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Environmental Assessment of Present and Future Marine Fuels

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Abstract

Our globalised world is connected by shipping, an industry powered by one of heaviest and dirtiest products of refining: heavy fuel oil. Tougher environmental regulations are now challenging the industry to take action. Ship-owners and operators are faced with the choice of installing exhaust gas cleaning technologies or switching to a different fuel altogether. The primary purpose of this thesis was to assess the environmental performance of present and future marine fuels and to evaluate potential methods and tools for their assessment.

Two different system approaches are used in this study: life cycle assessment (LCA) and global energy systems modelling. LCA is a well-established method for assessing the environmental performance of fuels. This type of assessment was complemented with the use of the Global Energy Transition (GET) model to investigate cost-effective fuel choices based on a global stabilisation of CO_2 emissions and the global competition for primary energy sources. The GET model includes all energy sectors and considers the interactions among them, but it is limited in scope to CO_2 emissions and costs. The LCAs involve a holistic systems perspective that includes the entire life cycle and various types of environmental impacts, but they are limited to analyses of one product or service at a time. These methods provide insights that are both contradictory and complementary.

This study concludes that there is substantial potential for reducing the environmental impact of shipping through a change in fuel types and/or the use of exhaust abatement technologies. A switch from heavy fuel oil to any of the alternatives investigated in this study reduces the overall environmental impact of marine fuels. The GET model indicates that it is cost-effective to phase out the use of crude oil-based fuels in the shipping sector and replace these fuels with the use of natural gas-based fuels during the next few decades. Based on the LCA results, the use of biofuels may be one possible way to reduce the impact of shipping on the climate, but biofuels may only be a cost-effective fuel in shipping if the corresponding annual available bioenergy resources are sufficiently large.

Three important implications are highlighted: the importance of reducing the NO_X emissions from marine engines, the need to regulate the methane slip from gas engines and the fact that a change in fuels may not reduce the impact of shipping on the climate.

Keywords: marine fuels, environmental impact, life cycle assessment, LCA, global energy systems modelling, shipping, heavy fuel oil, marine gas oil, liquefied natural gas, LNG, methanol, biofuels, exhaust gas abatement, scrubber, SCR

Preface

This thesis comprises work that was carried out at the Department of Shipping and Marine Technology at Chalmers University of Technology. The project, which is concerned with environmental assessment of marine fuels, is funded by Vinnova grants to Lighthouse. Lighthouse is a multidisciplinary maritime competence and research centre initiated by Chalmers, the School of Business, Economics and Law at the University of Gothenburg and the Swedish Shipowners' Association.

First and foremost, I would like to thank my supervisors Professor Karin Andersson and Adjunct Professor Erik Fridell who have supported me and contributed to this thesis by critically examining my assumptions, sharing their valuable comments and suggestions. Thanks also to Karin for always being available for questions and discussions and to Erik for questioning my opinions, correcting my fuzzy expressions and contributing with impressive knowledge in the field.

I would also like to thank the other co-authors of the appended papers. Mathias Magnusson for efficient collaboration with paper IV and Maria Taljegård, Maria Grahn and Hannes Johnson for the inspiring and challenging work with paper VI. It was rewarding and fun to collaborate!

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Furthermore, I am very grateful to everyone who has shown an interest in my work. They have all made it worthwhile and their interest in the subject has given my work meaning. I am grateful to all the informants and everyone who asked me questions and made comments. This has improved the work and I hope they will continue to show interest in my work and in which fuels will/should/could be used in shipping in the future.

Finally, I would like to thank all my colleges at Shipping and Marine Technology who helped me with information, comments, questions, discussions, supported me and cheered me up. I would also like to thank my family and friends for their support and for just being there. Special thanks go to Fredrik for putting up with and listening to all my talk about marine fuels, engines, emissions, LCA methodology and life as a doctoral student.

Selma Brynolf

Gothenburg, April 2014

List of Appended Papers

Paper I Bengtsson, S., Andersson, K. & Fridell, E. 2011. 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.

The author of this thesis contributed to the ideas presented, took part in the planning of the paper, collected data, performed the calculations in the life cycle assessment and prepared the majority of the manuscript.

Paper II Bengtsson, S., Fridell, E. & Andersson, K. 2012. Environmental assessment of two pathways towards the use of biofuels in shipping. *Energy Policy* 44, 451-463.

The author of this thesis contributed to the ideas presented, took part in the planning of the paper, collected data, performed the calculations in the life cycle assessment and prepared the majority of the manuscript.

Paper III Bengtsson, S., Fridell, E. & Andersson, K. 2014. Fuels for short sea shipping: A comparative assessment with focus on environmental impact. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 228, 42-52.

The author of this thesis contributed to the ideas presented, took part in the planning of the paper, collected data, performed the calculations in the life cycle assessment and prepared the majority of the manuscript.

Paper IV Brynolf, S., Magnusson, M., Fridell, E., Andersson, K., Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. Accepted (2013) for publication in a special issue of *Transportation Research D: Transport and Environment* with the theme of "Emissions Control Areas and their Impact on Maritime Transport."

The author of this thesis contributed to the ideas presented, took part in the planning of the paper, collected data, performed the calculations in the life cycle assessment and wrote parts of the manuscript.

Paper V Brynolf, S., Fridell, E. & Andersson, K. Environmental assessment of marine fuels: LNG, LBG, methanol and bio-methanol. Accepted (2014) for publication in *Journal of Cleaner Production*.

The author of this thesis contributed to the ideas presented, took part in the planning of the paper, collected data, performed the calculations in the life cycle assessment and prepared the majority of the manuscript.

Paper VI Taljegård, M., Brynolf, S., Granh, M., Johnsson, H. & Andersson, K. Cost-effective choices of marine fuels in a carbon-constrained world: results from a global energy model. Submitted for approval to scientific journal.

The author of this thesis contributed to the ideas presented, took part in the planning of the paper, collected portions of the data, participated in modifying the global energy model and analysing the results and wrote parts of the manuscript.

List of Other Relevant Publications

Bengtsson, S., Andersson, K. & Fridell, E. 2011. Life cycle assessment of marine fuels - A comparative study of four fossil fuels for marine propulsion. Gothenburg: Chalmers University of Technology.

Bengtsson, S., Andersson, K. & Fridell, E. 2011. Environmental feasibility of biogas and biodiesel as fuel for passenger ferries. SETAC Europe 17th LCA Case Study Symposium, 28 February - 1 March, 2011 Budapest. 53-54.

Bengtsson, S., Andersson, K., Fridell, E., 2012. Life Cycle Assessment of fuels for short sea shipping, 2012 International Research Conference on Short Sea Shipping, Lisbon.

Bengtsson, S., Andersson, K., Ellis, J., Haraldsson, L., Ramne, B., Stefenson, P., 2012. Criteria for future marine fuels, The IAME 2012 conference, 6-8 September, Taipei, Taiwan.

Baldi, F., Bengtsson, S., Andersson, K., 2013. The influence of propulsion system design on the carbon footprint of different marine fuels, Low Carbon Shipping Conference, London.

Grahn, M., Taljegård, M. Bengtsson, S., Andersson, K. & Johnson, H. 2013. Cost-effective choices of marine fuels under stringent carbon dioxide targets, Low Carbon Shipping Conference, London.

Brynolf, S., Kuvalekar, S., Andersson, K., 2014. Life cycle assessment of methanol and dimethyl ether (DME) as marine fuels. Department of Shipping and Marine Technology, Chalmers University of Technology, Gothenburg.

Table of Contents

Abbreviations, Acronyms and Terminology

This thesis uses terminology from two different fields. A list of the terminology has therefore been included to make it easier for readers. All abbreviations and acronyms used in the report are listed first, followed by the terms and concepts specific to environmental assessment, shipping and this thesis.

Abbreviations and Acronyms

BTL	Biomass-to-liquid (also called synthetic biodiesel)
BTL_w	Biomass-to-liquid (also called synthetic biodiesel) produced from willow (one of the fuels investigated in the LCAs)
CCS	Carbon capture and storage
CFC	Chlorofluorocarbons
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DALY	Disability-adjusted life year
DME	Dimethyl ether
ECA	Emission control area
EEDI	Energy Efficiency Design Index
FAME	Fatty acid methyl esters
FC	Fuel cells
GET	Global Energy Transition
GloTraM	Global transport model
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GTL	Gas-to-liquid (also called synthetic diesel)
GWP	Global warming potential
GWP_{100}	Global warming potential with a 100-year time horizon
GWP_{20}	Global warming potential with a 20-year time horizon
GWP_{500}	Global warming potential with a 500-year time horizon
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
HFO	Heavy fuel oil (one of the fuels investigated in the LCAs)
ICE	Internal combustion engines
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LBG	Liquefied biogas
LBG_{ar}	Liquefied biogas produced from agricultural residues, manure and municipal organic waste (one of the fuels investigated in the LCAs)
LBG_{fr}	Liquefied biogas produced from forest residues
LBG_w	Liquefied biogas produced from willow (one of the fuels investigated in the LCAs)
LCA	Life cycle assessment
LNG	Liquefied natural gas (one of the fuels investigated in the LCAs)
LPG	Liquefied petroleum gas
MCDA	Multi-criteria decision analysis
$MeOH_{ng}$	Methanol produced from natural gas (one of the fuels investigated in the LCAs)
$MeOH_w$	Methanol produced from willow (one of the fuels investigated in the LCAs)
MGO	Marine gas oil (one of the fuels investigated in the LCAs)

N_2O	Nitrous oxide
NECA	NO_X emissions control area
NH_3	Ammonia
nm	Nautical miles
NMVOC	Non-methane volatile organic compound
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxides
ODP	Ozone depletion potential
PM	Particulate matter
PM_{10}	Particulate matter with a diameter of 10 micrometres or less
$PM_{2.5}$	Particulate matter with a diameter of 2.5 micrometres or less
POCP	Photochemical ozone creation potential
RME	Rapeseed methyl ester (one of the fuels investigated in the LCAs)
Ro-ro	Roll-on-roll-off
SCR	Selective catalytic reduction
SECA	Sulphur emission control area
SEEMP	Ship Energy Efficiency Management Plan
SETAC	Society of Environmental Toxicology and Chemistry
SO_2	Sulphur dioxide
SOFC	Solid oxide fuel cells
SO_X	Sulphur oxides
TEAMS	Total Energy & Emissions Analysis for Marine Systems
UNEP	United Nations Environment Programme
VOC	Volatile organic compound

Terminology

Allocation	The term allocation refers to the distribution of flows between multiple units. 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 is described here as one method for solving allocation problems. Thus, allocation methods include both allocation (also called partitioning) and system expansion. Allocation can be achieved using, for example, a physical relationship or the monetary value of the products.
Alternative fuels	Alternative fuels are those potential fuels that can be used in shipping as alternatives to heavy fuel oil. In this study, these include both fossil and renewable fuels.
Areas of protection	Areas of protection are the entities that we want to protect and can be assigned to the categories of human health, the natural environment and natural resources.
Attributional	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 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.
Characterisation factors	Factors derived from a characterisation model that is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator. There are characterisation factors both at midpoints and endpoints.
Consequential	A consequential LCA is one that compares the environmental consequences of alternative causes of actions. 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 of resources and emissions associated with each process in the system.
Endpoint	The endpoint 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.
Eutrophication	Eutrophication is characterised by excessive plant and algal growth due to the increased availability of one or more limiting growth factors needed for photosynthesis. 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 first step in an LCA 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	In this study, 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 characterisation 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 analysis	The phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.
Methane slip	In this study, methane slip is the leakage of methane from marine engines.
Midpoint	Midpoints are considered to be links in the cause-effect chain (environmental mechanism) of an impact category. Common examples of midpoint

	characterisation factors include ozone depletion potentials and global warming potentials.
Natural environment	In this study, 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	In this study, 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	Ozone formation is complex and depends on a number of factors, e.g., the concentrations of NO, NO_2 and VOC and on the level of ultraviolet radiation.
Prospective	This term, meaning forward looking, is used to denote forward-looking LCAs.
Retrospective	This term, meaning backward looking, is used to denote backward-looking LCAs.
Ro-pax ferry	A ro-pax ferry is a ro-ro ship with high freight capacity and limited passenger facilities.
Ro-ro ships	Roll-on-roll-off (ro-ro) ships are designed for the loading and unloading of rolling cargo on ramps.
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.
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	In this study, used for 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	In this study, this term is used 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.

1 Introduction

There is growing interest in alternative fuels for marine propulsion, primarily as a result of stricter environmental regulations. Stricter requirements regarding the quality of fuel and the exhaust emissions in marine transportation are scheduled for introduction in various parts of the world during the next several years and will require the adoption of new technologies and/or fuels in the shipping industry.

Various fuels and exhaust-abatement technologies have been proposed for marine transportation, all of which have advantages and disadvantages in relation to the environment and human health. As new technologies and fuels are considered for marine transportation, knowledge of their performance at various system levels and from various perspectives will become increasingly important. Evaluations of various aspects of the choice of fuel will offer important support for decisions by ship-owners, businesses, administrators and policymakers. This thesis addresses environmental assessments of marine fuels, with particular attention to their life cycle performances.

1.1 Background

Shipping has a long history, and the first cargoes were transported by sea more than 5000 years ago (Stopford, 2008). Shipping is currently an important part of the global economy and is an essential part of global transportation, carrying approximately 80% of global merchandise trade by volume (UNCTAD, 2013). Shipping is also an efficient mode of transport and consumes less fuel than do other modes per a given mass and distance (Buhaug et al., 2009).

1.1.1 Shipping and Environmental Concerns

Environmental concerns have been raised regarding shipping's growing contribution to acidification, eutrophication, climate change and human health impacts. These contributions are caused by increasing emissions from shipping to the air, which have been well documented since the end of the 1990s (Buhaug et al., 2009; Corbett and Fischbeck, 1997; Corbett and Koehler, 2003; Endresen et al., 2003; Eyring et al., 2005b). This increase can be attributed to a lack of strict emissions regulations and an annual growth of 4% or more in sea-transported cargo from 1986 onwards (Buhaug et al., 2009; Eyring et al., 2010). Nearly 70% of the airborne emissions from shipping occur within 400 km of land (Eyring et al., 2010), causing the potential effects on coastal communities to be particularly important.

Carbon dioxide (CO_2), released during fossil fuel combustion and deforestation, is the largest contributor to radiative forcing in the climate system (IPCC, 2007). In 2007, shipping was responsible for the release of approximately 1.0 Gt of CO_2, representing approximately 3.3% of global anthropogenic CO_2 emissions (Buhaug et al., 2009). This figure constitutes a modest share of global CO_2 emissions, but these emissions are expected to increase to 1.1-3.7 Gt of annual release of CO_2 through 2050 in various future development scenarios, indicating a potential increase of up to 350% compared to the rate in 2007 (Buhaug et al., 2009; Eyring et al., 2005a; ICCT, 2011; Vergara et al., 2012). This increase stands in contrast to a shipping industry commitment to an equal sharing of the burden of limiting the temperature to a 2°C global increase,[1] which would require the industry to

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[1] The Bali Climate Declaration of 2007 states that the primary goal shall be to limit global warming to no more than 2°C above the pre-industrial temperature (CCRC, 2014), which, according to the Intergovernmental Panel on Climate Change

reduce its emissions significantly before 2050 (approximately 80% of 1990 levels) (Anderson and Bows, 2012).

