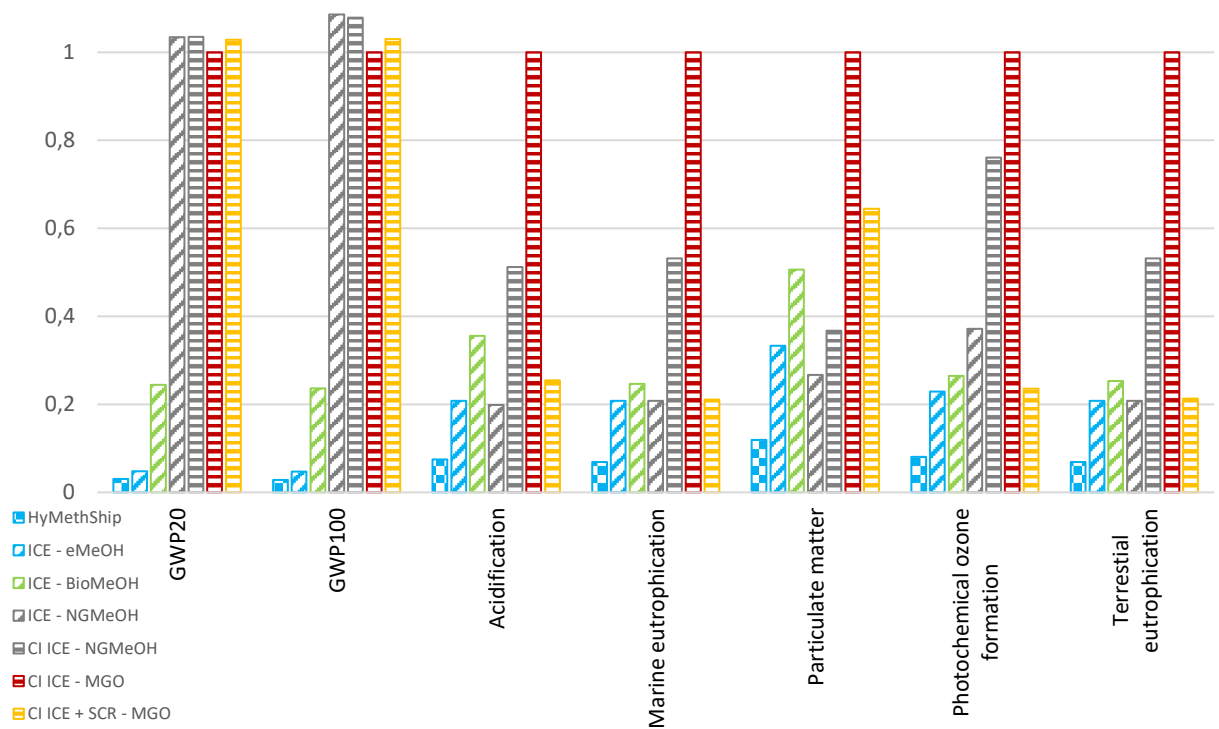


Figure 3 . Life cycle assessment results for GWP, Acidification, Marine eutrophication, Particulate matter, Photochemical ozone formation and Terrestrial eutrophication. The assessed concepts are: HyMethShip using electro-methanol from DAC and wind power (HyMethShip), SI ICE using electro-methanol (ICE - eMeOH), SI ICE using biomethanol (ICE - BioMeOH), SI ICE using fossil methanol (ICE - NGMeOH), CI ICE using fossil methanol and pilot diesel (CI ICE - NGMeOH) , CI ICE using marine gas oil (CI ICE - MGO), and CI ICE using MGO and Selective Catalytic Reduction (CI ICE+SCR - MGO). Results normalized per CI ICE using MGO and presented per round trip between Gothenburg and Kiel on a RoPax vessel. The y-axel indicates the same values for both sides of the graph, where 1= CI ICE – MGO.

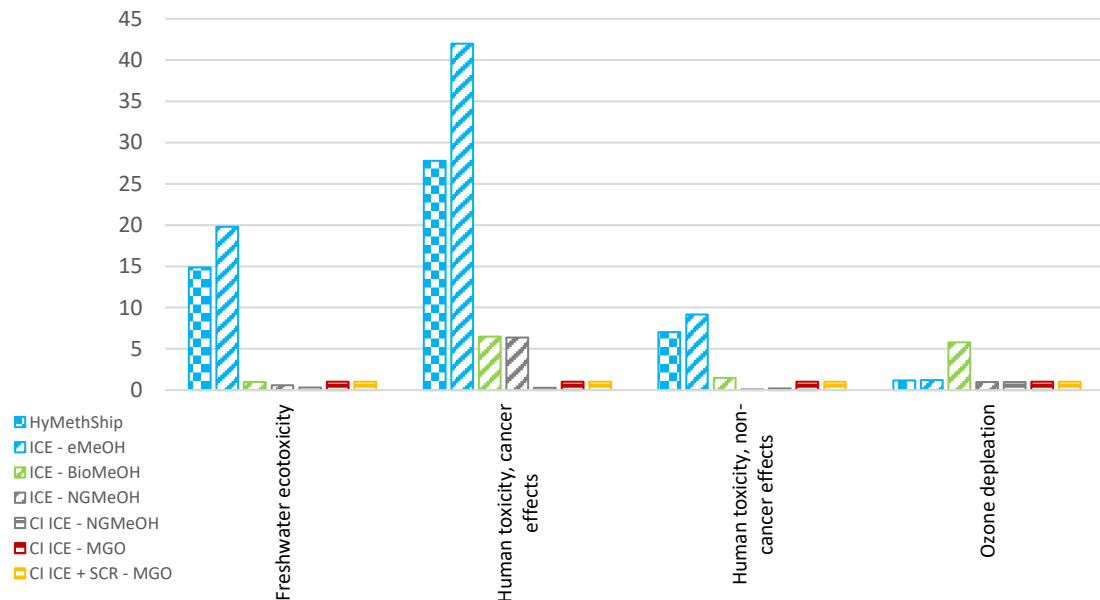


Figure 2 Life cycle assessment results for Freshwater ecotoxicity, Human toxicity cancer effects, Human toxicity non-cancer effects, Ozone depletion. The assessed concepts are: HyMethShip using electro-methanol from DAC and wind power (HyMethShip), SI ICE using electro-methanol (ICE - eMeOH), SI ICE using biomethanol (ICE - BioMeOH), SI ICE using fossil methanol (ICE - NGMeOH), CI ICE using fossil methanol and pilot diesel (CI ICE - NGMeOH) , CI ICE using marine gas oil (CI ICE - MGO), and CI ICE using MGO and Selective Catalytic Reduction (CI ICE+SCR - MGO). Results normalized per CI ICE using MGO and presented per round trip between Gothenburg and Kiel on a RoPax vessel. The y-axel indicates the same values for both sides of the graph, where 1= CI ICE – MGO

The system boundaries used in literature varies greatly, and Figure 4 presents an outline of the generic electrofuel life cycle including some system boundary set-ups. Both paper A and B indicates that upstream emissions have a significant impact on several impact categories. The amount of energy which is required to come from low-carbon electricity for the electrofuel to lead to reduction of climate impact varies between assessments, but an electricity grid mix with a high degree of renewables might be sufficient (see paper B). It is indicated that the forecasted electricity mix for Germany in 2040-50 would be enough for the global warming impact of power-to-gas to be comparable to conventional natural gas-based syngas production (Sternberg and Bardow, 2016). However, this is based on CO<sub>2</sub> emissions being used in the fuel instead of released (avoided emissions).

As can be seen in Figure 4, various production pathways are possible to produce electrofuels. The fuel usage stage of the electrofuel life cycle is similar between production pathways which lead to the same energy carrier/fuel, and as shown in Paper A, establishing if an electrofuel will be competitive with its fossil equivalent could be done by comparing the results cradle-to-gate. In Paper B, mainly cradle-to-gate LCAs were identified, as can be seen in Figure 4.