Nitrogen oxides (NO_X) emissions are, for example, contributing to acidification, eutrophication and human health impacts (Harrison, 2001), and approximately 15% of the global anthropogenic emissions of NO_X are estimated to originate from shipping (Eyring et al., 2010). In Europe, shipping contributed to approximately 20-40% of the NO_X emissions in 2010, and the emissions from shipping may potentially exceed emissions from land-based sources by 2020 (European Environment Agency, 2013).

Sulphur dioxide (SO_2) emissions contribute to the formation of acid rain and adversely impacts human health (Harrison, 2001). Marine fuels contain much higher amounts of sulphur than do road fuels, resulting in greater emissions of SO_2. The average sulphur content in residual fuel was approximately 2.7% in 2007 (European Environment Agency, 2013) compared to the maximum allowed sulphur content of 10 ppm in road fuels (European Commission, 2009b).[2] This contribution from shipping represents 4-9% of the total anthropogenic emissions (Eyring et al., 2010).

The primary concern regarding the emissions of particulate matter (PM) involves their health effects (Harrison, 2001). In addition, PM contributes to climate change due to both direct effects on the radiative balance and indirect effects through increased cloud formation (Eyring et al., 2010; Lauer et al., 2007). Corbett et al. (2007) estimated that approximately 3-5% of global mortality caused by PM less than 2.5 micrometres in diameter ($PM_{2.5}$) is attributed to marine transportation. The contribution of shipping to local PM concentrations can be as high as 20-30% in Europe (European Environment Agency, 2013).

1.1.2 Stricter Regulations of Shipping-related Emissions to the Air

The increased attention to air emissions from shipping in recent years[3] has resulted in stricter regulations. The International Maritime Organization (IMO), the special United Nations agency responsible for the safety and security of shipping and the prevention of marine pollution by ships,[4] has adopted regulations regarding the sulphur content in marine fuels and the emissions of NO_X (IMO, 2013a). It is also expected that the PM emissions will be reduced indirectly by these regulations.

The global limit on the sulphur content of marine fuels will be reduced significantly to 0.5% sulphur by 2020 or, at the latest, 2025,[5] versus the present cap of 3.5%. This regulation is stricter in certain emission control areas (ECAs). Beginning in 2015, emissions of SO_2 will be limited to the equivalent of 0.1 wt. % sulphur in combusted fuel within the sulphur emission control areas (SECAs) in the

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fourth assessment report, corresponds to a stabilisation of atmospheric CO_2 concentrations at 445–490 ppm, which is approximately 400 ppm CO_2 (IPCC, 2007).

[2] 2.7% is equal to 27,000 ppm, which is 2700 times more than 10 ppm.

[3] The concern regarding emissions to the air from shipping, however, is much older. This concern was mentioned in 1968, in Inter-Governmental Maritime Consultative Organization (IMCO) Resolution C.42 (XXI): “the effects of the behaviour of ships and vessels and other equipment operating in the marine environment upon interests, by: (a) placing restraints upon the contamination of the sea, land and air or other similar injury by or from ships and vessels and other equipment operating in the marine environment” (IMCO, 1968). The name of IMCO was changed to IMO in 1982.

[4] The primary international convention regulating pollution from shipping is the “International Convention on the Prevention of Pollution from Ships”, known as MARPOL 73/78. This convention was first adopted by the International Maritime Organization (IMO) in 1973. The convention was designed to reduce pollutant emissions from ships in the event of accidents and during routine operations. It includes six technical annexes, the last one being, Annex VI, titled “Regulations for the Prevention of Air Pollution from Ships”, which entered into force in May 2005.

[5] A review of the availability of fuel oil is to be completed in 2018. If the parties decide that it is impossible for ships to comply, then the standard will postponed until 2025 (IMO, 2013a). The sulphur content in marine fuels in the European Union is reduced to 0.5% by 2020 (European Commission, 2012).

Baltic Sea, the North Sea, the English Channel, the United States Caribbean Sea and along the coasts of the United States and Canada.

The first regulations of NO_X emissions were introduced for engines produced after the year 2000 (Tier I engines). The Tier II standard applies to engines produced after 2011 and represents a decrease of approximately 20% in NO_X emissions compared to Tier I levels. In the existing NO_X emission control areas (NECAs), the North American ECA and the United States Caribbean Sea ECA, Tier III will be required for ships constructed from 2016 (IMO, 2014a, b; Svensson, 2014), [6] and will represent a decrease of approximately 80% in NO_X emissions compared to Tier I levels.

The IMO adopted measures to reduce the emissions of greenhouse gases from shipping in 2011 by introducing the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships. These measures entered into force in 2013 (IMO, 2013a). In addition, the European Commission's white paper "Roadmap to a Single European Transport Area", dated 2011, states that CO_2 emissions from maritime transport in the European Union should be reduced by 40% by 2050 compared to 2005 levels (European Commission, 2011).

These environmental concerns regarding marine transportation and these new regulations are driving forces behind the introduction of new marine fuels. Other driving forces behind changes in the types of fuel are increasing fuel prices and uncertainties regarding future resource availabilities. Fuel costs represent a significant share of the current operating cost of maritime vessels and were estimated to be in the range of 30-54% of operating cost in 2006, depending on the type of vessel (Kalli et al., 2009). This fuel cost is expected to increase due to the upcoming sulphur regulations, resulting in an even greater impact on a vessel's operating cost (Kalli et al., 2009). The choice of fuel in the marine industry has historically been driven by economics to a large degree. In the 1940s, when a large-scale shift in fuel from coal to oil occurred, marine engines were developed for operation using the cheap residual fractions from crude oil refining, i.e., heavy fuel oil (HFO) (Corbett, 2004).

1.1.3 Historical Changes in Marine Propulsion and Fuels

Marine propulsion has changed a few times over the course of history (Figure 1-1). Human power (oars) and wind power were used in the beginning, followed by steam engines and steam turbines fuelled with coal at the start of the nineteenth century. Early steam ships used masts and sails because the engines were generally regarded as auxiliaries for assisting the sails (Clark, 1988), and the full transition from sail to steam spanned more than 50 years (Stopford, 2008). The steam engine changed marine transport in the sense that marine transportation was no longer dependent on the wind.

Most steam engines were replaced by marine engines fuelled by diesel and residual oil. Between the shift from steam engines to internal combustion engines (ICEs), there was a fuel shift from coal to oil that made the transition possible. During World War I, warships were built with oil-fired boilers or were converted from coal to oil. This shift increased the steam boiler output and/or reduced the storage requirements, thereby increasing the power output of the warship (Clark, 1988). Furthermore, oil-powered steam engines required smaller crews and provided a greater operational range and the possibility of easier refuelling at sea (Corbett, 2004).

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[6] There is and exception of a five year delay for large yachts (greater than 24 metres in length and of less than 500 gross tonnage) for Tier III in existing ECAs. In new NECAs Tier III will be required for ships constructed on or after the date of adoption of such an ECA, or a later date as may be specified in the amendment designating the NECA, whichever is later. This was agreed upon during the sixty-six session of the Marine Environmental Protection Committee (MEPC) held at IMO headquarters from 31 March to 4 April 2014 (IMO, 2014a, b; Svensson, 2014). The final report from the session was not available before this thesis was printed.

The first diesel powered ship went into service in 1912 and was followed by a transition to diesel engines over the next 50 years, with the exception of the most powerful ships (Stopford, 2008). Steam engines are still used in most LNG carriers, which use the boil-off gas as fuel. However, over the past decade, other types of propulsion systems have been considered for LNG carriers, involving various configurations of diesel engines, electric drives and gas turbines (MAN Diesel & Turbo, 2007). Steam turbines are less efficient than diesel engines, and the trend in new LNG carriers is toward propulsion by diesel or dual-fuel engines (Chang et al., 2008; Wiggins, 2011).

Currently, residual fuel, or HFO,[7] is used in the majority of marine engines. In 2007, nearly 350 million tonnes of fuel was consumed by shipping, and approximately 250 million tonnes of these fuels were residual fuels (Buhaug et al., 2009). The use of HFOs in marine engines followed John Lamb's experiments in the early 1950s and was first applied to slow-speed diesel engines. It came into general use in medium-speed diesel engines in the 1960s (Tree, 1979).

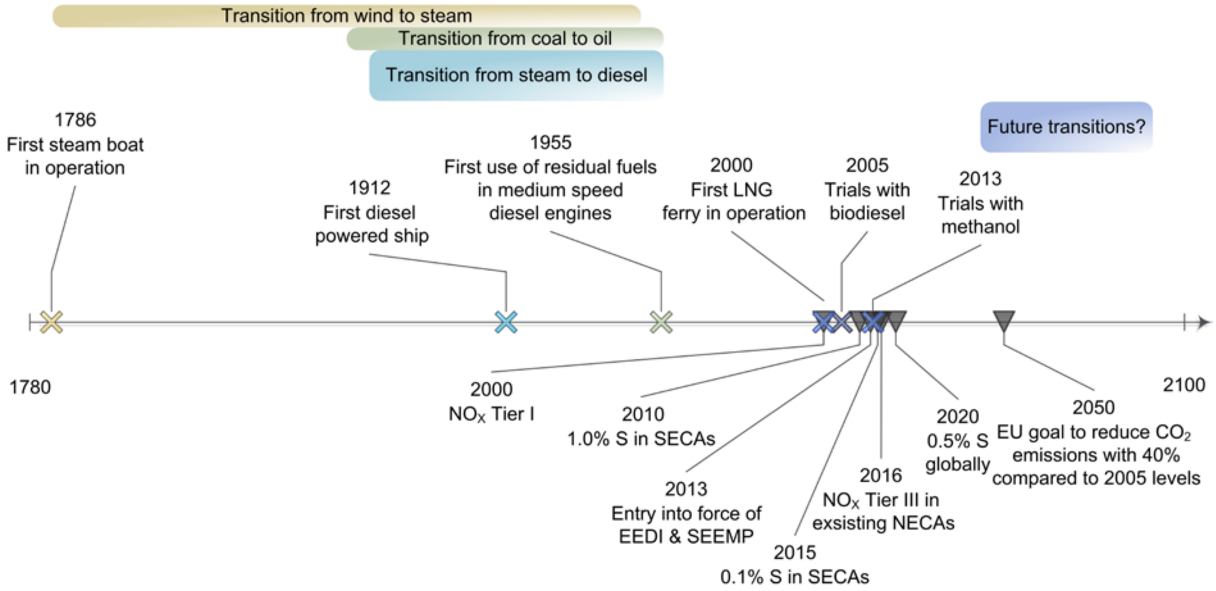

Figure 1-1 Timeline for the transitions of marine fuels from 1780 to 2100 with selected events in history and environmental regulations.

HFO is now the dominant shipping fuel, but a number of *alternative fuels*[8] are being proposed and tested, including, for example, liquefied natural gas (LNG), biodiesel, methanol and glycerol. LNG is used in Norway and is promoted as a future ship fuel. Biodiesel has been tested for marine propulsion by, for example, Maersk Line, a Danish container shipping company (Gallagher, 2010), and by the United States navy (Bruckner-Menchelli, 2011). It has also promoted as a suitable fuel for marine propulsion by, for example, Mihic et al. (2011) and Lin and Huang (2012). The potential use of methanol as a marine fuel gained attention through Effship, a Swedish research and development project (Fagerlund and Ramne, 2013). As a result of this work, Stena Line, a large ferry operator primarily operating in northern Europe, now plans to convert a number of their vessels to methanol propulsion (Einemo, 2013). Mitsui O.S.K. Lines, a Japanese ocean shipping company, signed a contract in December 2013 to build and charter three methanol carriers equipped with flex-fuel engines that can run on methanol, fuel oil or gas oil (Mitsui O.S.K. Lines, 2013). Glycerol is being evaluated in the GLEAMS project in the UK (Macqueen, 2014), and Vergara et al. (2012) suggested

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[7] The terms residual fuels and HFO are used interchangeably in this thesis.

[8] The term *alternative fuels* in this thesis is used to describe fuels that are alternatives to HFO in shipping. The term is occasionally used elsewhere as a synonym of renewable fuels but is not in this thesis.

the use of synthetic fuels produced from carbon dioxide and hydrogen. Thus, there are many alternatives to select from and to evaluate.

Recently, several fuels have been proposed for marine transportation, all of which have advantages and disadvantages in terms of the environment and human health. As new technologies and fuels are considered for marine transportation, knowledge of their performance at various system levels and from various perspectives will become increasingly important.

1.2 Purpose and Approach

The purpose of this thesis was to assess the environmental performance of present and future marine fuels and to evaluate potential methods and tools for their assessment. The challenge of developing relevant comparisons between various types of fuels for future shipping is one driving force behind this assessment. The primary question addressed in this thesis is the following: *What is the environmental performance associated with existing and potential future marine fuels?*

To answer this question, we must be able to measure environmental performance. However, what really is environmental performance? The concept is primarily used in environmental management, particularly when discussing the relationships between environmental performance and economic performance. However, a general definition of the concept is difficult to find. The concept of corporate environmental performance is described in detail by Trumpp et al. (2013) and by other authors. Environmental performance indicators are, according to Dada et al. (2013), used to measure the organisation’s impact on the environment, including its ecosystems, land, air and water. Analogous with this definition, the *environmental performance* of a product or service, such as fuels and marine transportation, may be defined as the environmental impact on the environment caused by the product or service. Products and services have environmental impacts throughout their life cycles. For example, marine fuels have an impact on the environment from the time when the raw materials are mined to produce the fuel and though its production, distribution and final use in marine transportation. These fuels may also be associated with several types of environmental impacts, such as acidification, global warming and adverse health effects. There is a need for a systems approach to gain a holistic view of the environmental impacts caused by marine fuels. A systems perspective and a systems approach are therefore the basis of this work.

Environmental systems analysis is a branch of systems analysis used to analyse, interpret, simulate and communicate complex environmental issues from various perspectives and includes several methods and tools for the systems-based environmental assessment of human-made systems. There are several definitions of environmental systems analysis, and all include complex decision situations and a multidisciplinary approach.

The environmental considerations can be integrated into several types of decisions using environmental assessments. There is a wide range of environmental assessment methods and tools available for evaluating and benchmarking various technology options (Wrisberg, 2002). These methods and tools include life cycle assessment (LCA), environmental impact assessment, environmental risk assessment, cost benefit analysis and multi-criterion decision analysis (MCDA). Each of these methods is suitable for a specific type of evaluation and for addressing a specific type of question.

Two primary tools are used in this thesis to assess marine fuels: LCA and the Global Energy Transition (GET) model. Both of these are based on a systems approach. LCA was used throughout to evaluate the fuels’ environmental performance. LCA is a commonly used tool in the environmental assessment of products and services and addresses the potential environmental impact of a product or service from a cradle-to-grave perspective (ISO, 2006a). The GET model provides another perspective in that it takes into account the most cost-efficient way to distribute limited resources on a global scale while allowing atmospheric CO_2 stabilisation targets to be reached. The fuel with the lowest life cycle environmental impact is not necessarily the best fuel for use in shipping when considering the most cost-efficient way to stabilise global atmospheric concentration of CO_2. Four more detailed questions related to the primary question were also addressed during the study:

1) *Which fuels are noteworthy and merit assessment?*

The focus in this thesis is on providing an overview of potential future marine fuels and a first analysis of their associated environmental impacts. Several strategies were used to understand which fuels are of interest in the shipping sector in the future. These strategies include, for example, visits to industry conferences, research of shipping journals and websites, discussions with industry representatives, evaluations of potential fuels against a set of criteria based on MCDA and the use of the GET model to assess which fuels are most cost-effective for use in a carbon-constrained world.

2) *How will the use of exhaust gas abatement technologies impact the results?*

Existing and future marine fuels can also be used with exhaust abatement technologies to comply with the upcoming regulations. It is therefore also interesting to assess the environmental performance of these combinations. Two possible exhaust abatement technologies were assessed: scrubbers (to reduce SO_2 emissions in the exhaust gas) and selective catalytic reduction (SCR) units (to reduce NO_X in the exhaust gas). These were combined with fuels that do not comply with the 0.1% sulphur regulations and/or the NO_X Tier III regulations and were assessed using LCA. This assessment complemented the assessments of fuel use without exhaust gas abatement technologies.

3) *What factors in the marine fuel life cycle are most important in their overall environmental performance?*

As mentioned above, marine fuels are associated with environmental impacts over the entire fuel life cycle, and to reduce these life cycle impacts, it is important to understand which factors and choices contribute the most to the overall environmental impact. This question was assessed using LCA to analyse the contributions of various emissions and various parts of the life cycles to the overall impacts.

4) *How will the choice of methods used in the assessment impact the results?*

It is also important to understand how the methods and tools used in the assessment impact the results. This understanding is critical to providing relevant comparisons between the various fuels. The LCA and the GET model were, therefore, continually evaluated as tools to support decisions regarding the choice of fuel in the shipping industry. The difficulties and issues with the use of LCA are identified and discussed.

1.3 Scope

The LCAs in this thesis are focused on merchant shipping in northern Europe. The results can therefore only be extrapolated with caution to the environmental performance of marine fuels beyond northern Europe and are not applicable to leisure craft and naval shipping. A global scope is provided with global energy systems modelling with the GET-model.

1.4 Outline of the Thesis

This thesis is divided into seven chapters that describe the environmental assessment of present and future marine fuels. The next section, *Systems Perspective and Environmental Assessment*, describes the theoretical framework of this thesis, including systems concepts, systems theory and the approaches used, i.e., LCA and global energy systems modelling. The LCA section describes the primary steps in an LCA and the important methodological choices. This section is followed by a description of a few of the most common impact categories used in an LCA. The importance of including each impact category is related to whether it is affected by a change in the fuels used in marine transportation. The section regarding the modelling of global energy systems introduces the primary types of models used and describes the GET model used in this study in more detail.

Chapter 3, *Present and Possible Future Marine Fuels*, provides an overview of the present and possible marine fuels and presents a set of criteria that can be used to evaluate these fuels. The chapter ends with a description of the availability of the primary energy sources. Chapter 4, *Method*, describes the specific choices made and data used in this thesis.

The results from the appended papers are presented and discussed holistically in chapter 5, *Results and Discussion*. The results of a life cycle inventory of the assessed marine fuels are presented as are their environmental performance with and without exhaust abatement technologies. In addition, two important aspects are discussed: the impact of methane leakage from LNG fuel systems and the future changes in refinery production. The results are also compared with those of other studies. This chapter ends with a discussion of the fuels that are cost-effective on a global level in a carbon-constrained world.

Chapter 6, *Systems Assessments for Evaluation of Marine Fuels*, discusses the most critical methodological choices in the LCAs and the GET model and reflects upon the appropriateness of the approaches as tools for the environmental assessment of marine fuels. The final chapter, *Concluding Remarks*, includes a summary of the main findings and implications for policy-making and provides directions for future work.

2 Systems Perspective and Environmental Assessment

Two systems approaches, starting from different levels in the system, were used in this study: LCA and energy systems modelling. This chapter provides a brief introduction to these approaches.

2.1 Systems Thinking

Systems theory or systems thinking has its roots in general systems theory of the 1950s developed by Boulding (1965), among others, and has since developed in several directions. A system can be regarded as consisting of a number of components and the connections between them (Ingelstam, 2002) (Figure 2-1). Together, these components and connections form a whole. The system is perceived as more than its components and, as such, it has properties that differ from the properties of the individual components. The system is separated from the rest of the world by system boundaries, and the parts outside are called the surroundings or environment. Interactions with the surroundings occur through input or output of, for example, information, material and energy. It is important to make a distinction between a real system and a system model. A system model is created by an analyst for a specific purpose and is inevitably a simplification of the “real” system. There are various types of systems, 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 also involves society; thus, nature-society-technology systems are assessed in this study.

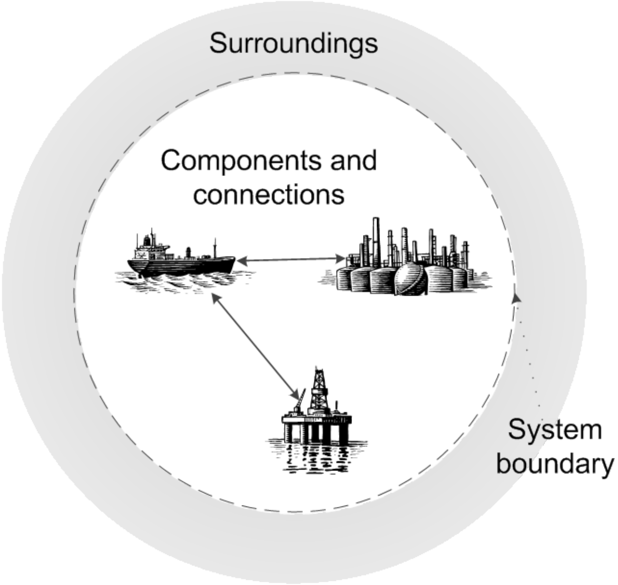

Figure 2-1 General concepts of system theory (adopted from Ingelstam (2002)).

A system can usually be divided into sub-systems that are considered part of the larger system. There are thus many system levels. A marine engine can be considered a system that consists of engine parts and that interacts with the surroundings, i.e., the ship, by converting chemical energy into mechanical energy. The conversion of chemical energy into mechanical energy is thus the function of the system.

The marine engine can also be perceived as one part of the engine room, and the engine room is an important sub-system of a vessel, which is part of a much larger transport system. The environmental impact of marine transportation can be studied using various system boundaries. The system boundaries can be extended both in time and space.

Life cycle thinking and life cycle perspective are broad concepts with roots in systems thinking. The standardised method LCA, which is based on the life cycle perspective, is a common tool in the field of environmental systems analysis. The life cycle model in LCA is a typical example of a system that consists of several processes connected by a flow of goods (Figure 2-2). The system uses raw materials from the natural system (inputs), and the system emits emissions and waste to the natural system (outputs). LCA is used to systematically evaluate all environmental impacts caused by the inputs and outputs of the system throughout the life cycle. The method for conducting an LCA and the possibilities and problems with the use of LCA are described further in the following section.

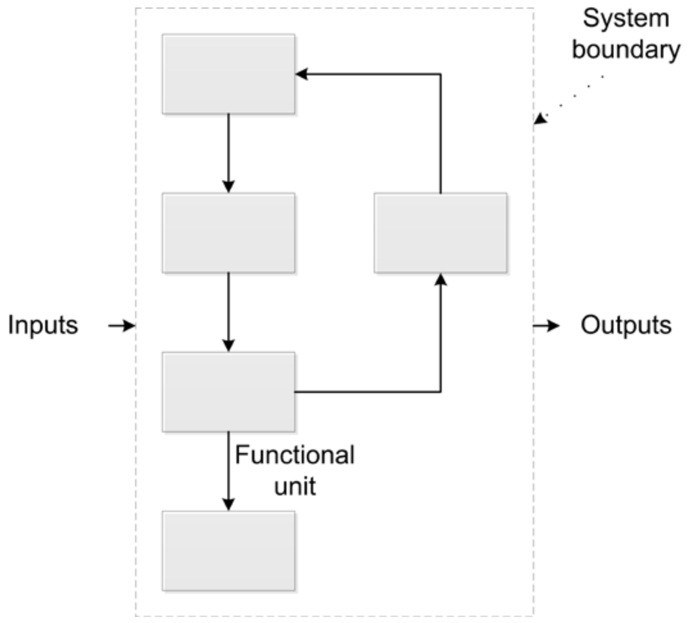

Figure 2-2 Life cycle model consisting of various processes and the connections between them.

2.2 Life Cycle Assessment

An LCA addresses the potential environmental impact of a product or service from a cradle-to-grave perspective (ISO, 2006a). This holistic perspective is a unique feature of LCA that is designed to avoid problem-shifting from one environmental problem to another, from one phase in the life cycle to another and from one region to another. An LCA can typically be used for decision-making, learning, exploration and communication.[9] Because an LCA addresses the environmental impacts of a service or production system, economic and social impacts are typically not included. LCA needs to be combined with other tools for more extensive assessments. There are certain recent trends in LCA toward more comprehensive life cycle sustainability assessments that also include economic and social aspects (Guinée et al., 2010).

Because the regulation of emissions from shipping may require a change in fuel type, it is important to assess the upstream environmental impact of such a change to avoid shifting problems from one phase

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[9] Baumann and Tillman (2004) described, for example, the following application areas: product development for market communication, e.g., eco-labelling; in procurement, e.g., comparing existing products with similar functions; and production and waste treatment processes.

of the life cycle to another. LCA is therefore considered an appropriate tool in this thesis for assessing the environmental performance of marine fuels. Furthermore, LCA is well established in the evaluations of fuels for road transportation (Arteconi et al., 2010; Brinkman et al., 2005; Edwards et al., 2007a; Hekkert et al., 2005; Strömman et al., 2006; Weiss et al., 2000). The majority of these studies, however, have focused on a limited number of impact categories, primarily energy use and greenhouse gas emissions (Arteconi et al., 2010; Edwards et al., 2007a; Hekkert et al., 2005; Weiss et al., 2000).

Over the last three decades, there has been strong methodological development of LCA (Guinée et al., 2010), which has resulted in the development of international standards: ISO (2006a) and ISO (2006b). These standards include general requirements for conducting an LCA. It is important to note that LCA methods are not standardised in detail. ISO 14040 states that "*there is no single method for conducting an LCA*" (ISO, 2006a). More detailed requirements and practical advice have been compiled in guidelines, e.g., those by Guinée (2002), ReCiPe (Goedkoop et al., 2013) and IES (2010b), and in textbooks, e.g., the book by Bauman and Tillman (2004). There is also at least one textbook addressing the computational structure of LCAs (Heijungs and Suh, 2002).

The procedure for conducting an LCA consists of four phases, according to the ISO 14040 standard: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation (Box 2-1). These phases are dependent on one another, and conducting an LCA is therefore often an iterative process. As an example, the goal and scope usually need to be refined during the study.

There are various types of LCAs, and the most common division of LCA types in the literature is between attributional[10] and consequential[11] studies. Attributional studies explore the system and its causes, whereas consequential studies explore the system's effects. Attributional LCAs are designed to be as complete as possible, accounting for all environmental impacts of a product, whereas consequential LCAs are intended to describe the environmental consequences of alternative courses of action. An attributional LCA addresses such questions as "What would be the overall environmental impact of marine transportation using Fuel A?" A consequential LCA addresses such questions as "What would be the environmental consequence of using Fuel A instead of Fuel B?" Other possible divisions include retrospective and prospective LCAs. Both attributional and consequential studies can be forward-looking, i.e., prospective, or backward-looking, i.e., retrospective (Finnveden et al., 2009; Hillman, 2008). An assessment of the impact of emerging technologies in a future system is an example of a prospective study. Assessments of past or current systems are called retrospective. There has been and still is a great deal of debate in the LCA community regarding when the various types should be used (Finnveden et al., 2009).[12]

Hillman (2008) discussed two major problems regarding the use and interpretation of assessments of emerging technologies,[13] both of which are relevant to this study. First, there is a risk that more advanced future technologies will be favoured because they are likely to display better environmental performance in a prospective attributional study. This viewpoint may result in a belief that "*there will always be more advanced future technologies worth waiting for*" (Hillman, 2008, p. 64). The second problem is linked to consequential studies. In consequential LCAs of near-term interventions, it is impossible to include all relevant cause-effect chains thoroughly. This results in the inclusion of only the easily accountable effects.

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[10] The term *accounting* is also used, e.g., by Baumann and Tillman (2004).

[11] The term *change-oriented* is also used, e.g., by Baumann and Tillman (2004).

[12] Finnveden et al. (2009) provided an overview of various opinions.

[13] In this case, renewable transportation fuels.

Box 2-1 Description of the four phases in LCA

Goal and scope definition
The goal and scope definition describes the system being studied and the purpose of the assessment. The goal should include, for example, the intended application and reasons for the assessment. The question addressed in the LCA affects the modelling choice; defining the goal and scope is therefore a central step in an LCA. An important modelling specification that should be stated in the goal and scope is the selection of a *functional unit*, i.e., a quantitative unit representing the function of the system. This enables comparisons of various products that fulfil the same function. In marine transportation, the functional unit could be, for example, one tonne of cargo transported one km using a roll-on-roll-off (ro-ro) vessel, which is the functional unit in Paper I, or one year of ro-pax ferry service between the island of Gotland and the Swedish mainland, which is the functional unit in Paper II.

Inventory analysis
The inventory analysis consists of three parts: construction of a flow model based on the system boundaries, data collection and calculation of resource use and emissions of the system in relation to the functional unit. There are three major types of system boundaries in an LCA: those between the technical system and the environment, those between significant and insignificant processes and those between the technological system under study and other technological systems (Finnveden et al., 2009). The flows of resources and emissions associated with each process in the system are often called elemental flows in an LCA. The term *elemental flow* will also be used in this thesis.

Impact assessment
The elemental flows quantified during the inventory analysis are classified during the impact assessment into various impact categories and are characterised, e.g., the relative contribution of the emissions and resource consumptions are calculated. Emissions of greenhouse gases, for example, are aggregated into an indicator of global warming. This step results in more compact information that is easier to interpret. The use of characterisation models, however, may increase the uncertainties of the result because they are simplified. This step is compulsory. An LCA without an impact assessment is called a life cycle inventory analysis.

Interpretation
Interpretation is the final phase of the LCA, in which the results from either or both the inventory analysis and the impact assessment are summarised and discussed. This interpretation can be used as a basis for developing conclusions and recommendations.