Paper B concludes that a central concept to the sustainability of electrofuels is the sustainability of the carbon source. When presented as “emissions-to-fuel”, the role of electrofuels is either centered on utilizing carbon emissions from fossil sources or industries and giving more value, per emitted carbon unit, than earlier. This perspective is based on the new product replacing fossil products on the market, lowering the total emissions, or increasing value being a central core to the market. The carbon budget concept, therefore, becomes central to the way carbon sources are treated.

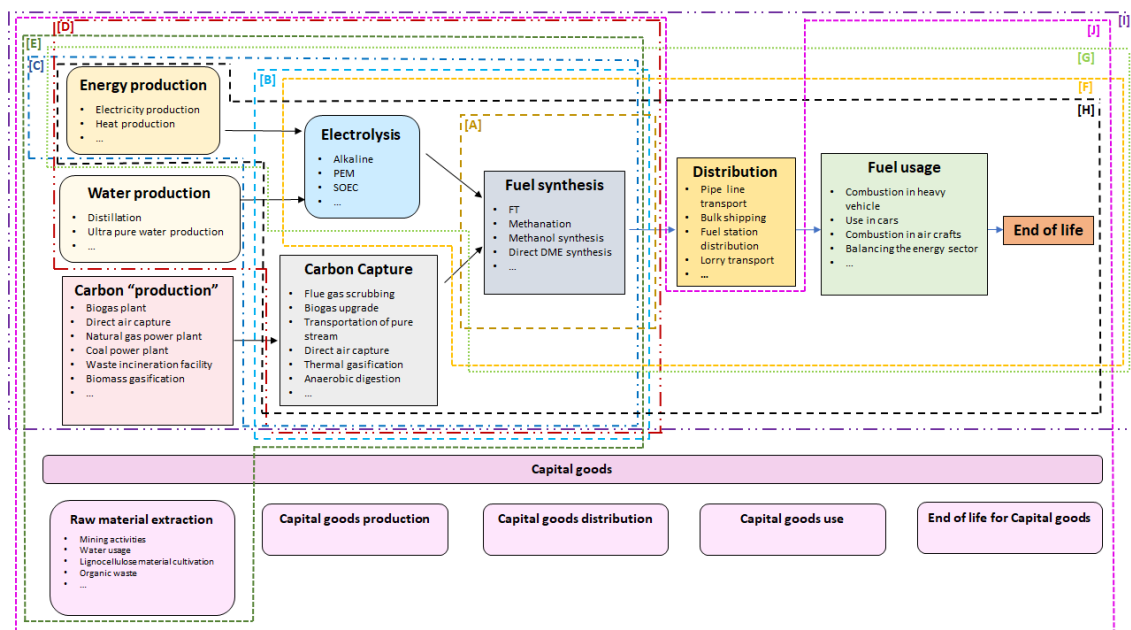


Figure 4 Simplified illustration of the electrofuel life cycle from cradle to grave as presented in Paper B. Dotted lines mark system boundaries used in reviewed environmental assessments. Within each box different production alternatives for the same process step in the life cycle are listed. A) Pérez-Fortes et al. (2016b), B) Tschiggerl et al. (2018) (Pérez-Fortes et al., 2016a, Matzen and Demirel, 2016, Sternberg and Bardow, 2016, Walker et al., 2017, Artz et al., 2018) Matzen and Demirel 2016; Pérez-Fortes, et al. 2016a; Sternberg and Bardow 2016; Walker, et al. 2017; Artz, et al. 2018, C) Biernacki, et al. 2018 (however only for one of the cases, the other no energy production included), Bokinge 2020, Artz 2018, D) Hoppe 2018, E) Sternberg 2016, F) Fernández-Dacosta, et al. 2019, G) KOj 2018, Walker 2017, H) Bongartz, et al. 2018, Uusitalo 2017 Collet 2017, Zhang 2017, I) Deutz, et al. 2018, J) Liu 2020, Matzen 2016.

#### 5.4 MAIN CHALLENGES OF CURRENT METHODS AND PRACTICES IN LIFE CYCLE ASSESSMENT OF CARBON-BASED ELECTROFUELS

Results from paper A and B have primarily been applicable to electrofuel compared to conventional fuels. The following section aims to identify the main challenges also related to comparisons to or benchmarking against other future prospective technologies. The results in paper A points to the importance of including several impact categories and potential electricity sources, as the most beneficial electricity production option varies between impact categories. This result was confirmed in paper B, where the reviewed papers which analyzed a broader scope of impact categories showed a dependency on the electricity source.

One of the main challenges in LCA is to capture all relevant impact categories. In the work of this thesis some gaps in the knowledge of the environmental impacts have been identified. Acidification, eutrophication, and ozone depletion is indicated to be lower for electrofuels than conventional options both in Paper A and B. The impacts appear to be driven by material requirements, and the scope of the papers have primarily been limited to emissions from the direct production and use of the fuels rather than materials required in those processes. The results of Vo et al. (2018) indicate that if not renewable electricity is used for the fuel production emissions from the electricity production would be the main source of emissions contributing to acidification. However, this has only been assessed in a few papers in a few perspectives. When producing H<sub>2</sub> from electricity all articles found in paper B looked at production through water electrolysis. This technology has been available for the past 100 years but has not been used at a large commercial scale. Fresh water is a scarce resource and increased water use can be critical in some regions, and electrolysis requires water. The impact of water demand from electrofuels have not yet been assessed but might be of direct importance (Paper B). In the comparison with biofuels land use is established as a potential impact category of interest. This has also so far not been investigated fully.

Due to the losses of energy in each conversion step, it is easily assumed that direct use of electricity is probably beneficial from an environmental perspective. However, as shown in Paper C, the currently available direct electric propulsion technologies are limited by the range and space requirement to store electricity onboard vessels. Electrofuels and biofuels might therefore have to be used in this sector rather than direct electrification. In Figure 5 alternative routes to use electricity in maritime propulsion is outlined based on the analysis done in Paper C.

The functionality for an LCA of a different fuel and propulsion options varies parameters, and a more sophisticated functional unit might therefore be required if the differences in functionality between technologies are identified. For example, Paper C points out how a key aspect for using H<sub>2</sub> or electricity for shipping is related to the issue of storing large amounts of onboard storage. This might lead to lower capacity for shipping goods or humans on the vessel, and therefore slightly different functions. Another example is that the explosion risks for H<sub>2</sub> need to be considered in applications close to highly populated areas.

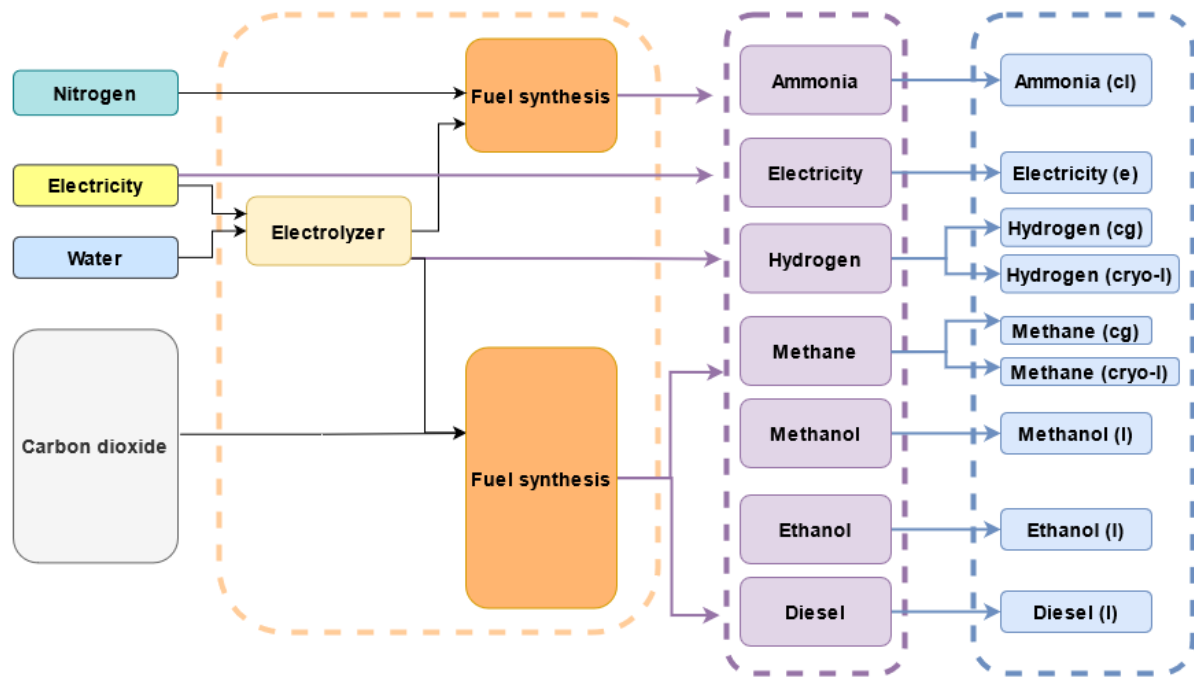


Figure 5 Different fuel production pathways, energy sources and final fuels for marine propulsion. The following abbreviation is used for physical state: l = liquid at standard temperature and pressure, e = energy in form of electrons stored in batteries, cg = compressed gas, cl = compressed liquid (liquid in compressed form), cryo-l = cryogenic liquid

In development processes decisions are consciously taken on how to design the technology (Sanden and Hillman, 2011). Initially few choices have been made and a lot of design freedom remains, however as the technology matures fewer decisions can be changed without stepping back in the design process (Unruh, 2000). This duality creates a scenario where information required to perform a full LCA is available at later stages in the design process, while decisions made early could be optimized for higher environmental performance if information on what would affect this were available (Arvidsson et al., 2018). Electrofuels are still at an early development stage, where a lot of uncertainty are still inherent to the system. Some of the technologies included in the LCA are under rapid development or are expected to be optimized further in the coming years (Ostergaard et al., 2020). As shown in Table 3, only four known production facilities are currently in use or in construction.

In summary, the selection of the functional unit is a key methodological step. The system boundaries should include all relevant processes (e. g., carbon capture), only excluding those common for two scenarios in a strict comparative analysis. A geographical scope must be defined, as this significantly influences several methodological choices (e. g., electricity source). All assumptions and simplifications should be justified and sufficiently described. The quality of data should be assessed. Uncertainty and sensitivity analyses must be performed to assess the quality and robustness of the results obtained.

Table 3 Operating and planned facilities for electrofuel production.

PROJECT NAME	OBJECTIVE	PROJECT TYPE	FOUNDER/MAIN PARTNERS
SUNFIRE PTL	Building of a demonstration electrofuel plant, combining hydrogen produced from renewable electricity and captured CO <sub>2</sub>	Operating production facility	
KOPERNIKUS P2X	Development of Power-to-X technologies, including to produce liquid fuels	Production facility	
CARBON RECYCLING INTERNATIONAL	Commercial electrofuel plant, producing methanol from hydrogen produced from geothermal electricity and captured CO <sub>2</sub>	Production facility	Carbon Recycling International
UNNAMED, PLANNED AT WACKERS BURGHAUSEN SITE	Production of electromethanol, a 20-megawatt electrolysis plant to generate hydrogen, using CO <sub>2</sub> from existing production processes. Expected capacity of 15,000 metric ton/year.	Planned production facility	Wacker Chemie AG, Linde GmbH
LIQUID WIND	Building of a commercial plant for an annual production of 50,000 ton electro-methanol (approx. 68 MW). Örnsköldsvik, Sweden. Expected to be ready 2024.	Production facility	Liquid Wind

Table 4 main challenges of assessing electrofuels using life cycle assessment

MAIN CHALLENGES	PROBLEM DESCRIPTION
<b>DETERMINING THE FUNCTION OF THE SYSTEM</b>	Identifying all functions of the system and benchmark against one or more comparative functionality set ups
<b>IDENTIFYING THE BENCHMARK SYSTEMS</b>	Assessments needs to be benchmark against the competing technologies for the relevant research question If several functionalities are identified the benchmark system needs to include all the same functions
<b>SETTING A SCOPE IN LINE WITH THE INVESTIGATED RESEARCH QUESTION</b>	Including the relevant and likely processes to include in the analyzed system, such as carbon source and electricity mix
<b>METHODICALLY INVESTIGATE THE LIMITATIONS OF THE RESULTS THROUGH SENSITIVITY ANALYSIS</b>	Technical development, or lack thereof, needs to be investigated for emerging technologies The interpretation of the results needs to be investigated for biases
<b>CHOICE OF SYSTEM BOUNDARY</b>	The choice of system boundary establishes the precise system investigated and is a central part of setting up a correct life cycle inventory
<b>DATA AVAILABILITY</b>	The limitation of available data can significantly impact the results or lead to simplifications which are not a reflection of reality Data gaps cannot always be considered at zero emissions or lack of impact
<b>FUTURE TECHNOLOGICAL DEVELOPMENT</b>	The unknown variable of future development is a challenge as it is a direct unknown factor and the uncertainty range not fully explored
<b>INCLUDING A BROAD SET OF ENVIRONMENTAL IMPACT CATEGORIES WITH A REASONABLE LEVEL OF UNCERTAINTY</b>	Essential to identifying trade-offs and create knowledge about the model and its functionality

# 6

*“Science is not about building a body of known ‘facts’. It is a method for asking awkward questions and subjecting them to a reality-check, thus avoiding the human tendency to believe whatever makes us feel good.”*

*– Terry Pratchett, The Science Of Discworld*

## DISCUSSION

The main part of the work in this thesis has been performed in the context of LCA. LCA is not the only assessment method to establish environmental effects from technologies and has its limitation. A primary aspect of LCA is that it looks at a steady-state system. The assessment is based on processes with fixed inflows and outflows related to processes. The work in this thesis on a system where many wicked problems interact, and the methodology discussion around system transformation, therefore, becomes essential. The techno-environmental system transforms from one equilibrium to another, and inheritably contains lock-in effects from interactions between technological systems and governing systems as discussed by Unruh (2000). The transition from one system to another might be affected by feedback interactions, which cannot be studied since they don't exist in the current reality.

In the context of this thesis, this phenomenon mainly becomes apparent regarding carbon lock-in effects. The availability of infrastructure for carbon-based fuels is discussed as a benefit to the electrofuels, but this could instead be given bias as we view the future system from a specific system starting point. The inherent risk is to value this too high or in the wrong way and reach a scenario where for example, limits in electrofuel production lead to future dependency on fossil fuels. Therefore, when providing guidelines to LCA and discussing research results, it is essential to analyze the specific context for each concept and not extrapolate results investigating one specific research question beyond the scope of that research. Some degree of dynamic models can and have been developed within this framework, and the model can also be set within a more dynamic model, such as the case for some ex-ante LCAs. In this thesis, the primary dynamic aspect considered is the uncertainties accounted for and the various concepts



compared, which does not qualify as a dynamic model. The results found in this thesis are from this perspective limited to analysis of potential trade-offs between electrofuels, fossil fuels, and biofuels, where the surrounding political, ecological, and technical systems are assumed to not change significantly. As such, to know the environmental performance of electrofuels in a scenario where the main environmental concern is not to keep a carbon budget but to maintain biodiversity, new analysis and assessments need to be performed.

## LESSONS LEARNED FROM USING LIFE CYCLE ASSESSMENT

The high variance of method choices in assessments of e-fuels have been analyzed and discussed in several scientific papers (Koj et al., 2019, Thonemann, 2020, Artz et al., 2018, Garcia-Garcia et al., 2021). A common conclusion for these earlier reviews is the need for a coherent assessment method for comparable results. Several methodological choices in LCA studies can significantly influence results, as shown in the result section of this thesis. The discrepancy between the climate change impact results from LCAs analyzing the same electrofuels was discussed in detailed by Artz et al. (2018). The main reasons identified for the differences were assumptions around how feedstocks should be viewed, the system boundary definition and the multifunctionality. Thonemann (2020) on the other hand concluded the functional unit, system boundary and the multifunctionality as key issues.