2.2.1 Environmental Impact Categories

The impact assessment phase of an LCA is aimed at “understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system” (ISO, 2006b). The purpose of this phase is to interpret the impact of a product’s or service’s life cycle emissions and resource consumption on the entities that we wish to protect, which are often referred to as areas of protection. The areas of protection can be divided into human health, the natural environment and natural resources.[14]

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[14] These areas are considered in IES (2010a) and are generally accepted in the LCA community (Finnveden et al., 2009). In the ReCiPe project, the same areas were considered but are designated as human health, ecosystems and resources (Goedkoop et al., 2013). A fourth area of protection, the man-made environment, is occasionally also considered (Finnveden et al., 2009).

Adverse effects on human health are measured by mortality and morbidity[15] through space and time. The impact on the natural environment is measured by the loss or the disappearance of species and the loss of biotic productivity. The third area of protection, natural resources, is difficult to quantify using a single indicator. 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 (Dewulf et al., 2007).

An indicator of an impact category can be chosen anywhere along the impact pathway. The impact pathway is the chain from emissions and resource use to the final impact on the areas of protection. Impact categories related to environmental issues, such as climate change and acidification, are called *midpoint impact categories*, whereas *endpoint impact categories* are associated directly with the areas of protection. A midpoint impact category is, for example, the acidification potential connected to the environmental issue of acidification, whereas an example of an endpoint indicator is damage to human health, which is assigned to the human health area of protection. The majority of impact categories that are used are midpoint impacts that affect at least one of the areas of protection. Only midpoint impact categories were considered in this study. The most common midpoint impact categories associated with environmental issues are presented in Figure 2-3, and their relevance to the evaluation of marine fuels are assessed in the following section. The characterisation factors for the specific impact categories used in this study are presented in section 4.1.2.

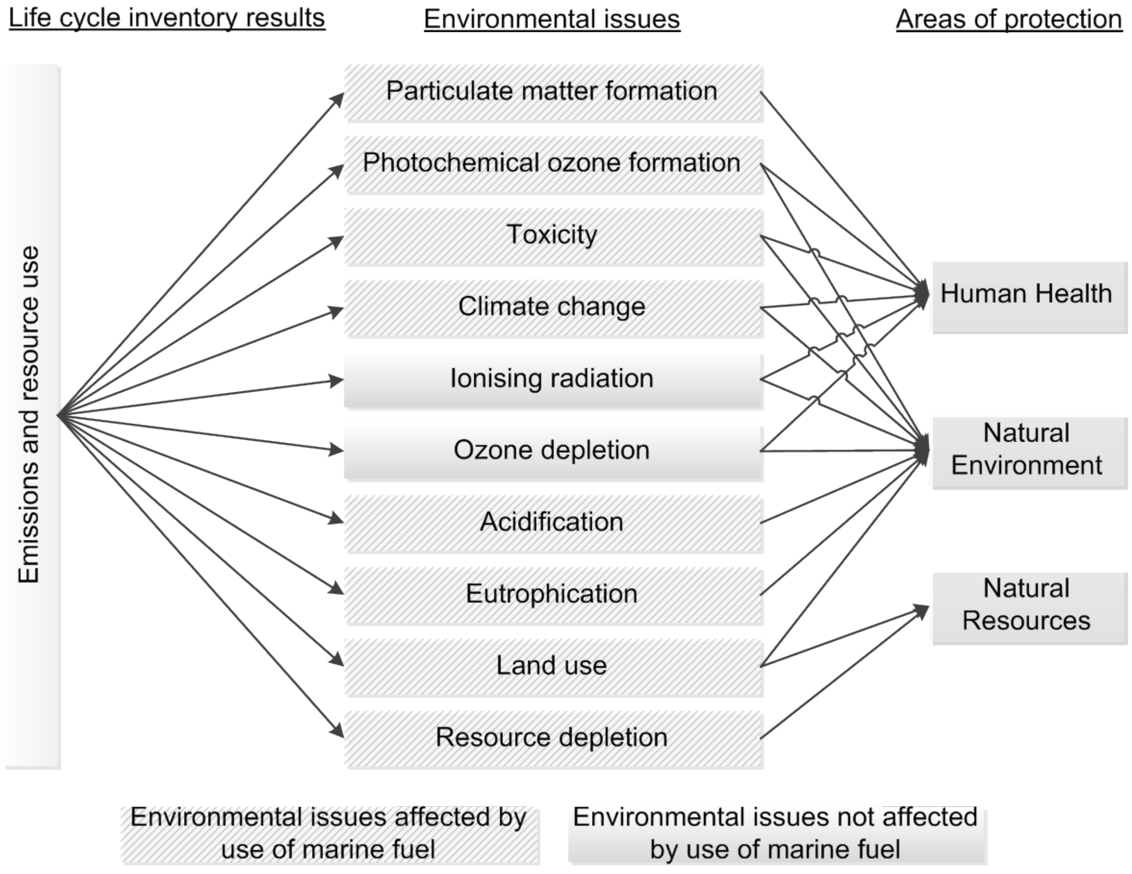

Figure 2-3 Framework of the impact categories for the characterisation of elementary flows at the midpoint and endpoint (adapted from IES (2010a) and Goedkoop et al. (2013)).

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[15] Mortality refers to the incidence of death or the number of deaths in a population, whereas morbidity refers to the incidence of ill health in a population.

Particulate Matter Formation

PM has both natural and anthropogenic origins and is typically quantified as PM_{10} or $PM_{2.5}$ (particulate matter less than 10 and 2.5 µm in diameter, respectively). Secondary particles are formed in the air from emissions of SO_2, ammonia (NH_3) and NO_X, among others (Finlayson-Pitts and Pitts, 2000). PM has a well-established impact on human health, and long-term exposure to fine particles has been shown to increase the risk of premature mortality (Pope et al., 2002).

The characterisation factors for PM include the environmental fate, exposure, the dose-response of the pollutant midpoint factors and the severity of the endpoint factors. The fate and exposure can be combined into an intake fraction, and the dose-response and severity can be combined into an effect factor. Characterisation factors for human health effects due to fine particulates in Europe were developed by van Zelm et al. (2008). The characterisation factors express the change in disability-adjusted life years (DALYs) of European inhabitants due to a change in the emissions of NH_3, NO_X, SO_2 and PM_{10}.

Photochemical Ozone Formation

Ground level ozone is a secondary pollutant formed in the troposphere, and it is a health hazard to humans because, among other effects, it can inflame airways and damage lungs. Ozone formation is complex and depends on a number of factors, e.g., NO, NO_2, volatile organic compounds (VOC) and ultraviolet radiation. The effects of various emissions depends on the location and the background concentration of NO_X.

There are two types of characterisation models, which are based on two simplification strategies. The first approach[16] is based on the concept of the photochemical ozone creation potential (POCP). The individual characterisation factors are provided for many types of VOCs, but local conditions, such as the simultaneous presence of other non-methane VOCs and NO_X and the intensity of the solar radiation, are not included in the model. The second approach[17] is adopted in regionally differentiated models that attempt to capture the non-linear nature of ozone formation, but it largely ignores the differences between various VOCs (IES, 2010a).

The emissions of NO_X and VOCs depend on the type of fuel used and therefore are important to consider. Use of the POCP model requires detailed knowledge of the VOCs that are emitted. It can therefore be easier to apply the second approach to characterise the impact of the photochemical ozone formation potential.

Toxicity

Toxicity is the degree to which a substance can cause damage to an organism, such as a plant, an animal or a cell. Both human health and the natural environment can be affected by toxicity. The most common impact categories associated with toxicity are human toxicity and eco-toxicity, and these categories in turn are related to the environmental persistence (fate), accumulation (exposure) and toxicity (impact) of the toxic substances. Human toxicity and eco-toxicity are considered difficult to incorporate into LCAs due to a lack of inventory data for emissions and due to the problems and uncertainties in the models and the related data (Finnveden et al., 2009).

According to the IES (2010a), the model for human toxicity effects must account for the environmental fate, the exposure and the dose response of a chemical for midpoint factors and additionally, the severity for endpoint factors. However, the characterisation factors for eco-

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[16] Described, for example, by Guinée (2002).

[17] Described, for example, by Hauschild et al. (2006).

toxicological effects account for the environmental persistence and eco-toxicity of a chemical. USEtox is model intended to gain a consensus of scientific approval for use in life cycle impact assessment of chemicals. The model was developed as part of the Life Cycle Initiative, a joint effort by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) (Hauschild et al., 2008). The Life Cycle Initiative intends to use USEtox as the basis of future recommendations (Finnveden et al., 2009).

The human and eco-toxicological impacts will most likely vary from one fuel to the next and should therefore ideally be included in an LCA of marine fuels. For example, the work environment of marine engineers may vary depending on the types of fuels being used. However, the information regarding toxic substances has been very limited, and the impact categories associated with toxicity were not included in this work.

Climate Change

Climate change impacts both the natural environment and human health through a wide variety of environmental mechanisms. The natural environment is affected by the loss of species due to temperature increases, by the changes in oceans and seas and by the impacts of extreme weather. Human health, for example, is affected directly by heat waves and indirectly by infectious diseases and malnutrition. Modern climate change is caused by greenhouse gas absorption of infrared radiation. The greenhouse gases differ in their warming effects on the global climate system due to their different radiative properties and lifespans in the atmosphere.

The Intergovernmental Panel on Climate Change (IPCC) has calculated the radiative forcing properties of all greenhouse gases, and these properties are referred to as global warming potentials (GWPs).[18] The GWP of 1 kg of a substance is defined as the ratio between the increased infrared absorption it causes and the infrared absorption caused by 1 kg of CO_2. The GWP of a substance will depend on the time horizon, as different substances have different lifespans in the atmosphere (IPCC, 2007). The time horizon most frequently used in LCAs is 100 years. The IES (2010a) recommends the use of the IPCC's GWPs at the midpoint. The three most common greenhouse gases and their GWPs are shown in Table 2-1.

Table 2-1 Global warming potentials of compounds over various time horizons (IPCC, 2007, 2013).

	GWP 100 years (kg CO_2 eq./kg)[a]	**GWP 20 years (kg CO_2 eq./kg)[a]**	**GWP 500 years (kg CO_2 eq./kg)**
Carbon dioxide (CO_2)	1	1	1
Methane (CH_4)	25 (28, 34)	72 (84, 86)	7.6
Nitrous oxide (N_2O)	298 (265, 298)	289 (264, 268)	153

[a] The GWPs from the latest IPCC report, the IPCC Fifth Assessment report; without and with climate-carbon feedback are included in parenthesis (IPCC, 2013).

There are emissions other than greenhouse gases addressed by the IPCC that have a secondary impact on radiative forcing. These are emissions that contribute to the formation of ozone, aerosols and cloud formation, such as NO_X, SO_2 and black carbon.[19]

The change in soil organic carbon due to land use change is important to consider when assessing the climate impacts of biofuels. Brandão et al. (2011) compared four crops and demonstrated that the

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[18] There are also other measures that can be used to quantify the contribution from different greenhouse gases, such as the global temperature change potential (GTP). The GTP goes one step further than the GWP in the cause-effect chain by considering changes in global mean surface temperatures at a selected point in time (IPCC, 2013).

[19] The radiative forcing due to total shipping is estimated at 0.001 W m^{-2}, excluding indirect aerosol effects, and -0.408 W m^{-2}, including indirect aerosol effects (Eyring et al., 2010).

change in the soil organic carbon dominated the greenhouse emissions associated with the cultivation of energy crops. A clear method of including this carbon in LCA is needed. For further discussion of the impacts of land use change, see the section *Land Use*.

Ionising Radiation

Human health can be damaged by the release of radioactive material into the environment. The impact category at the midpoint level in the ReCiPe project is the exposure level, the unit of which is Sieverts per Becquerel (Goedkoop et al., 2013). This impact category is not relevant to marine fuels and applies only to situations in which the electricity used in the marine fuels' life cycle was produced using nuclear power or coal. Therefore, ionising radiation has not been considered in this study.

Ozone Depletion

Stratospheric ozone is continually being formed and destroyed by sunlight and chemical reactions in the atmosphere. It is vital for life because it blocks a portion of harmful ultraviolet radiation. Ozone depletion is the thinning of the stratospheric ozone layer caused by emissions of ozone-depleting substances, such as chlorofluorocarbons and halons (Harrison, 2001), and this depletion affects human health and the natural environment. These ozone-depleting substances are persistent chemicals that contain chlorine or bromine atoms. Chlorine and bromine have the ability to destroy large quantities of ozone molecules by acting as free radical catalysts in a sequence of degradation reactions. The ozone depletion potential (ODP) of a substance is calculated using a theoretical steady-state model that reflects the change in the stratospheric ozone column due to the quantity of emissions of that substance relative to that of CFC-11.

Ozone-depleting substances are used onboard ships in the refrigeration of cargo and provisions and in air conditioning. The ozone-depleting substances may be emitted to the atmosphere by leakage of the substances during operation and maintenance and when a unit containing these substances is scrapped. Buhaug et al. (2009) estimated the change in emissions of ozone-depleting substances from shipping between 1998 and 2006. The emissions of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) decreased by 98% and 78% respectively, whereas the emissions of hydrofluorocarbons (HFCs) increased by 315% because HCFs were substituted for the CFCs and HCFCs. The emission of ozone-depleting substances is not linked to the use of fuels but rather to the transportation of various types of cargo and therefore does not merit assessment in this thesis.

Acidification Potential

The acidification potential addresses the impact generated by emissions of airborne acidifying pollutants. These pollutants affect soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings). Acidification primarily affects the natural environment area of protection by decreasing biodiversity and bio-productivity.

The major acidifying pollutants are SO_2, NO_X and NH_3. They form acidifying H^+ ions and can be characterised based on this capacity. The acidification potential is defined as the number of H^+ ions produced per kg of substance relative to SO_2. This simplified model does not take into account the effects of the fate, the background deposition and the sensitivity of a given ecosystem. The actual acidifying potential depends on where the acidifying pollutants are deposited. This potential can be modelled using an atmospheric dispersion model. It is also important to consider the sensitivity of the ecosystem in which the deposition occurs.

Posch et al. (2008) compared three approaches for calculating the acidification and eutrophication potentials: (1) the no-fate method, (2) the atmospheric dispersion method and (3) the atmospheric dispersion and critical load methods.[20] They concluded that the no-fate method was good for generating a first approximation and for global applications. They also demonstrated that there were no large differences between the models and European average characterisation factors. However, the differences are significant when considering data specific to certain countries in Europe. The third approach, based on the method of accumulated exceedence presented by Seppälä et al. (2006), is recommended by the IES (2011). The ReCiPe methodology for life cycle impact assessment uses an approach based on the base saturation,[21] which is an alternative to the critical load-based methods and thus far has been developed only for assessing forest ecosystems on a European scale (Goedkoop et al., 2013).

The attention placed on emissions of SO_2 from shipping causes the acidification potential to be an important impact category in the assessment of marine fuels.