We have shown that the carbon intensity for the fuels when considering the full life cycle is dependent on the energy source for all fuels as well as the carbon source for carbon-based e-fuels. This result is confirmed by other studies, the newest being the review by Ueckerdt et al (2021), where the carbon mitigation effects of using e-fuels were discussed in detail. How to treat the carbon supply varies greatly between assessments, and the full options available was not investigated in any paper. For paper A, a direct carbon capture technology not yet in use was modeled as the carbon supply. This potentially led to increased uncertainty in the results, but as options which currently appears as directly preferred in the form of waste flows and biogenic sources was not used, it is unlikely to directly invalidate the results. The concept of net carbon emissions is central to the performance of electrofuels, and a life cycle perspective is essential in assessing if a technology leads to actual negative emissions.

### 5.5.1 The validity of the results

LCA is strongly dependent on the background system, as shown regarding the dependency on the emissions from the electricity production in the case study in paper A. It is therefore important to assess how different technologies perform in several potential future systems to indicate which emissions and processes have a large impact on the natural environment. Different technologies are assessed in several potential future systems to indicate which emissions, processes and over all circumstances (local regulations, electric mix or carbon taxes for instance) has a large impact on which technologies that are competitive and their environmental impacts. What is the current socio-technical system and how can the socio-technical regime change over time? In the scope of an LCA study the time period investigated is stated, but it is difficult to predict the future and an LCA study itself often does not investigate that change. Instead it makes assumptions about how the socio-technical system will look like, which of course are stated in the study but, if wrong, might affect the results greatly. Something a reader nor the writer might be aware of, or have investigated. LCA has moved from being used in waste management issues (something acknowledged to be a wicked problem), to database creation, to standardization, to the current methodology discussion (Hunt and Franklin

(1996), Bjørn et al (2018)).

Moving towards a more complex analysis where all aspects of limited environmental resources or critical ecosystem aspects are considered might lead to some points where electrofuels prove less efficient than today's conventional options. The focus of today's LCA research of electrofuels is, as shown in Paper B, often on greenhouse gas emissions and other air emissions, but the research is moving forward with better and better assessments of how emissions to seawater affect the marine environment. For these to be included in LCA, further development around what is emitted, in which quantities, how the emission occurs, and the impacts on the environment from these emissions is needed.

Despite the challenges within the assessment of electrofuels, important insights were gained by using LCA to assess electrofuels as marine fuels. It was possible to identify critical factors that significantly impact the overall results and highlight potential improvement areas. The results also show that emissions from fuel production significantly influence climate change and health, whereas direct emissions from marine engines are a significant part of other impact categories.

## 5.6 COMPLEXITY AND DATA UNCERTAINTY

A challenge when conducting this thesis was the availability of data both in the fuel production and in the use phase. The data used for fuel production was primarily extracted from process simulation papers, where modelling tools were used to simulate full plant production. LCAs of emerging technologies are sometimes limited to known direct physical relationships (Arvidsson et al., 2018), rather than full plant production. This can lead to assumption of higher energy efficiency that achieved in the real system, or underestimates of the need for supporting systems such as distillation or purification. The literature on electrofuels is still primarily based on these simpler analysis (Artz et al., 2018). These simplifications might have a significant impact on the LCA results, but only assessment connected to real measured data on a production plant could confirm the degree of the discrepancies.

The choice of what impacts we look at and what is included in each has both inherit values and explicit values, but there is rarely an ethical discussion round the implications. Human health is for instance often included when choosing environmental impacts to analyze in an LCA, whereas extinction of certain species is not. Intra-generational and inter-generational justice are both reflected in the choices of impact categories. As many LCA researchers aims at making results comparable geographical distribution of emissions are not compared separately, instead all impacts of one type of emissions are aggregated into the same number. This is not a major issue for substances with a global impact, such as greenhouse gas emissions effect on climate change, but sulphur emissions will affect acidification differently depending on the local environment where they are released and where these emissions occur will also affect which people are affected. Inter-generational justice becomes part of the LCA discourse when we talk about how long-time span into the future that is considered.

## 5.7 LIFE CYCLE ASSESSMENT AS A BASIS FOR DECISION MAKING

As presented in the introduction of this thesis, reaching regulatory requirements and having to

choose a specific marine fuel when building a vessel are drivers for the need of environmental assessment of shipping fuel. As life cycle assessment should not be aggregated into one singular decision parameter, determining the choice of fuel solely based on LCA is not recommended. To include a broader scope of factors this thesis looked at multi-criteria thinking as a potential route to increase information about a wider scope of impacts to decision makers. It was shown to also be possible to use as a basis for setting the scope of an LCA. The study in Paper C helped identifying future comparative alternative concepts as well as identifying variances in the function between options. Investigating if multi-criteria decision analysis or other methods such as social LCA or environmental impact assessment would be beneficial in decision making lies outside the scope of this thesis, but further discussions on the limitations of LCA is needed.

The need to formulate a coherent standardized framework for assessing electrofuels was brought forward in several review papers (Artz et al., 2018, Koj et al., 2019), and developing easy to use average data sets would be valuable and useful. However, using standardization to formulate regulatory frameworks and track the progress towards environmental goals is a different application from addressing research questions. There is a need to decouple the standardization based on comparison and feasibility in legislation and the method applied to give reasonable answers to research oriented enquires. The concept of avoided emissions is for example used in European regulation of biofuels produced from waste, however, when assessing the emissions of greenhouse gases from a technology in the distant future using avoided emissions incorporates assumptions of how the surrounding techno-environmental systems looks. As a prospective emerging technology, the scenario in which the assessment is conducted needs to be stated clearly and not limited by assumptions based in current techno-environmental reality.

LCAs is a tool that can be used to continually improve the environmental performance of shipping, although LCAs should be seen as one tool among several in decision support. The thesis highlights three important regulatory aspects:

- 1) First, the deemed environmental sustainability of the electrofuels in regulations must be tied to the primary energy used for production. The use of renewable energy is key to if the fuels meet their primary purpose of decreasing the impact on climate change, and therefore no general conclusion can be stated regarding their performance if the energy source is not considered.
- 2) Secondly, the carbon capture technology must be considered as well as if the production of electrofuels is driving demand of the carbon source. This relationship will likely change as the socio-technical system evolves, and a flexible framework is therefore likely preferable.
- 3) Thirdly, the potential supply of renewable fuels needs to be considered when regulation is developed to avoid or limit lock-in effects.

Further development of LCA and other forms of sustainability assessment such as multi-criteria analysis as a natural place in the maritime sector as regulations are introduced and the sector has a real impact on the environment and human health. New conceptual frameworks around sustainable innovation and which parameters are to be considered are still under development. The early description of sustainability as the consisting of three pillars; society, the economy, and the environmental, has been adjusted and adapted in various directions, including examples such as the concept of planetary boundaries or adding additional dimensions such as functional

or rational (Orellano et al., 2021). Increasing the complexity of assessments for shipping fuels to highlight further perspectives and create models closer to reality is thereby in line with research performed in the larger research community around sustainable development.

# 7

## FUTURE WORK

The next step within the research project HyMethShip involves establishing life cycle data connected to the performance of an onshore test system. The finalization of the demonstration unit means that the onboard carbon capture technology reaches a new technology readiness level, and more detailed information on today's performance can be gathered. Many technologies discussed in this paper are in their initial stages of technological development, and as such, the research will continue to update existing frameworks and results as new technological maturity arises. For future work, this also includes including a broader set of data points when assessing electrofuels. The current analysis is strictly limited to available data, and to develop stable evaluation methods, a more extensive set of known emission flows is needed. In the HyMethShip project, data is shared between the project partners, and further collaborations between industry and researchers to share data and insight would move the LCA field forward.