Eutrophication Potential

The eutrophication potential is associated with high levels of nutrients, which lead to increased biological productivity in seas and lakes, e.g., algae blooms. Nitrogen and phosphorus are the most common growth-limiting nutrients. The primary area of protection affected by eutrophication is the natural environment.

Because different ecosystems are limited by different nutrients, the eutrophication potential varies geographically. Models have been developed that were intended to take this variation into account, e.g., the model of Huijbregts et al. (2000).[22] Separate impact categories have been developed for terrestrial and aquatic eutrophication. The IES (2011) recommended using the accumulated exceedence method for terrestrial eutrophication and the ReCiPe impact assessment methods for marine and freshwater eutrophication.

Nitrogen oxides are a major pollutant produced by marine transportation. The eutrophication potential is also important when assessing crop-based biofuels because these can be linked to emissions of ammonia from agriculture.

Land Use

Land use impacts generally consist of ecosystem damage from the effects of occupation and transformation of land. There is currently no agreement regarding the way in which these impacts should be included in LCAs (Finnveden et al., 2009), but work to resolve this issue is ongoing, e.g., work by Brandão et al. (2011) and Koellner et al. (2013). Land use affects the natural environment and natural resources directly and human health indirectly. Land use is an important factor when evaluating biofuels because biofuels produced from dedicated crops are generally associated with land use and/or land use changes. The ReCiPe project takes into account three midpoint impact categories: agricultural land occupation, urban land occupation and natural land transformation (Goedkoop et al., 2013). Koellner et al. (2013) presented principles and recommendations for the calculation of the impacts of land use on biodiversity and ecosystem services on a global scale. They stressed the need for further development of regional models of biodiversity and ecosystem services.

Resource Depletion

The Earth contains a finite amount of non-renewable resources, such as metals and energy resources. This impact category includes both renewable and non-renewable resources. There is a wide variety of

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[20] Critical loads are the maximum amount of pollutants that ecosystems can tolerate without being damaged.

[21] Base saturation is used as an indicator to express acidity and is the degree to which the adsorption complex of a soil is saturated with basic cations (Goedkoop et al., 2013)

[22] This model concerns terrestrial eutrophication.

characterisation methods available for assessing non-renewable resources. The question regarding the method that should be used is still a topic of debate (Finnveden et al., 2009).

Three impact categories are considered to be associated with resource depletion in the ReCiPe project: water depletion, mineral resource depletion and fossil fuel depletion (Goedkoop et al., 2013). Many "well-to-wheel" studies of road fuels are limited to the assessment of energy use.[23] Arvidsson et al. (2012) evaluated the type of energy use indicators used in LCAs of biofuels and found that five inherently different types of indicators are used: (1) fossil fuels, (2) secondary energy, (3) cumulative energy demand, (4) net energy balance and (5) total extracted energy.

The only resources considered with regard to marine fuels are the raw materials for fuel production, e.g., natural gas, crude oil and biomass. The depletion of water was not assessed due to a lack of information in the data sources found. If, however, the life cycle impact of a vessel is considered, resources other than energy and water could be included, such as metals. The impact category referred to as total extracted energy, as defined by Arvidsson et al. (2012), is used in this thesis. In Papers I through IV, this parameter is called primary energy use instead of total extracted energy.

2.2.2 Allocation or System Expansion[24]

Allocation problems occur when several products (or functions) share the same processes and the environmental load of these processes has to be expressed by only one function (see Figure 2-4). One example of a process with multiple outputs is the refining of crude oil, which results in a number of products (e.g., liquefied petroleum gas, petrol, diesel and asphalt) that are used in various applications. When assessing the life cycle impact of, for example, truck transportation, the environmental impacts of the outputs need to be distributed. Another example is the leachates from landfills. How much leachate should be attributed to food waste and how much to other types of waste? This is an example of a problem associated with multiple inputs.

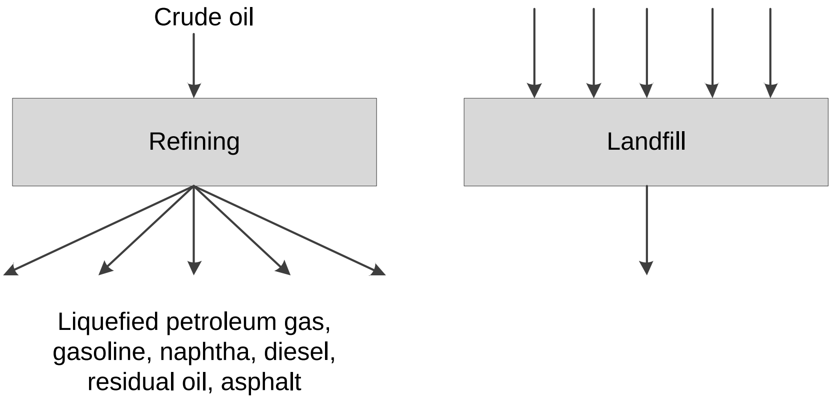

Figure 2-4 Examples of multi-output and multi-input processes (adapted from Baumann and Tillman (2004), p. 84).

Allocation can be achieved using, for example, a physical relationship or the monetary value of the products. It is also possible to avoid the allocation problem by using system expansion, which involves incorporating additional functions into the system. The ISO standard 14044 states that allocation shall, if possible, be avoided by either refining the system or expanding it (ISO, 2006b).

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[23] See, for example, Edwards et al. (2007b).

[24] In this thesis, allocation is considered to be one method for solving allocation problems. Thus, allocation methods include both allocation (also called partitioning) and system expansion.

System expansion implies expanding the system to include the affected processes outside of the cradle-to-grave system. This is the preferred option for consequential LCAs[25] because these LCAs are designed to include all of the activities that contribute to the environmental consequences of change, regardless of whether they are inside or outside of the cradle-to-grave system. Many authors argue that partitioning is a way to solve allocation problems in attributional LCAs (Finnveden et al., 2009).

2.2.3 Uncertainties in LCAs[26]

Uncertainty is often not considered in LCAs, even though it can be high. Finnveden et al. (2009) distinguished between the sources and types of uncertainties. These are described in Table 2-2. Many of these uncertainties appear in a typical LCA.

Table 2-2 Sources and types of uncertainties in LCAs, adopted from Finnveden et al. (2009).

Sources of uncertainties	Types of uncertainties	Example
Data	Variability	Fuel consumption may vary between different engines of the same type, change over time or depend on external conditions.
	Mis-specified	Instead of data for natural gas extraction in the North Sea in 2010, there may be data for natural gas extraction in North Africa in 2006.
	Erroneous	There may be a typographical error or a mistake in units, or a decimal point may have been confused for a thousands separator.
	Incomplete	Information regarding certain environmental flows are missing.
Choices	Rounding	The number 0.564 may have been entered as 0.6.
	Inconsistent with goal and scope	The average technology rather than the best available technology for a purpose was evaluated.
	Inconsistent across alternatives	Different allocation methods are used for different processes in the same study.
Relations	Wrong relationship	A linear dependence on acidification from SO_2 emissions may not reflect the true relationship.
	Incomplete	The effect of background levels of contaminants may be incomplete.
	Inaccurate implementation in software	Matrix inversion routines may be sensitive to the choice of algorithm.

Finnveden et al. (2009) also suggested three methods for addressing uncertainties in LCAs: (i) the “scientific way”, (ii) the “social way” and (iii) the “statistical way”. The scientific way includes, for example, identifying better data and developing better models. The social way addresses uncertainties through discussion with stakeholders. The aim is to reach a consensus regarding the data and choices together with the stakeholders. The last method, the statistical way, involves including the uncertainties in the analysis instead of removing them. This method can include, for example, parameter variation, scenario analysis and/or Monte Carlo simulations.

2.2.4 Use of LCA Associated with Shipping

There are a number of studies that have used the life cycle perspective or an LCA to analyse the various environmental impacts of the shipping industry. An overview of the publicly available studies that were located[27] is presented in Table 2-3. The topics of these studies are grouped into four categories: (i) fuels and prime movers, (ii) abatement technologies and auxiliary energy, (iii) vessels and (iv) other topics. Areas that are not addressed or only addressed briefly in the LCAs associated with shipping include various scrubber technologies, various antifouling paints and the manufacturing of the engines. The studies in the first two groups are relevant to this work and will be compared and

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[25] Proposed by, for example, Tillman (2000).

[26] This section is based on Finnveden et al. (2009).

[27] There likely are studies conducted in private companies that have not been made publicly available. One such example is the LCA study made by Det Norske Veritas, which is presented by Chryssakis et al. (2014).

analysed in more detail in this section, with the exception of the studies by Basurko and Mesbahi (2014) and Blanco-Davis and Zhou (2014), in which ballast water treatment technologies were analysed. In section 5.3, the previously published results regarding marine fuels are compared to the results of this thesis.

Most of the studies were published after 2010, and it can therefore be assumed that the interest in analysing various parts of the shipping sector using a life cycle perspective has increased in recent years. The doctoral thesis “Systems Engineering Methods and Environmental Life Cycle Performance within Ship Industry” by Margerholm-Fet (1997) was perhaps the first study discussing LCA in connection with the shipping industry. This work resulted in a “screening life cycle assessment of the M/V Color Festival”, which demonstrated that the operational phase is the primary contributor to most environmental impact categories during a ship’s life cycle (Johnsen and Magerholm-Fet, 1998).

Winebrake et al. (2007) used the Total Energy & Emissions Analysis for Marine Systems (TEAMS) model to conduct fuel cycle analyses of six fuel pathways (Table 2-3). This model is based on the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model but has been adapted to the shipping industry. These authors did not use the LCA methodology, and their results can be categorised as a life cycle inventory analysis because they calculated the emissions and energy use during the fuel life cycle without assigning the results to environmental impact categories (i.e., they did not include the impact assessment step of an LCA). In a later paper, Corbett and Winebrake (2008) used the TEAMS model to analyse trade-offs among alternative fossil fuels, i.e., residual oil, marine gas oil (MGO) and marine diesel oil. They concluded that a switch from residual oil to MGO and marine diesel oil would result in a slight increase in CO_2 emissions (0.5% in the best estimate), whereas the emissions of SO_X would significantly decrease (a 70-85% reduction).

Verbeek et al. (2011) used a life cycle perspective to investigate the environmental aspects of using LNG compared to HFO, marine distillate fuels and diesel as fuel on various types of ships. LNG was demonstrated as having the lowest greenhouse gas emissions (approximately 10% lower than the diesel fuel chains) and having the lowest emissions of SO_X, NO_X and PM, even when the diesel fuels comply with the Tier III requirements. The authors also stressed the need for precise NO_X and CH_4 emission data.

Lowell et al. (2013) compared the life cycle greenhouse gas emissions of eight LNG fuel pathways to HFO and distillate fuels. They concluded that the climate impact of the LNG pathways varies between an 18% reduction and a 5% increase compared to distillate and residual fuels. These authors also concluded that the impact on the climate could be reduced by a maximum of 12-27% if LNG is used as a fuel alongside the use of best practices.

Andersson and Winnes (2011) used an LCA to investigate the use of SCR units for NO_X emission control onboard passenger vessels. The studies indicated that the use of an SCR unit decreased the overall environmental impact compared with using a diesel engine without a catalyst. The GWP was the only impact category that increased slightly (approximately 2%). This was due to urea production, transportation and use. The production of the SCR unit was not included within the system boundaries.

Ma et al. (2012) at Shell Global Solutions investigated the life cycle energy consumption and greenhouse gas emissions of various SO_X abatement options, i.e., low-sulphur fuels and various scrubber solutions. To calculate the energy use and emissions associated with various refinery products, they combined two approaches. The first was an allocation approach based on the energy of the high-sulphur HFO, and the second was a marginal approach for the low-sulphur fuels based on the report by CONCAWE (2009). The allocation of refinery products is problematic and the subject of

Table 2-3 Selected studies using a life cycle approach to assess environmental aspects of various systems associated with the shipping sector.

Study		System/systems assessed (functional unit)	Environmental flows, impact categories and indices used in the assessment
Fuels and prime movers	**Baldi et al. (2013)**	HFO, MGO, LNG	GWP
	Corbett and Winebrake (2008)	Residual oil, MGO and marine diesel oil	CO_2, SO_x
	Laugen (2013)	LNG and HFO	GWP and acidification
	Lowell et al. (2013)	LNG (8 pathways), HFO, marine distillates, ultra-low sulphur diesel	CO_2, CH_4, N_2O
	Ryste (2012)	LNG	Greenhouse gases
	Verbeek et al. (2011)	LNG, HFO, marine distillate fuels and diesel (EN590)	Greenhouse gas emissions (CO_2, CH_4, N_2O), NO_X, SO_X and PM
	Winebrake et al. (2007)	Residual oil, conventional diesel, low-sulphur diesel, compressed natural gas, Fischer-Tropsch diesel from natural gas, biodiesel produced from soybeans	CO_2, N_2O, CH_4, VOC, CO, NO_X, PM_{10}, SO_X, total energy consumption, fossil fuel consumption and petroleum consumption
	Øberg (2013)	HFO, MGO/marine diesel oil, LNG, methanol, DME and BTL produced from woody biomass	Agricultural and occupational potential, GWP, particulate matter formation potential (plus 15 more impact categories not investigated in detail)
Abatement technologies and auxiliary power	**Andersson and Winnes (2011)**	Selective catalytic reduction units	GWP, human toxicity, photo-oxidant formation, acidification, eutrophication
	Basurko and Mesbahi (2014)	Three ballast water treatment units (filter, UV and electro-chemical oxidation)	Carcinogens, resp. organics, resp. inorganics, climate change, radiation, ozone layer depletion, ecotoxicity, acidification/eutrophication, land use, mineral resources, fossil fuels[a]
	Blanco-Davis and Zhou (2014)	Three ballast water treatment technologies	GWP
	Ma et al. (2012)	SO_X abatement options	CO_2, SO_X
	Strazza et al. (2010)	Solid oxide fuel cells as auxiliary power onboard ships fuelled by methanol, bio-methanol, natural gas, biogas and hydrogen and compared with a traditional diesel engine	GWP, ozone layer depletion, photochemical oxidation, acidification, eutrophication, non-renewable energy resources, renewable energy resources, non-renewable resources
Vessels	**Gratsos et al. (2010)**	Bulk carriers	CO_2
	Johnsen and Magerholm-Fet (1998)	Ro-ro passenger vessel	GWP, ozone depletion, acidification, photo-oxidant formation, eutrophication, winter smog, toxic to humans, toxic to ecology, solid waste, material consumption, energy consumption
	Tchertchian et al. (2013)	Hybrid passenger ferry	Abiotic depletion, acidification, eutrophication, GWP, ecotoxicity, photochemical pollution
	Walsh and Bows (2011)	Eight vessel categories and various sizes of these vessels	CO_2
Other	**Carvalho et al. (2011)**	Ship dismantling	Eco-indicator 99 (H), IMPACT2002+
	Drakopoulos et al. (2009)	Ship hull repair	Human health, ecosystem quality, ecosystem production capacity, resources, abiotic stock resources and biodiversity
	Ewing et al. (2011)	Inland marine freight transportation company	GWP, acidification, particulate matter emissions, eutrophication, ozone depletion and water use
	Zuin et al. (2009)	Ship generated waste	Carcinogens, resp. organics, resp. inorganics, GWP, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, mineral resources, fossil fuels

[a] The authors also included aspects of economic and social sustainability.

debate, and there are no generally accepted methods presented in the literature. Furthermore, the energy use and emissions associated with the production and transport of the consumables used in the closed scrubber and the dry scrubber are included but not explicitly described. Ma et al. (2012) concluded that a scrubber system used with HFO has the potential to reduce the energy use and greenhouse gas emissions during the fuel life cycle in comparison with low-sulphur marine fuels.

Strazza et al. (2010) used an LCA to evaluate the use of methanol in solid oxide fuel cells (SOFCs) as an auxiliary power system. The results indicate that the fuel production stage strongly affects the environmental impact of electricity generation via SOFCs. The use of SOFCs for electricity production improved the overall environmental performance significantly in comparison to a traditional system using all of the fuels investigated. The use of bio-methanol and hydrogen from cracking and electrolysis in the SOFC reduced the GWP the most.

Three master's theses in which various marine fuels using the LCA approach were assessed were prepared at the Norwegian University of Science and Technology. Ryste (2012) conducted a screening LCA of LNG, focusing on only one part of the life cycle, i.e., the bunkering of LNG, and considered only emissions of greenhouse gases. Øberg (2013) used a process LCA to evaluate six fuel types and concluded that Fischer-Tropsch diesel and dimethyl ether produced from wood were the most promising alternative marine fuels when considering agricultural and occupational land use, GWP and particulate matter formation potential. Methanol produced from biomass was also included, but a different feedstock (forest wood instead of short-rotation wood) was compared to the Fischer-Tropsch diesel and the dimethyl ether, resulting in higher impacts. Laugen (2013) used an LCA to compare HFO and LNG and considered two impact categories: GWP and acidification.

There is also a growing body of literature regarding the use of LCAs in the design of ships (Baldi et al., 2013; Jivén et al., 2004; Johnsen and Magerholm-Fet, 1998; Prinĉaud et al., 2010; Tchertchian et al., 2013). The majority of these studies do not explicitly evaluate or assess the use of the life cycle approach. However, Blanco-Davis and Zhou (2014) concludes that LCA is a beneficial tool for ship-owners and fleet managers to use in selecting a design associated with the lowest environmental impacts. They applied LCA to the case of retrofitting of ballast water treatment technologies. This application was also stressed by Strazza et al. (2010), who highlighted the usefulness of LCA as a decision making tool for process selection and environmental improvement.

2.3 Global Energy System Modelling

The other tool (also based on systems thinking) used in this work is energy systems modelling. In this work, the term energy system refers to global or regional energy systems and not specific technical energy systems, such as the energy system onboard a vessel. Energy system modelling is used in this work to obtain a better understanding of the ways that marine fuel choices are affected by the choices and technology options in other energy sectors when competing for the same limited energy resources.

Energy system models are used to analyse the ways that resources, technologies and services can be combined under different conditions and can be used to provide insights regarding energy/environmental policies and planning. Energy system models include a wide variety of models applied to various system boundaries of the energy system, such as the entire global energy system (including transportation) or only parts of the system (such as a specific region/country or sector). There are both descriptive models (simulation models) and normative models (optimisation models). The energy systems models vary widely in terms of their purpose, philosophy, features, capabilities, possible overlaps and demand for data. Original work in global systems modelling was performed in the early 1970s with the publication of *Limits to Growth* and resulted in increased interest and use of global models (Meadows and Meadows, 2007).

One group of energy system models consists of energy-economic-climate models, which are used to address issues concerning energy planning and climate policies. An overview of these types of models was provided by Hedenus et al. (2013). These models are used to address several issues involving climate policy, such as (1) the cost of climate stabilisation, (2) the feasibility, (3) the burden sharing and timing, (4) the role of technologies and (5) the exploration of the future and creation of baseline scenarios.

Energy system models have been used to assess the cost-effectiveness of technologies and fuels when used in efforts to reduce the emissions of CO_2 on a global level (Azar et al., 2003; Grahn et al., 2007; Grahn et al., 2009b; Takeshita and Yamaji, 2008; Turton and Barreto, 2007). The GET model, developed by the Physical Resource Theory research group at Chalmers University of Technology, is one of the models that have been used extensively for this purpose.

2.3.1 Type of Models

There are various types of modelling approaches applied to energy and climate policy issues. These approaches are usually divided into (1) bottom-up and (2) top-down models, but there are also models that combine both approaches, so-called (3) hybrid models (Bhattacharyya and Timilsina, 2010; Söderholm, 2007; Springfeldt et al., 2010).

Bottom-up models are traditionally technology-oriented and designed to model the energy system in relatively great detail. They generally do not include the overall economic activity and are also called partial-equilibrium models in the sense that economic equilibrium is achieved between supply and demand for energy and not for the entire economy (Springfeldt et al., 2010). These models are typically optimisation models that attempt to minimise the total discounted system cost under various technological and environmental constraints (Söderholm, 2007). In contrast to bottom-up models, top-down models are intended to include the entire economy. They analyse the past behaviour of energy markets using statistical techniques to estimate the supply and demand responses that might be expected with a change in price of another variable (Canes, 2002).

The two types of models are complementary and can be used for different purposes. Bottom-up models can be helpful in identifying prospects for new energy technologies and possible barriers to the market’s acceptance. Generally, bottom-up models result in lower cost estimates of climate change mitigation policies than do top-down models (Söderholm, 2007; Springfeldt et al., 2010). However, they are not based on actual behaviour but instead on engineering data regarding the cost and efficiency of various energy technologies. The transaction costs associated with new technologies, e.g., the costs associated with learning about the new technologies, attempting to use them initially, training people to use them, financing them and measuring the results, are typically not included. These models can therefore overestimate the feasibility of introducing new technologies (Canes, 2002). Top-down models avoid many of the problems associated with bottom-up models because the behaviour they reflect includes all of the cost of employing the energy technologies (Canes, 2002). Such models are, however, based on the technology and institutions existing at the time of the data collection and therefore encounter difficulties in modelling rapid expansions of new technologies (Hedenus et al., 2013).

Hedenus et al. (2013) stated that to provide new knowledge and understanding, perhaps the most important requirement for energy systems models is that the model results must be explainable in terms of the mechanisms that drive the model.

2.3.2 Description of the GET Model

The GET model was developed by Azar and Lindgren and co-workers for analysing future transitions in the global energy system (Azar et al., 2000; Azar et al., 2003). It is a bottom-up linear programming model that is designed to meet exogenous energy demands for heat, electricity and transportation while meeting a specific atmospheric CO_2 concentration at the lowest total system cost during the modelled period (which is 1990-2130). To compare costs at various periods of time, a global discount rate, typically set to 5%, is used. CO_2 emissions are the only greenhouse gas emissions considered in the model.

The model describes a large number of technologies for converting and supplying energy and includes data on such factors as costs, efficiency, load factors and carbon emissions. In addition, resource estimates and various restrictions of the technologies are included. One such restriction is that solar and wind power can supply only 30% of electricity demand due to their intermittent nature. The model focuses on the transportation sector, in which vehicle costs and infrastructure are treated explicitly. The use of electricity and heat is treated in an aggregated manner, particularly in the heat sector. Heat is used as a generic term including low- and high-temperature heat in the residential, service, agricultural and industrial sectors.

The GET model is a simplification of the real energy system. These simplifications include (1) a limited number of technologies, (2) demands that are exogenous and not elastic to changes in price, (3) choices of fuels and technologies in the model that are based only on cost considerations and (4) the “perfect foresight” of the model, i.e., no uncertainty regarding future costs, climate targets or energy demand. These simplifications are important to keep in mind when analysing the results from the model.

The model has been used extensively, and new versions of it (e.g., GET-R 6.0, GET-RC 6.1, GET 7.0) have been developed by the Physical Resource Theory research group at Chalmers University of Technology (Grahn et al., 2009a; Grahn et al., 2009b; Hedenus et al., 2010).

2.3.3 Use of Energy Systems Modelling Associated with Shipping

There are very few reports and articles presenting energy system modelling associated with shipping issues in the sense described in section 2.4 above. However, scenario analyses have been performed in attempts to project the future energy supply and CO_2 emissions of the global fleet (Buhaug et al., 2009; Eide et al., 2013; Eyring et al., 2005a; Vergara et al., 2012). There have also been studies evaluating the cost-effectiveness of reducing CO_2 emissions (Eide et al., 2009; Eide et al., 2011).

The global transport model (GloTraM) developed by the low carbon shipping project in the UK, is a bottom-up model that has been used to estimate, for example, the CO_2 emissions of the international shipping fleet. The model selects configurations of and changes in both the existing fleet and future fleet to maximise profits for ship-owners and operators (Smith et al., 2013). Profit maximisation is thus used as the basis for optimisation instead of the cost minimisation used by many energy system models, e.g., the GET model. Only a few publications thus far have presented results from the uses of GloTraM. One of these studies was performed by Raucci et al. (2013), in which GloTraM was used to evaluate the uptake of alternative fuels and new technologies in three scenarios of international shipping (Status Quo, Global Common and Competing Nations) presented in the study titled *Global Marine Trends 2030* (2013). The scenarios were assigned various prices, growth assumptions and regulatory demands, and the GloTraM model was used to forecast how the shipping fleet might evolve in the different scenarios.

3 Present and Possible Future Marine Fuels

As mentioned in the *Introduction*, there are a wide variety of potential future marine fuels, including MGO, LNG and methanol. These fuels vary in terms of the energy carrier of the fuel, the primary energy sources used to produce it and the type of prime mover used to convert the energy carrier to work. A simplified diagram of the chain from energy resources to mechanical energy for marine propulsion is presented in Figure 3-1. This chapter starts by defining how these terms are used in this work. To be able to compare the fuels and their various characteristics, a set of criteria for future marine fuels is presented, and selected marine fuels are then evaluated using the criteria. This chapter also discusses the possible routes from energy sources to energy carriers and explores the available energy sources that can be used to produce those fuels.

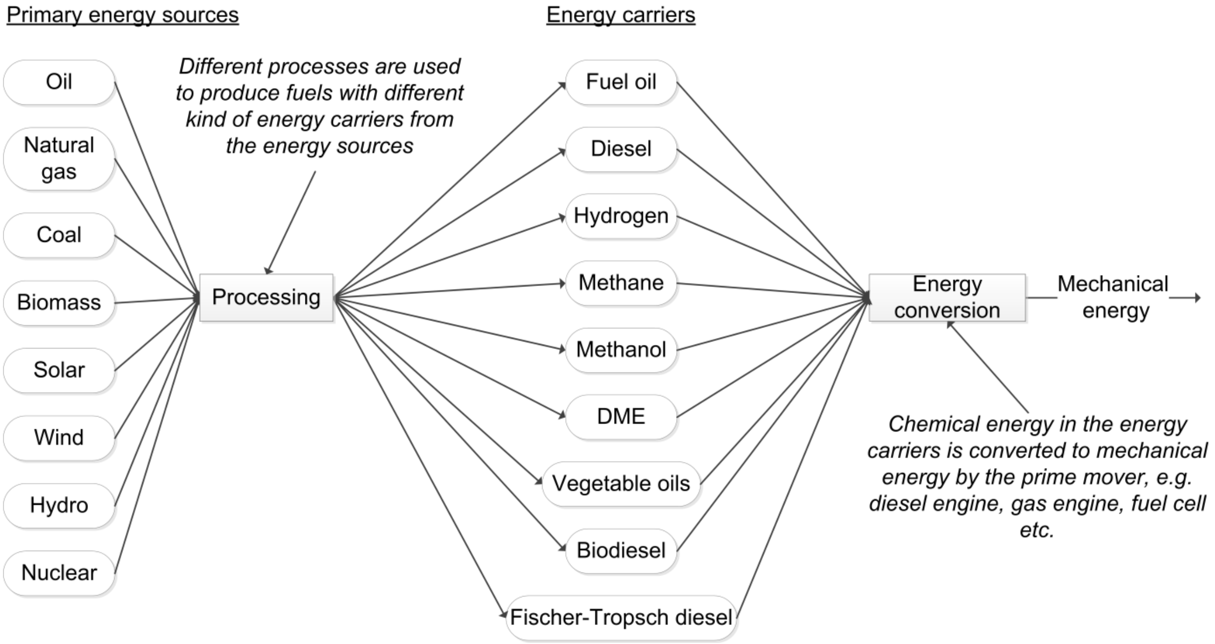

Figure 3-1 A simplified diagram of the chain from energy resources to mechanical energy for marine propulsion.

3.1 Fuels, Energy Carriers and Primary Energy Sources

Fuel is a broad term used for a material, such as coal, oil, or gas that is burned to produce heat and power. In this work, the term fuel is used in a narrower sense. In this thesis, a *fuel* is considered to be a material that can be used to produce heat and power associated with a specific type of primary energy source and processing option. An energy carrier is a substance or sometimes a phenomenon that contains energy that later can be converted to other forms. In this work, *energy carriers* are used to define the component of the fuels that carries the chemical energy that can be converted into mechanical energy. Several different fuels may thus share the same type of energy carrier. For example, LNG and liquefied biogas (LBG) are fuels in which methane is the primary energy carrier. *Primary energy sources* are unrefined sources of energy found in nature, such as coal, oil and wind. These are used to produce fuels with different types of energy carriers. The type of energy carrier in the fuel will affect what types of prime movers can be used to convert the chemical energy into mechanical energy. A prime mover is a machine that converts a form of energy into work.

3.2 Criteria for Future Marine Fuels

What are the most important aspects to evaluate when considering future marine fuels? Efficiency, safety, costs and environmental aspects are all factors that have different weights in the many alternative perspectives, and the various stakeholders have conflicting views of the importance of these aspects. A set of criteria that can be useful when assessing future marine fuels is presented in Figure 3-2.