The next step in investigating the potential role of electrofuels in shipping and their environmental impacts involves broadening the scope of analyzed fuels. To reach imminent environmental goals, a transition of the total current vessel fleet needs to be considered. The work in this thesis has been limited to comparison with conventional fuels, and the question of electrofuels could be a preferable option in relation to today's system. As the world moves from fossil fuels to future renewable fuel options, comparisons of electrofuels to future carbon-free propulsion options are of interest. Further method development is required to establish the context for future alternative options. As discussed in this thesis, large-scale implementation of electrofuels is dependent on already existing infrastructure or the timescale of implementation. The surrounding future system will likely affect the differences between the environmental performance of using electrofuels in existing infrastructure and lower-emitting technologies, such as the use of H<sub>2</sub> in marine fuel cells. Therefore, including infrastructure and large-scale system changes is central when assessing electrofuels against other future low-carbon fuel options. When LCA is performed on such concepts, parameters such as carbon-lock in or other system resilience need to be considered.

A more detailed analysis of electrofuels that could replace fuels for the existing fleet is also needed. As LNG is a growing fuel in several vessel segments, electromethane could be a future

alternative to fossil fuels. Therefore, a central part of the future work is to establish a detailed LCA model for electromethane used in shipping. In this work, influence on the results from carbon utilization and climate change mitigation principles will be examined to take a step further into developing life cycle approaches where the environmental performance of the technology is investigated based on different potential future surrounding systems.

# 8

## CONCLUSION

This thesis aims to contribute to a life cycle perspective on the potential environmental performance of electrofuels within the maritime sector and provide insight into under what circumstances they might be beneficial. The aim was achieved by providing an LCA on the performance of electromethanol onboard a vessel, presenting a meta-analysis of the state-of-the-art of environmental assessment of electrofuels, and couple the results with the current knowledge of marine fuels in the current shipping fleet. A generic outline for the life cycle of electrofuels was established, and the main challenges of assessing the environmental performance of electrofuels were shown to relate to what is included in the life cycle.

Fuel does not only affect the surrounding environment when the vessel is used at sea but also the human activities connected to producing the fuel and propulsion equipment have emissions and would not occur if the fuel was not required. To be able to assess the environmental impacts of electrofuels, knowledge on the future production path, use characteristics, emissions to the environment, and efficiencies are therefore needed. It has been shown how accessibility to renewable electricity is a requirement for electrofuels to contribute to lower climate change impact. However, a reduction might only require electricity mixes on par with today's European nations. Other main influencing factors include the sustainability of the carbon source, marine engine characteristics, raw material extraction, and energy requirements for supporting systems in fuel production.

This thesis concludes that LCA can be used to address questions related to the life cycle environmental performance of marine fuels, but its ability to support decision-makers is currently limited on its own. The method is, however, less appropriate for addressing non-linear and non-environmental aspects of the fuel choice. The involvement of stakeholders and awareness of the limitations associated with method choices are central to the assessment's validity. LCAs should therefore be complemented with other tools for comprehensive assessments. It is also possible that the results from an LCA will not influence the final fuel choice decision but can still be used to support such a decision or impact the design of production processes.

## REFERENCES

- ABAD, A. V. & DODDS, P. E. 2020. Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. *Energy Policy*, 138.
- AGRAWAL, H., WELCH, W. A., MILLER, J. W. & COCKER, D. R. 2008. Emission measurements from a crude oil tanker at sea. *Environmental Science & Technology*, 42, 7098-7103.
- AL-BREIKI, M. & BICER, Y. 2021. Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization. *Journal of Cleaner Production*, 279.
- AL-MAMOORI, A., KRISHNAMURTHY, A., ROWNAGHI, A. A. & REZAEI, F. 2017. Carbon Capture and Utilization Update. *Energy Technology*, 5, 834-849.
- ALBRECHT, F. G. & NGUYEN, T.-V. 2020. Prospects of electrofuels to defossilize transportation in Denmark – A techno-economic and ecological analysis. *Energy*, 192.
- ANDERSSON, K., BRYNOLF, S., HANSSON, J. & GRAHN, M. 2020. Criteria and decision support for a sustainable choice of alternative marine fuels. *Sustainability (Switzerland)*, 12.
- ANDERSSON, K. B., F.; BRYNOLF, S.; LINDGREN, J. F.; GRANHAG, L.; SVENSSON, E.; 2016. Shipping and the environment. In: ANDERSSON, K. B., S.; LINDGREN, J. F.; WILEWSKA-BIEN, M. (ed.) *Shipping and the environment*. Berlin Heidelberg: Springer-Verlag.
- ARTZ, J., MULLER, T. E., THENERT, K., KLEINEKORTE, J., MEYS, R., STERNBERG, A., BARDOW, A. & LEITNER, W. 2018. Sustainable Conversion of Carbon Dioxide: An Integrated Review of Catalysis and Life Cycle Assessment. *Chem Rev*, 118, 434-504.
- ARVIDSSON, R., TILLMAN, A. M., SANDEN, B. A., JANSSEN, M., NORDELOF, A., KUSHNIR, D. & MOLANDER, S. 2018. Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA. *Journal of Industrial Ecology*, 22, 1286-1294.
- BAENA-MORENO, F. M., RODRÍGUEZ-GALÁN, M., VEGA, F., ALONSO-FARIÑAS, B., VILCHES ARENAS, L. F. & NAVARRETE, B. 2018. Carbon capture and utilization technologies: a literature review and recent advances. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 41, 1403-1433.
- BALCOMBE, P., BRIERLEY, J., LEWIS, C., SKATVEDT, L., SPEIRS, J., HAWKES, A. & STAFFELL, I. 2019. How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management*, 182, 72-88.
- BALCOMBE, P., STAFFELL, I., KERDAN, I. G., SPEIRS, J. F., BRANDON, N. P. & HAWKES, A. D. 2021. How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. *Energy*, 227.
- BALDI, F., AZZI, A. & MARECHAL, F. 2019. From renewable energy to ship fuel: ammonia as an energy vector and mean for energy storage. *29th European Symposium on Computer Aided Process Engineering, Pt B*, 46, 1747-1752.
- BAUMANN, H. T., A.; 2002. *The hitch hiker's guide to LCA*, Lund, Studentlitteratur.
- BENGTSSON, S., ANDERSSON, K. & FRIDELL, E. 2011a. A comparative life cycle assessment of marine fuels: Liquefied natural gas and three other fossil fuels. *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, 225, 97-110.
- BENGTSSON, S., ANDERSSON, K. & FRIDELL, E. 2011b. A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels. *Proceedings of the Institution of Mechanical Engineers Part M-Journal of Engineering for the Maritime Environment*, 225, 97-110.
- BICER, Y. & DINCER, I. 2018a. Clean fuel options with hydrogen for sea transportation: A life cycle approach. *International Journal of Hydrogen Energy*, 43, 1179-1193.
- BICER, Y. & DINCER, I. 2018b. Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: A comparative evaluation. *International Journal of Hydrogen Energy*, 43, 4583-4596.
- BIERNACKI, P., RÖTHER, T., PAUL, W., WERNER, P. & STEINIGEWEG, S. 2018. Environmental impact of the excess electricity conversion into methanol. *Journal of Cleaner Production*, 191, 87-98.
- BILGILI, L. 2021a. Comparative assessment of alternative marine fuels in life cycle perspective. *Renewable and Sustainable Energy Reviews*, 144.
- BILGILI, L. 2021b. Life cycle comparison of marine fuels for IMO 2020 Sulphur Cap. *Science of the Total Environment*, 774.
- BOKINGE, P., HEYNE, S. & HARVEY, S. 2020. Renewable OME from biomass and electricity—Evaluating carbon footprint and energy performance. *Energy Science & Engineering*, 8, 2587-2598.
- BONGARTZ, D., DORÉ, L., EICHLER, K., GRUBE, T., HEUSER, B., HOMBACH, L. E., ROBINIUS, M., PISCHINGER, S., STOLTEN, D., WALTHER, G. & MITSOS, A. 2018. Comparison of light-duty transportation fuels produced from renewable hydrogen and green carbon dioxide. *Applied Energy*, 231, 757-767.
- BOULDING, K. E. 1956. General Systems-Theory - the Skeleton of Science. *Management Science*, 2, 197-208.
- BRUNEKREEF, B. & HOLTGATE, S. T. 2002. Air pollution and health. *Lancet*, 360, 1233-1242.
- BRYNOLF, S., FRIDELL, E. & ANDERSSON, K. 2014a. Environmental assessment of marine fuels: Liquefied natural gas, liquefied biogas, methanol and bio-methanol. *Journal of Cleaner Production*, 74, 86-95.
- BRYNOLF, S., MAGNUSSON, M., FRIDELL, E. & ANDERSSON, K. 2014b. Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. *Transportation Research Part D-Transport and Environment*, 28, 6-18.
- CHERUBINI, F., BIRD, N. D., COWIE, A., JUNGMEIER, G., SCHLAMADINGER, B. & WOESS-GALLASCH, S. 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges



- and recommendations. *Resources, Conservation and Recycling*, 53, 434-447.
- COMER, B. O., N.; MAO, X.; ROY, B.; RUTHERFORD, D. 2017. Black carbon emission and fuel use in global shipping, 2015. 1225 Street NW, Suite 900, Washington DC 20005, USA: International Council on Clean Transportation.
- COOPER, D. G., T. 2004. Methodology for calculating emissions from ships: 2. Emission factors for 2004 reporting *Report series for SMED and SMED&SLU*. Folkborgsvägen 1, 601 76 Norrköping, Sweden: SMHI Swedish Meteorological and Hydrological Institute.
- CORBETT, J. J. & KOEHLER, H. W. 2003. Updated emissions from ocean shipping. *Journal of Geophysical Research-Atmospheres*, 108.
- CORBETT, J. J. & KOEHLER, H. W. 2004. Considering alternative input parameters in an activity-based ship fuel consumption and emissions model: Reply to comment by Oyvind Endresen et al. on "Updated emissions from ocean shipping". *Journal of Geophysical Research-Atmospheres*, 109.
- CORBETT, J. J. & WINEBRAKE, J. J. 2008. Emissions tradeoffs among alternative marine fuels: Total fuel cycle analysis of residual oil, marine gas oil, and marine diesel oil. *Journal of the Air and Waste Management Association*, 58, 538-542.
- CORMOS, A.-M., DINCA, C., PETRESCU, L., ANDREEA CHISALITA, D., SZIMA, S. & CORMOS, C.-C. 2018. Carbon capture and utilisation technologies applied to energy conversion systems and other energy-intensive industrial applications. *Fuel*, 211, 883-890.
- COYNE, R. 2005. Wicked problems revisited. *Design Studies*, 26, 5-17.
- CREUTZIG, F., RAVINDRANATH, N. H., BERNDES, G., BOLWIG, S., BRIGHT, R., CHERUBINI, F., CHUM, H., CORBERA, E., DELUCCHI, M., FAAIJ, A., FARGIONE, J. & HABERL, H. 2014. Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*.
- CUCINOTTA, F., RAFFAELE, M., SALMERI, F. & SFRAVARA, F. 2021. A comparative Life Cycle Assessment of two sister cruise ferries with Diesel and Liquefied Natural Gas machinery systems. *Applied Ocean Research*, 112.
- CUCURACHI, S., VAN DER GIESEN, C. & GUINÉE, J. Ex-ante LCA of Emerging Technologies. In: FANTKE, P., DONG, Y., LAURENT, A., OLSEN, S. I., BEY, N., NIERO, M. & LECLERC, A., eds. 25th CIRP Conference on Life Cycle Engineering, , CIRP LCE 2018, 2018. Elsevier B.V., 463-468.
- CUÉLLAR-FRANCA, R., DIMITRIOU, I., GARCÍA-GUTIERREZ, P., ELDER, R. H., ALLEN, R. W. K. & AZAPAGIC, A. 2015. Carbon Capture and Utilisation: Application of Life Cycle Thinking to Process Design. *Computer Aided Chemical Engineering*. Elsevier B.V.
- CUÉLLAR-FRANCA, R. M. & AZAPAGIC, A. 2015. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of CO2 Utilization*, 9, 82-102.
- CURRAN, M. A., VIGON, B. W., TOLLE, D. A., CORNABY, B. W., LATHAM, H. C., HARRISON, C. L., BOGUSKI, T. L., HUNT, R. G. & SELLERS, J. D. 1993. Life-cycle assessment: Inventory guidelines and principles. Cincinnati, Ohio, USA: Environmental Protection Agency.
- DAGGASH, H. A., PATZSCHKE, C. F., HEUBERGER, C. F., ZHU, L., HELLGARDT, K., FENNELL, P. S., BHAVE, A. N., BARDOW, A. & MAC DOWELL, N. 2018. Closing the carbon cycle to maximise climate change mitigation: power-to-methanol vs. power-to-direct air capture. *Sustainable Energy & Fuels*, 2, 1153-1169.
- DEUTZ, S., BONGARTZ, D., HEUSER, B., KÄTELHÖN, A., SCHULZE LANGENHORST, L., OMARI, A., WALTERS, M., KLANKERMAYER, J., LEITNER, W., MITSOS, A., PISCHINGER, S. & BARDOW, A. 2018. Cleaner production of cleaner fuels: wind-to-wheel – environmental assessment of CO<sub>2</sub>-based oxymethylene ether as a drop-in fuel. *Energy & Environmental Science*, 11, 331-343.
- EKVALL, T., AZAPAGIC, A., FINNVEDEN, G., RYDBERG, T., WEIDEMA, B. P. & ZAMAGNI, A. 2016. Attributional and consequential LCA in the ILCD handbook. *International Journal of Life Cycle Assessment*, 21, 293-296.
- ENDRESEN, O., SORGARD, E., BAKKE, J. & ISAKSEN, I. S. A. 2004. Substantiation of a lower estimate for the bunker inventory: Comment on "Updated emissions from ocean shipping" by James J. Corbett and Horst W. Koehler. *Journal of Geophysical Research-Atmospheres*, 109.
- EYRING, V., KOHLER, H. W., LAUER, A. & LEMPER, B. 2005. Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. *Journal of Geophysical Research-Atmospheres*, 110.
- FINNVEDEN, G., HAUSCHILD, M. Z., EKVALL, T., GUINEE, J., HEIJUNGS, R., HELLWEG, S., KOEHLER, A., PENNINGTON, D. & SUH, S. 2009. Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, 91, 1-21.
- GABRIELLI, P., GAZZANI, M. & MAZZOTTI, M. 2020. The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO<sub>2</sub> Emissions Chemical Industry. *Industrial & Engineering Chemistry Research*, 59, 7033-7045.
- GARCIA-GARCIA, G., FERNANDEZ, M. C., ARMSTRONG, K., WOOLASS, S. & STYRING, P. 2021. Analytical Review of Life-Cycle Environmental Impacts of Carbon Capture and Utilization Technologies. *ChemSusChem*, 14, 995-1015.
- GIBBINS, J. & CHALMERS, H. 2008. Carbon capture and storage. *Energy Policy*, 36, 4317-4322.
- GILBERT, P., WALSH, C., TRAUT, M., KESIEME, U., PAZOUKI, K. & MURPHY, A. 2018. Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production*, 172, 855-866.
- GOH, C. S. & LEE, K. T. 2010. A visionary and conceptual macroalgae-based third-generation bioethanol (TGB) biorefinery in Sabah, Malaysia as an underlay for renewable and sustainable development. *Renewable and Sustainable Energy Reviews*, 14, 842-848.