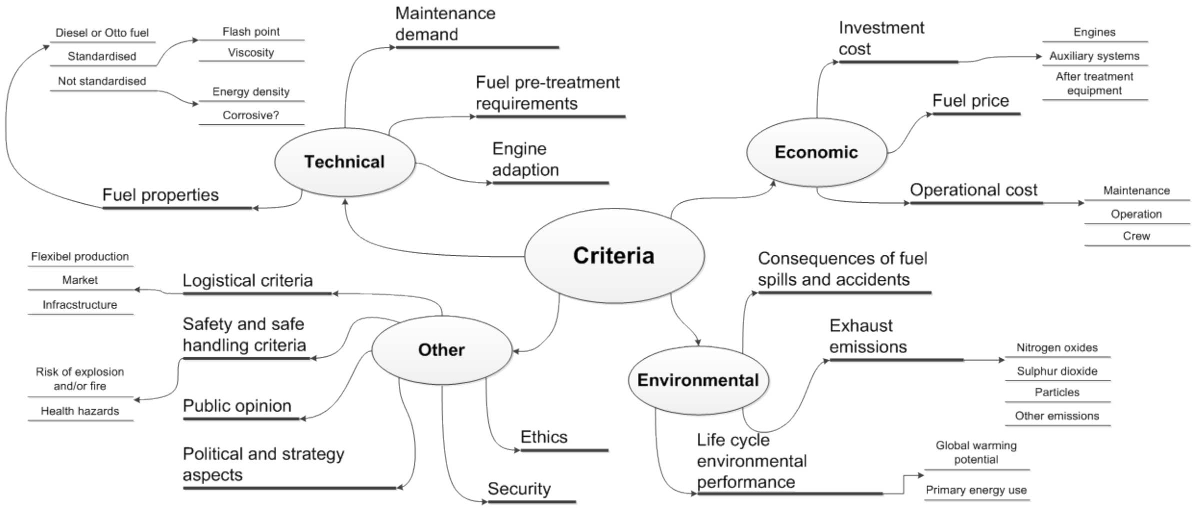

Figure 3-2 Aspects to consider when selecting future marine fuels.

This set is divided into four groups: technical, economic, environmental and other criteria. Certain criteria involve minimum levels that must be satisfied, and these act as boundary conditions in the selection. This work is based on a workshop and continuous discussions as part of the Effship project[28] and presented in Bengtsson et al. (2012).

3.2.1 Technical Criteria

The technical system in the fuel chain includes the system onboard a ship that is associated with the fuel (e.g., engines, storage tanks, pumps, pipes and exhaust funnel), the bunkering ships and the fuel storage terminal. All of these systems need to be technically feasible; thus the boundary condition is that it must be possible to construct and operate such systems. The primary criteria under consideration are fuel properties (both standardised and non-standardised), propulsion systems and fuel pre-treatment requirements. International fuel standards have been developed to ensure the safe use of fuels in ship engines and to ensure compliance with (inter)national environmental standards. ISO 8217:2012 defines such fuel requirements as the fuel density, ash content, water content and sulphur content (ISO, 2012).

The properties of thirteen fuels were investigated by Astbury (2008), and all except hydrogen were demonstrated as having properties similar to those of existing fuels. The cetane number is an indication of the ignition quality of diesel fuel. It is a measure of the fuel's ignition delay between the start of injection and the start of combustion. The octane number is a measure of the tendency of the

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[28] The Effship project was funded by VINNOVA and by the participating research organisation and companies, i.e., SSPA Sweden AB, ScandiNAOS, Wärtsilä, S-MAN AB, D.E.C. Marine AB, Chalmers University of Technology, StoraEnso AB, Göteborg Energi and Stena AB. The goal of the project was to design methods of efficient shipping with low emissions.

fuel to detonate during combustion in ICEs based on the Otto cycle. Examples of fuel properties that are not standardised include the energy density and boiling point. The boiling point is related to the volatility of the fuel; fuels with low boiling points will readily evaporate. The energy density is a measure of the energy content per volume of fuel. This measure provides an indication of the fuel's onboard storage demands. The energy density is a limiting factor that is particularly important in ocean transportation because vessels travel long distances between bunkering.

Reciprocating ICEs are the dominant prime mover technology today. However, it has been considered positive if the fuels may be used in different propulsion systems in the future. Possible alternative propulsion systems for shipping include fuel cells (e.g., Marc (2005) and McConnell (2010)) and gas and steam turbines (e.g., Haglind (2008)).

3.2.2 Environmental Criteria

The air emissions from shipping have received a great deal of attention in recent years, and the focus has been on SO_X, NO_X, PM and greenhouse gas emissions. It is required that the fuel alternatives fulfil the present environmental regulations (emissions of NO_X and SO_X). It is also likely that the environmental regulations will become stricter in the future, and the fuel alternatives therefore need to be able to meet tougher future environmental requirements to avoid there being yet another fuel change in the near future. It is also important that the environmental life cycle performance of the fuel alternatives are acceptable. Here, two aspects are considered the most important: the total extracted energy and the GWP.[29]

A third category involves the consequences of fuel leaks, such as those caused by accidents. Certain of the environmental criteria, because they can be quantified, are easily used to compare fuel alternatives. The consequences of fuel spills and accidents are not one of these because they depend on the characteristics of the environment that is affected. One property that affects the consequences of fuel spills is the biodegradability of the fuel.[30]

3.2.3 Economic Criteria

The choice of fuel in the marine industry has, to a large degree, been historically driven by economics, as mentioned in the *Introduction*. However, the cost of fuel is only one cost that needs to be considered when evaluating fuels; others include the investment and operational costs.

Fuel cost is a considerable expense in shipping. As an example, "the bunker market is extremely price sensitive, with ships often basing decisions on where to bunker on the relative price of fuel available in respective ports" (Notteboom and Vernimmen, 2009). As mentioned in the *Introduction*, fuel costs were estimated to represent between 30 and 54% of the operating costs in 2006, depending on the type of vessel (Kalli et al., 2009). Fuel costs are expected to increase due to the upcoming sulphur regulations, causing the impact on a vessel's operating cost to grow further. It can also be expected that the price differential between different fuel qualities will increase, according to Eriksson (2011).

The investment cost includes all costs related to the purchase of the ship and the equipment installations (e.g., engine retrofitting, storage tanks and installation of emissions abatement equipment). The high investment cost acts as a barrier to new investments, even if the payback time is short. In this work, the operational cost excludes fuel cost, which is analysed separately. The operational cost can be divided into two parts: the operational cost, which includes crew costs,

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[29] Ideally, all environmental impact categories would be important to consider, but as a first set of criteria, these two categories have been considered the most important. Many of the other impacts are curtailed by reducing emissions during marine transportation.

[30] Blin et al. (2007) compared the biodegradability of a number of fossil and biofuels.

insurance and overhead cost and the maintenance cost, which includes, for example, the service and repair of engines and the cost of spare parts.

3.2.4 Other Criteria

Other criteria include logistics, safety, security, public opinion, ethics and political and strategic aspects. Logistical criteria include requirements concerning the market, flexibility of production and infrastructure. It is important that the energy carrier is available in a given market and that there are sufficient raw materials to produce the desired volumes. If the energy carrier can be produced from a number of different raw materials, this will increase the flexibility.

Safety criteria include the risk of explosion and fire and the health hazards encountered by people handling the fuel. The flammability limits are the concentrations in air between which a fuel is flammable. Fuels with wide limits can generate a large potential volume of flammable atmosphere, and the time required to dilute the fuel below the lower flammability limit may be substantial (Astbury, 2008). If a fuel is soluble in water, it can be diluted to a non-flammable level at ambient temperatures and thereby no longer present a fire or explosion risk. Water solubility is not of interest for gases because they disperse quickly (Astbury, 2008). A specific safety concern regarding gases is the potential for them to replace air in confined spaces, if leaked, and to act as an asphyxiant, if not detected. The health hazards of fuels include acute and chronic toxicity resulting from exposure and their cancer-causing properties.

Public opinion involves the attitudes expressed by the general public, such as the demand for sustainable transportation. A political and strategic aspect may be related to a situation in which new jobs are created by producing a fuel locally. Ethical considerations include whether the production and use of the fuel causes hardships for certain populations. For example, the production of ethanol from corn or other food crops could potentially cause higher food prices for citizens of poorer nations (Mueller et al., 2011).

3.3 Present and Possible Future Marine Fuels

A list of possible future fuels for marine propulsion is shown in Figure 3-3. The fuels are grouped into four categories: fuels of diesel quality, gases, alcohols and solid fuels, based on the type of energy carrier.

Fuels of diesel quality	Heavy fuel oil (HFO) Low sulphur HFO (<1 wt. % S) Low sulphur distillate fuels (<0.1 wt. % S) Vegetable oils Biodiesel Biomass-to-liquid (BTL)/synthetic biodiesel Gas-to-liquid (GTL)/synthetic diesel (Fischer-Tropsch)
Gases	Liquefied natural gas (LNG) Liquefied biogas (LBG) Dimethyl ether (DME) Liquefied petroleum gas (LPG) Hydrogen
Alcohols	Methanol Ethanol Buthanol OBATE-fuel
Solid fuels	Uranium Coal Wood

Figure 3-3 Possible future marine energy carriers.

3.3.1 Fuels of diesel quality

The diesel engine and therefore diesel fuels have been dominant in the shipping industry for the last 50 years (Corbett, 2004). Fuels of diesel quality form a group of fuels which can be used in diesel engines derived from both fossil and biomass resources.

HFO fulfils the technical criteria and has been proven to work efficiently in marine diesel engines for more than 50 years. However, this fuel is also associated with various environmental issues and will not comply with the strictest environmental regulations in place without exhaust abatement technologies. Its price has also increased significantly in recent years (Danish Maritime Authority, 2012). The prices of HFO have fluctuated between 10 and 11 Euro/GJ in Rotterdam during October 2013 (Bunkerworld, 2013), and a forecasted HFO price of approximately 12 Euro/GJ was used by the Danish Maritime Authority (2012). Avis and Birch (2009) estimated a price increase of 30-50% for HFO with 0.5 wt. % sulphur in comparison to the high-sulphur HFO in 2009. HFO typically has a sulphur content of 1% or greater, but it is possible to produce HFO with a low sulphur content (0.5 wt. % and lower) via technical measures in the refinery, such as desulphurisation (Avis and Birch, 2009).

MGO is also used currently; it is a distillate fuel with a lower sulphur content, possibly below 0.1 wt. % sulphur. It is also a technically proven fuel with an existing infrastructure and market. Its advantage is that it will comply with the 0.1% sulphur limits for marine fuels in the ECAs and, when combined with an SCR unit, will comply with the NO_X Tier III requirements. However, MGO is more expensive than HFO. The Danish Maritime Authority (2012) estimates the future MGO price to be in the range of 1.6-2.2 times the HFO price, whereas Avis and Birch (2009) estimated an MGO price increase of 60-75% relative to the price of fuel with 1.5 wt. % sulphur in 2009. The availability of both HFO and MGO is determined by the future availability of crude oil, and these two fuels are therefore not flexible with regard to fuel sources.

Vegetable oils, such as jatropha oil and rapeseed oil, and animal fat can be used in diesel engines. Jiménez Espadafor et al. (2009) analysed the physical and chemical properties of various vegetable oils as alternatives to HFO and concluded that the current technical methods of storage and distribution of HFO on large ships are compatible with the use of vegetable oils. Vegetable oils have very low sulphur contents, typically below 20 wt. ppm (He et al., 2009). Petzold et al. (2011) compared HFO and MGO with four vegetable oils, and the emissions of NO_X were observed to be of the same order of magnitude, but the emissions of particles were reduced significantly compared to HFO. Vegetable oils will comply with the strictest sulphur regulations but need to be combined with exhaust abatement technologies to comply with the NO_X Tier III requirements. They are biodegradable and will be less harmful to the environment than HFO and MGO in cases of spills. Instead of using the vegetable oil directly, it can be refined into biodiesel. Biodiesel has been tested for marine propulsion by Maersk and by the United States navy (Bruckner-Menchelli, 2011; Gallagher, 2010). Vegetable oils can replace HFO in diesel engines but are less compatible with diesel engines designed for MGO. Biodiesel can therefore be a better alternative in these engines (Opdal and Hojem, 2007). It is also possible to produce a diesel quality fuel from various feedstocks using the Fischer-Tropsch process. If natural gas is used, the fuel is usually called gas-to-liquid (GTL), and if biomass is used, the fuel is called biomass-to-liquid (BTL).

The production of biofuels has increased during recent years. As their production increases, more arable land is needed. Certain crops can be used both as food, feed and to produce biofuels, and thus the arable land can be used to produce either food or energy crops. This has resulted in land use competition between food and energy crops and has, in the short term, resulted in increased food prices (Rathmann et al., 2010). This competition poses a global dilemma, i.e., that of society's need to feed itself versus the greater monetary returns to farmers through the use of lands for energy crops.

3.3.2 Gases

Gases include all fuels that are gaseous at standard temperature and pressure, e.g., LNG, dimethyl ether (DME), liquefied petroleum gas (LPG) and hydrogen. Natural gas is already established as a fuel for domestic and commercial heating and large-scale electricity generation. Compressed natural gas (CNG) is used in short-range distribution, but to make long-distance distribution cost-effective, it has to be liquefied. To form a liquid, natural gas must be cooled to -162°C, which is performed in a number of compression steps. LNG usually consists of methane, nitrogen and a small proportion of ethane and propane. The use of LNG as a fuel in shipping is limited to LNG carriers, which use the boil-off gas as fuel in steam turbines, and more than 30 LNG-fuelled ships, primarily operating in Norway (Blikom, 2012).

The LNG-propelled ships in operation in Norway are either equipped with spark-ignited (SI) lean-burn gas engines or dual-fuel (DF) engines. DF engines can run on either LNG or HFO/MGO. When using LNG, a small amount of diesel pilot fuel is injected for ignition (see section 4.1.3 for more information). One of the downsides of LNG is the complicated and costly retrofits required of existing engines. LNG has gained substantial interest as a marine fuel because it can comply with the strictest environmental regulations currently in force. It has a sulphur content of only a few ppm, and four-stroke SI and DF engines will comply with the NO_X Tier III regulations. However, one potential problem associated with the use of LNG is the potential leakage of methane, which is a stronger greenhouse gas than CO_2 (see section 2.2.1).

It is also possible to use liquefied biogas (LBG), which is produced from biomass, instead of LNG. LBG consists primarily of methane and does not contain any higher proportions of other hydrocarbons, such as ethane and propane. The most common way to produce LBG currently is by anaerobic digestion, but it is also possible to produce LBG from the gasification of biomass. In terms of the engine, LNG and LBG are nearly identical; it is the upstream portion of their fuel life cycles that differ, i.e., the raw material used, the production process, the price and the availability. A future price for LBG in the range of 11-50 Euro/GJ was estimated by Florentinus et al. (2012). The upper range is significantly higher than estimates for LNG, which was in the range of 7-12 Euro/GJ in one study (Danish Maritime Authority, 2012).

LNG and LBG have a lower energy density than do traditional fuels and need to be stored in cryogenic tanks (Gullberg and Gahnström, 2011). This non-traditional storage requirement may have an impact on the space requirement onboard. The cargo capacity was demonstrated to be reduced by 4% following an LNG retrofit of a feeder container vessel, whereas a retrofit of an ocean-going tanker vessel did not result in any reduced cargo capacity (Gullberg and Gahnström, 2011). The actual space requirement will vary from vessel to vessel and is difficult to estimate. The space requirement needs to be considered for each case of new shipbuilding and retrofit.