- GOLDSWORTHY, L. & GOLDSWORTHY, B. 2015. Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data - An Australian case study. *Environmental Modelling & Software*, 63, 45-60.
- HARTO, C., MEYERS, R. & WILLIAMS, E. 2010. Life cycle water use of low-carbon transport fuels. *Energy Policy*, 38, 4933-4944.
- HEIJUNGS, R. 2019. On the number of Monte Carlo runs in comparative probabilistic LCA. *The International Journal of Life Cycle Assessment*, 25, 394-402.
- HEINRICH, A. B. 2010. International reference life cycle data system handbook. *International Journal of Life Cycle Assessment*, 15, 524-525.
- HERMANSSON, F., JANSSEN, M. & SVANSTROM, M. 2020. Allocation in life cycle assessment of lignin. *International Journal of Life Cycle Assessment*, 25, 1620-1632.
- HO, D. P., NGO, H. H. & GUO, W. 2014. A mini review on renewable sources for biofuel. *Bioresource Technology*, 169, 742-749.
- HOPPE, W., THONEMANN, N. & BRINGEZU, S. 2018. Life Cycle Assessment of Carbon Dioxide-Based Production of Methane and Methanol and Derived Polymers. *Journal of Industrial Ecology*, 22, 327-340.
- HWANG, S., JEONG, B., JUNG, K., KIM, M. & ZHOU, P. 2019. Life cycle assessment of lng fueled vessel in domestic services. *Journal of Marine Science and Engineering*, 7.
- IMO 2018. Adoption of the initial IMO strategy on reduction of GHG emissions from ships and existing IMO activity related to reducing GHG emissions in the shipping sector. Note by the International Maritime Organization to the UNFCCC Talanoa Dialogue. In: ORGANIZATION, I. M. (ed.). London, UK.
- JALKANEN, J. P., JOHANSSON, L. & KUKKONEN, J. 2016. A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011. *Atmospheric Chemistry and Physics*, 16, 71-84.
- JEONG, B., JEON, H., KIM, S., KIM, J. & ZHOU, P. 2020. Evaluation of the lifecycle environmental benefits of full battery powered ships: Comparative analysis of marine diesel and electricity. *Journal of Marine Science and Engineering*, 8.
- JEONG, J., SEO, S., YOU, H. & CHANG, D. 2018. Comparative analysis of a hybrid propulsion using LNG-LH2 complying with regulations on emissions. *International Journal of Hydrogen Energy*, 43, 3809-3821.
- JESWANI, H. K., CHILVERS, A. & AZAPAGIC, A. 2020. Environmental sustainability of biofuels: a review. *Proc Math Phys Eng Sci*, 476, 20200351.
- KESIEME, U., PAZOUKI, K., MURPHY, A. & CHRYSANTHOU, A. 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. *Sustainable Energy and Fuels*, 3, 899-909.
- KLEINEKORTE, J., FLEITMANN, L., BACHMANN, M., KATELHON, A., BARBOSA-POVOA, A., VON DER ASSEN, N. & BARDOW, A. 2020. Life Cycle Assessment for the Design of Chemical Processes, Products, and Supply Chains. *Annu Rev Chem Biomol Eng*, 11, 203-233.
- KOJ, J. C., WULF, C. & ZAPP, P. 2019. Environmental impacts of power-to-X systems - A review of technological and methodological choices in Life Cycle Assessments. *Renewable and Sustainable Energy Reviews*, 112, 865-879.
- KORBERG, A. D., BRYNOLF, S., GRAHN, M. & SKOV, I. R. 2021. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. *Renewable and Sustainable Energy Reviews*, 142.
- KOYTSOUMPA, E. I., BERGINS, C. & KAKARAS, E. 2018. The CO2 economy: Review of CO2 capture and reuse technologies. *Journal of Supercritical Fluids*, 132, 3-16.
- LADANAI, S. & VINTERBÄCK, J. 2009. Global Potential of Sustainable Biomass for Energy. SLU, University of Agricultural Sciences. Department of Energy and Technology Uppsala.
- LIU, C. M., SANDHU, N. K., MCCOY, S. T. & BERGERSON, J. A. 2020. A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production. *Sustainable Energy and Fuels*, 4, 3129-3142.
- LUNDE HERMANSSON, A., HASSELLÖV, I.-M., MOLDANOVÁ, J. & YTREBERG, E. 2021. Comparing emissions of polyaromatic hydrocarbons and metals from marine fuels and scrubbers. *Transportation Research Part D: Transport and Environment*, 97, 102912.
- MALMGREN, E., BRYNOLF, S., FRIDELL, E., GRAHN, M. & ANDERSSON, K. 2021. The environmental performance of a fossil-free ship propulsion system with onboard carbon capture-a life cycle assessment of the HyMethShip concept. *Sustainable Energy and Fuels*, 5, 2753-2770.
- MANISALIDIS, I., STAVROPOULOU, E., STAVROPOULOS, A. & BEZIRTZOGLU, E. 2020. Environmental and Health Impacts of Air Pollution: A Review. *Frontiers in Public Health*, 8.
- MANOUCHEHRINIA, B., DONG, Z. & GULLIVER, T. A. 2020. Well-to-Propeller environmental assessment of natural gas as a marine transportation fuel in British Columbia, Canada. *Energy Reports*, 6, 802-812.
- MARON, M., IVES, C. D., KUJALA, H., BULL, J. W., MASEYK, F. J. F., BEKESSY, S., GORDON, A., WATSON, J. E. M., LENTINI, P. E., GIBBONS, P., POSSINGHAM, H. P., HOBBS, R. J., KEITH, D. A., WINTLE, B. A. & EVANS, M. C. 2016. Taming a Wicked Problem: Resolving Controversies in Biodiversity Offsetting. *BioScience*, 66, 489-498.
- MATZEN, M. & DEMIREL, Y. 2016. Methanol and dimethyl ether from renewable hydrogen and carbon dioxide: Alternative fuels production and life-cycle assessment. *Journal of Cleaner Production*, 139, 1068-1077.
- MCDONAGH, S., DEANE, P., RAJENDRAN, K. & MURPHY, J. D. 2019a. Are electrofuels a sustainable transport fuel? Analysis of the effect of controls on carbon, curtailment, and cost of hydrogen. *Applied Energy*, 247, 716-730.

- MCDONAGH, S., WALL, D. M., DEANE, P. & MURPHY, J. D. 2019b. The effect of electricity markets, and renewable electricity penetration, on the levelised cost of energy of an advanced electro-fuel system incorporating carbon capture and utilisation. *Renewable Energy*, 131, 364-371.
- MEADOWS, D. H. & MEADOWS, D. L. 1975. Study of Limits to Growth - Its Critics and Its Challenge. *Forensic Quarterly*, 49, 147-162.
- MERIEN-PAUL, R. H., ENSHAEI, H. & JAYASINGHE, S. G. 2018. In-situ data vs. bottom-up approaches in estimations of marine fuel consumptions and emissions. *Transportation Research Part D-Transport and Environment*, 62, 619-632.
- MEYER, C. B. 2001. A Case in Case Study Methodology. *Field Methods*, 13, 329-352.
- MULLER, L. J., KATELHON, A., BACHMANN, M., ZIMMERMANN, A., STERNBERG, A. & BARDOW, A. 2020. A Guideline for Life Cycle Assessment of Carbon Capture and Utilization. *Frontiers in Energy Research*, 8.
- OLINDO, R. & VOGTLÄNDER, J. G. 2019. The role of hydrogen in the ecological benefits of ultra low sulphur diesel production and use: An LCA benchmark. *Sustainability (Switzerland)*, 11.
- ORELLANO, M., LAMBHEY-CHECCHIN, C., MEDINI, K. & NEUBERT, G. 2021. A methodological framework to support the sustainable innovation development process: A collaborative approach. *Sustainability (Switzerland)*, 13.
- OSTERGAARD, P. A., DUIC, N., NOOROLLAHI, Y., MIKULCIC, H. & KALOGIROU, S. 2020. Sustainable development using renewable energy technology. *Renewable Energy*, 146, 2430-2437.
- OSTROM, E. 1990. Governing the commons: the evolution of institutions for collective action. *Governing the commons: the evolution of institutions for collective action*.
- PARRA, D., ZHANG, X., BAUER, C. & PATEL, M. K. 2017. An integrated techno-economic and life cycle environmental assessment of power-to-gas systems. *Applied Energy*, 193, 440-454.
- PAUL, J. & CRIADO, A. R. 2020. The art of writing literature review: What do we know and what do we need to know? *International Business Review*, 29.
- PÉREZ-FORTES, M., SCHÖNEBERGER, J. C., BOULAMANTI, A., HARRISON, G. & TZIMAS, E. 2016a. Formic acid synthesis using CO<sub>2</sub> as raw material: Techno-economic and environmental evaluation and market potential. *International Journal of Hydrogen Energy*, 41, 16444-16462.
- PÉREZ-FORTES, M., SCHÖNEBERGER, J. C., BOULAMANTI, A. & TZIMAS, E. 2016b. Methanol synthesis using captured CO<sub>2</sub> as raw material: Techno-economic and environmental assessment. *Applied Energy*, 161, 718-732.
- QUARTON, C. J. & SAMSATLI, S. 2020. The value of hydrogen and carbon capture, storage and utilisation in decarbonising energy: Insights from integrated value chain optimisation. *Applied Energy*, 257.
- RIDJAN, I., MATHIESEN, B. V. & CONNOLLY, D. 2016. Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: a review. *Journal of Cleaner Production*, 112, 3709-3720.
- RITTEL, H. W. J. & WEBBER, M. M. 1973. Dilemmas in a General Theory of Planning. *Policy Sciences*, 4, 155-169.
- SANDEN, B. A. & HILLMAN, K. M. 2011. A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. *Research Policy*, 40, 403-414.
- SANDEN, B. A. & KARLSTROM, M. 2007. Positive and negative feedback in consequential life-cycle assessment. *Journal of Cleaner Production*, 15, 1469-1481.
- SCHEMME, S., BREUER, J. L., KÖLLER, M., MESCHÉDE, S., WALMAN, F., SAMSUN, R. C., PETERS, R. & STOLTEN, D. 2020. H<sub>2</sub>-based synthetic fuels: A techno-economic comparison of alcohol, ether and hydrocarbon production. *International Journal of Hydrogen Energy*, 45, 5395-5414.
- SMITH, J. F. S. H. S. Z. P. P. B. C. E. H. W. S. V. D. L. T. 2020. Fourth IMO GHG Study. Delft, CE Delft: CE Delft.
- SMITH, T. W. P. J., J. P.; ANDERSON, B. A.; CORBETT, J. J.; FABER, J.; HANAYAMA, S.; O'KEEFFE, E.; PARKER, S.; JOHANSSON, L.; ALDOUS, L.; RAUCCI, C.; TRAUT, M.; ETTINGER, S.; NELISSEN, D.; LEE, D. S.; NG, S.; AGRAWAL, A.; WINEBRAKE, J. J.; HOEN, M.; CHESWORTH, S.; PANDEY, A. 2015. Third IMO GHG Study 2014. London, UK, .
- SNYDER, H. 2019. Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, 333-339.
- SOFIEV, M., WINEBRAKE, J. J., JOHANSSON, L., CARR, E. W., PRANK, M., SOARES, J., VIRA, J., KOUZNETSOV, R., JALKANEN, J. P. & CORBETT, J. J. 2018. Cleaner fuels for ships provide public health benefits with climate tradeoffs. *Nature Communications*, 9.
- STERNBERG, A. & BARDOW, A. 2015. Power-to-What? – Environmental assessment of energy storage systems. *Energy & Environmental Science*, 8, 389-400.
- STERNBERG, A. & BARDOW, A. 2016. Life Cycle Assessment of Power-to-Gas: Syngas vs Methane. *ACS Sustainable Chemistry & Engineering*, 4, 4156-4165.
- STOCKER, T. F., QIN, D., PLATTNER, G. K., TIGNOR, M. M. B., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. 2013. *Climate change 2013 the physical science basis: Working Group I contribution to the fifth assessment report of the intergovernmental panel on climate change*, Cambridge University Press.
- STOPFORD, M. 2009. *Maritime economics 3rd edition*, Abingdon, Oxon, Routledge.
- TAN, E. C. D., HAWKINS, T. R., LEE, U., TAO, L., MEYER, P. A., WANG, M. & THOMPSON, T. 2021. Biofuel Options for Marine Applications: Technoeconomic and Life-Cycle Analyses. *Environmental Science and Technology*.
- TANZER, S. E., POSADA, J., GERAEDTS, S. & RAMÍREZ, A. 2019. Lignocellulosic marine biofuel:

- Technoeconomic and environmental assessment for production in Brazil and Sweden. *Journal of Cleaner Production*, 239.
- TANZER, S. E. & RAMIREZ, A. 2019. When are negative emissions negative emissions? *Energy & Environmental Science*, 12, 1210-1218.
- THOMSON, H., CORBETT, J. J. & WINEBRAKE, J. J. 2015. Natural gas as a marine fuel. *Energy Policy*, 87, 153-167.
- THONEMANN, N. 2020. Environmental impacts of CO<sub>2</sub>-based chemical production: A systematic literature review and meta-analysis. *Applied Energy*, 263.
- TRILLOS, J. C. G., WILKEN, D., BRAND, U. & VOGT, T. 2021. Life cycle assessment of a hydrogen and fuel cell ropax ferry prototype. *Sustainable Production, Life Cycle Engineering and Management*. Springer Science and Business Media Deutschland GmbH.
- TSCHIGGERL, K., SLEDZ, C. & TOPIC, M. 2018. Considering environmental impacts of energy storage technologies: A life cycle assessment of power-to-gas business models. *Energy*, 160, 1091-1100.
- TURNPENNY, J., LORENZONI, I. & JONES, M. 2009. Noisy and definitely not normal: responding to wicked issues in the environment, energy and health. *Environmental Science and Policy*, 12, 347-358.
- UNRUH, G. C. 2000. Understanding carbon lock-in. *Energy Policy*, 28, 817-830.
- UUSITALO, V., VÄISÄNEN, S., INKERI, E. & SOUKKA, R. 2017. Potential for greenhouse gas emission reductions using surplus electricity in hydrogen, methane and methanol production via electrolysis. *Energy Conversion and Management*, 134, 125-134.
- VALENTE, A., IRIBARREN, D. & DUFOUR, J. 2017. Life cycle assessment of hydrogen energy systems: a review of methodological choices. *International Journal of Life Cycle Assessment*, 22, 346-363.
- VILLARES, M., İŞILDAR, A., VAN DER GIESEN, C. & GUINÉE, J. 2017. Does ex ante application enhance the usefulness of LCA? A case study on an emerging technology for metal recovery from e-waste. *International Journal of Life Cycle Assessment*, 22, 1618-1633.
- VO, T. T. Q., RAJENDRAN, K. & MURPHY, J. D. 2018. Can power to methane systems be sustainable and can they improve the carbon intensity of renewable methane when used to upgrade biogas produced from grass and slurry? *Applied Energy*, 228, 1046-1056.
- VON DER ASSEN, N., JUNG, J. & BARDOW, A. 2013. Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls. *Energy & Environmental Science*, 6, 2721-2734.
- WALKER, S. B., VAN LANEN, D., MUKHERJEE, U. & FOWLER, M. 2017. Greenhouse gas emissions reductions from applications of Power-to-Gas in power generation. *Sustainable Energy Technologies and Assessments*, 20, 25-32.
- ZHANG, X. J., WITTE, J., SCHILDHAUER, T. & BAUER, C. 2020. Life cycle assessment of power-to-gas with biogas as the carbon source. *Sustainable Energy & Fuels*, 4, 1427-1436.