DME and LPG are similar with respect to handling and storage (Verbeek and Weide, 1997). Both are gases at normal temperatures and pressures and are compressed to form liquids. These gases do not need to be cooled, as is the case with LNG and LBG. DME is a colourless gas at room temperature and atmospheric pressure and is considered an alternative fuel in compression ignition diesel engines. DME is produced from synthesis gas, whereas LPG is composed of hydrocarbon gases, usually a mixture of propane and butane. LPG is produced during crude oil refining or is extracted during natural gas production. The engine manufacturer MAN is promoting a two-stroke marine engine that runs on LPG and can be adapted to DME propulsion (MAN Diesel & Turbo, 2011). DME has also received a great deal of attention as a future road fuel (Arcoumanis et al., 2008; Salsing, 2011).

Hydrogen is seen as a potential future fuel because it produces no CO_2 during combustion and results only in water as emission if it is used in fuel cells. The life cycle performance of hydrogen as a fuel depends primarily on the raw material extraction, fuel production and distribution; the pathways selected will have an impact on the environmental performance (see, for example, Cetinkaya et al. (2012)). There are a number of problems associated with hydrogen, which, so far, have not been solved. It is, for example, difficult to store and transport. Even in liquid form, hydrogen has a very low energy density, approximately 1500 MJ/kg. Thus far, hydrogen is not discussed a great deal as a future marine fuel. The use of liquid hydrogen in ICEs in a long-haul feeder container ship has, however, been evaluated by Veldhuis et al. (2007). It is not thought that hydrogen can be implemented within the next ten years on a large scale, but the use of hydrogen in fuel cells for auxiliary power is possible.

3.3.3 Alcohols

Of the possible alcohols that could be used as fuels in shipping, methanol has received the greatest attention thus far. Ethanol is also a possibility, and it is currently used primarily as a car fuel to replace petrol (Goldemberg, 2007). Ethanol may be produced from agricultural feedstock, such as sugarcane grown in Brazil. Although, this thesis focuses on methanol, one last potential alcohol that has received attention is glycerol, which is also called glycerine (see Box 3-1).

Methanol is the simplest alcohol and has traditionally been used as a chemical base material. Currently, ethanol is primarily produced from natural gas but can also be produced from coal, as is done in China in particular (Yang and Jackson, 2012). Chemicals that use methanol in their production include formaldehyde, methyl tert-butyl ether and acetic acid (Höhlein et al., 2006). Methanol displays many desirable combustion and emissions characteristics that make it a good fuel for premixed combustion in Otto engines. Methanol can also be used in a diesel process, where a glow plug or pilot fuel is used as the ignition source. Olah et al. (2009) suggested the use of methanol as a marine fuel in fuel cells, and methanol fuel cells have been tested for auxiliary power on the car carrier Undine. Two engine concepts involving methanol were evaluated as part of the EffShip project: the premixed DF concept and the methanol-diesel concept (see section 4.1.3 for more information). It is easier and less expensive to convert engines to the methanol-diesel configuration than to the DF configuration, and the former is therefore seen as a possible intermediate-term solution (Fagerlund and Ramne, 2013).

Methanol was tested in a fuel cell application as part of the MEETHANU project by installing Wärtsilä's WFC20 fuel cell unit onboard the Undine, a car carrier. The fuel cell unit, which has a nominal output of 20 kW, is based on planar SOFCs and is fuelled with methanol (Fontell, 2010). It may also be possible to use methanol in an engine provided with a glow plug as ignition assist; this concept has been tested in heavy-duty engines, as described by Richards (1990).

From 1975 to 2008, the average wholesale price of methanol has fluctuated between 4 and 15 Euro/GJ. The small number of peaks in methanol prices during this period were the result of increased demand, production problems and high natural gas prices (Olah et al., 2009).

Methanol will comply with the strictest sulphur regulation and could potentially comply with the NO_X Tier III requirements, depending on the selected engine technology. There is a risk of increased emissions of formaldehyde, which would need to be considered. Methanol will most likely be associated with lower impacts resulting from fuel spills because it is not persistent in the environment and biodegrades quickly. It is, however, toxic at high concentrations; thus, there could be local affects before dilution occurs (Clary, 2013).

Methanol can be produced from a broad range of energy sources, e.g., biomass, coal and natural gas, making it a flexible fuel to produce. It is also possible to produce methanol by using electricity to split water into hydrogen, which is then combined with CO_2 to form an electrofuel. More information on electrofuels is provided in Box 3-2.

Box 3-1 Glycerol

Glycerol, also called glycerine, is a simple alcohol used, for example, in the cosmetics and pharmaceutical industries. It is a by-product of biodiesel production, and the supply has grown with the growth in biodiesel production. One potential use of glycerol is as a fuel. It is non-toxic and non-volatile. McNeil et al. (2012) developed a combustion cycle that makes it possible to use glycerol in compression ignition engines. Glycerol is expected to yield low emissions of NO_X and PM and no emissions of SO_2. The world supply of glycerol was 3.2 million tonnes in 2008 (Day et al., 2011), and it may also be possible to produce glycerol from Dunalieila algae in saline water. This process was investigated by Ben-Amotz et al. (1982). The GLEAMS project in UK intends to develop marine engines that can use glycerol and comply with the strictest environmental regulations in force.

3.3.4 Solid Fuels

It is also possible to use solid fuels. Coal was used earlier as a ship fuel to produce steam for steam turbines (Corbett, 2004). Coal was also recommended as the future marine fuel in 1980 in a report by the Maritime Transportation Research Board (Committee on Alternative Fuel for Maritime Use, 1980). Nuclear reactor propulsion has been used by a large number of military vessels, e.g., submarines and aircraft carriers, and by a few civilian vessels, e.g., icebreakers and aircraft carriers, for more than 50 years (World Nuclear Association, 2014). The nuclear merchant ships have been difficult to operate economically, although higher fuel prices may change this. Before the Fukushima accident, there were far-reaching discussions regarding building new nuclear merchant ships. However, due to security issues, the International Atomic Energy Agency (IAEA) is concerned about the use of nuclear reactors in merchant shipping and in research (IAEA, 2010), and the introduction of new nuclear vessels may be slow due to these constraints and due to public opinion in port states.

Box 3-2 Electrofuels

Electrofuel is an umbrella term for carbon-based fuels that are produced using electricity as the primary source of energy. The carbon in the fuel is from carbon dioxide and can be captured from the air, the sea or exhaust gases. Electrofuels can also help in the balancing of energy production when that production is intermittent, as in electricity generation from wind and solar sources. The electrofuels may be produced during periods of excess energy and used later for various purposes in the energy system (Nikoleris and Nilsson, 2013).

Electrofuels offer feedstock flexibility and potential high-efficiency synthesis of fuels directly from renewable energy resources without competition for arable land and scarce water resources. However, production of electrofuels is still in its infancy, and many challenges need to be overcome before these products are brought to market on a large scale (Conrado et al., 2013).

Methanol is produced from carbon captured from industrial emissions, water and geothermal energy at Island by Carbon Recycling International. This firm operates a pilot plant and a commercial plant. The commercial plant has operated since the end of 2011 and has the capacity to produce 5 million litres of methanol per year (Carbon Recycling International, 2014).

3.4 Primary Energy Sources

There are many potential pathways to produce energy carriers, and various types of primary energy sources can be used. An overview of several possible pathways is shown in Figure 3-4, below. A few of these pathways are assessed in this work; these are highlighted in the figure and described in more detail in section 4.1.3.

There are both renewable and non-renewable primary energy sources. A renewable resource is a resource that can be replenished reasonably quickly (from hours to a hundred years). Non-renewable resources are of essentially fixed quantity, or stock, in the Earth’s crust, although on a time scale of millions to billions of years, geological processes can renew such resources.

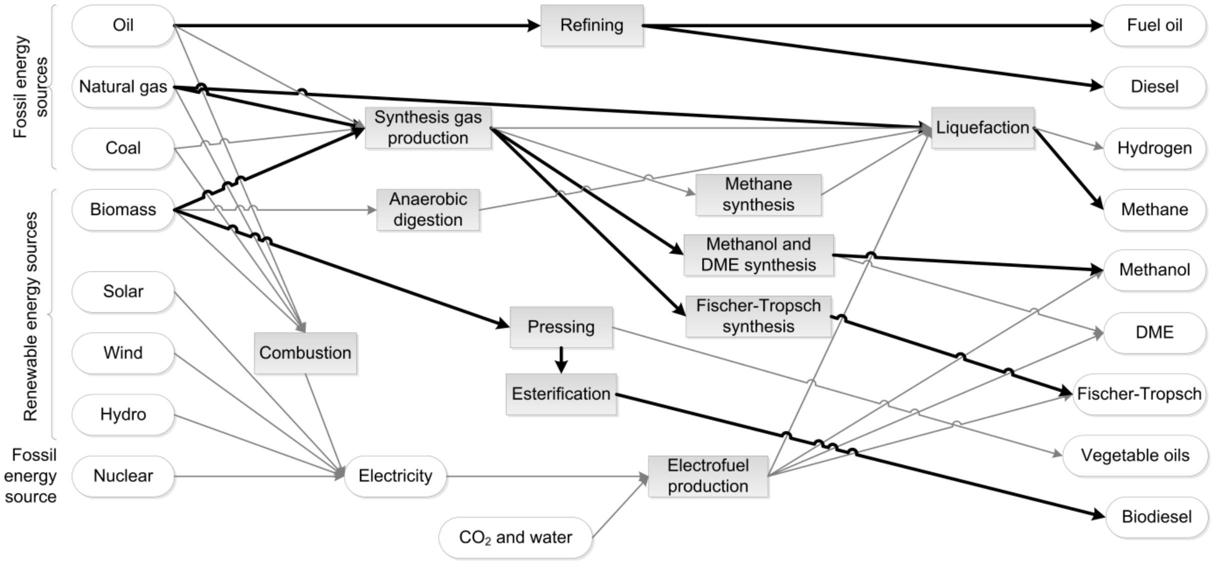

Figure 3-4 Potential pathways from raw material to fuels (highlighted pathways are assessed in this thesis).

3.4.1 Fossil Energy Sources

The energy sources now used most are non-renewable and are extracted from the Earth. Oil, natural gas, coal and nuclear energy represented approximately 80% of the global primary energy use in 2010 (IEA, 2012). The supplies of oil and gas are expected to be seriously diminished by the middle of the twenty-first century. This picture is further complicated by the great regional disparities in the distribution of fossil fuel reserves. Table 3-2 presents the reserves, resources and distribution of fossil energy sources, including oil, gas, coal and uranium.

Table 3-2 distinguishes between conventional and unconventional resources. However, there is no clear boundary between what is called conventional and unconventional. Conventional oil is oil that is mobile in situ[31] and can be produced economically using conventional methods. Gas condensate and natural gas liquids are also usually included. Unconventional oil includes oil of high viscosity and shale oil. Deep offshore and Arctic oil is also occasionally considered unconventional oil because of the difficulty of deep-sea drilling or Arctic production. Today, the total amount of oil extracted from the Earth's crust is approximately equal to the current remaining conventional oil reserves (Rogner H-H et al., 2012). The production of conventional oil will most likely peak soon and begin to decline shortly thereafter. Massive development of unconventional oil occurrences would be necessary to shift the peak of oil production to 2050 or later (Rogner H-H et al., 2012). The peak concept is discussed further in Box 3-3.

The remaining resources of gas are abundant compared to oil, and estimates of these resources have risen steadily during recent decades (Rogner H-H et al., 2012). Natural gas consists of a mixture of gases, in which methane (CH_4) is the main component. Gas reservoirs may be associated with oil reservoirs but not necessarily. Associated gas is recovered together with oil and is separated above ground. The associated gas may be recovered, reinjected or flared.[32] The choice of method depends on the location, field size, geology and the amount of gas in the reservoir. Approximately 17% of all gas that is recovered in association with oil is currently flared (Rogner H-H et al., 2012).

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[31] BRG defines conventional oil as oil having a specific gravity of less than 0.01g/cm^3, which is equivalent to API gravity of 10°. The USGS defines conventional oil as oil having an API greater than 15°.

[32] To flare means to burn the fuel directly into the atmosphere, which results in the release of the combustion products to the atmosphere.

Box 3-3 The peak debate

How much fossil energy does the Earth's crust hold? This question has troubled many researchers and analysts since the beginning of the twenty-first century, and opinions differ, particularly between researchers from different disciplines. The focus has primarily been on the peak in conventional oil production, but peak gas, peak coal and peak uranium have also received attention lately.

The augments regarding peak oil are based on the fact that large oil discoveries ended in the mid 1960s and were followed by a decline in discoveries of new reserves. Extraction of more oil than is offset by new reserves will eventually result in a peak in oil production at approximately the time when half of the oil reserves have been used. A large number of estimates of the total amount of the world's available conventional oil have been developed; the majority of these estimates are in the range of 12,600-16,700 EJ. It is assumed that conventional oil production will peak in the foreseeable future, most likely before 2040, with a peak production rate of approximately 4 Gt (≈200 EJ) per year (Rogner H-H et al., 2012). When considering both conventional and unconventional oil production, it is expected that the maximum production will be characterised by a fluctuating plateau instead of a peak.

Arguments against a peak include the assertion that human creativity will keep ahead of resource depletion as has been the case in the past. Technological innovation will continue to unlock new reserves currently not identified or understood or not economically extractable with existing technology and market conditions. Furthermore, scarcity will result in higher prices, which will increase available reserves and decrease the demand. There might be a level when renewable resources are more economical, leaving plenty of untapped oil in the ground. This section is based on section 7.1.2 in Rogner et al. (2012).

The separation between conventional and unconventional gas is even more blurred than that of oil. Conventional gas is extracted using standard extraction technologies, but those technologies considered to be standard shift over time. Shale gas, coal-bed methane, tight gas, deep gas, water-dissolved gas and gas hydrate are all considered to be unconventional gas. The recent development of shale gas in the United States has received a great deal of attention, and the United States is now estimated to become a net exporter of natural gas instead of a net importer by 2021 (Wang et al., 2014). Natural gas-based fuels in shipping could potentially be produced from shale gas in the future. The development of shale gas is discussed further in Box 3-4.

Coal reserves remain substantial and are expected to last for more than 100 years. Portions of global coal deposits are located in remote areas or in areas with harsh conditions, and it will be a challenge to bring this coal to market. The productivity of coal mining has increased significantly during recent years, and coal is the lowest-cost fossil energy source (Rogner H-H et al., 2012). Uranium is another fossil resource that could potentially be used in shipping to fuel nuclear reactors or be used to produce electrofuels. The resources of fissile material are abundant and are not expected to limit a future expansion of nuclear power (Rogner H-H et al., 2012).

Table 3-1 Reserves and resources of fossil fuel and uranium (Rogner H-H et al., 2012).

	Historic production through 2005 [EJ]	Production 2005 [EJ]	Reserves [EJ][a]	Resources [EJ][b]
Conventional oil	6069	147.9	4900-7610	4170-6150
Unconventional oil	513	20.2	3750-5600	11,280-14,800
Conventional gas	3087	89.8	5000-7100	7200-8900
Unconventional gas	113	9.6	20,200-67,100	40,200-121,900
Coal	6712	123.8	17,300-21,000	291,000-435,000
Conventional uranium[c]	1218	24.7	2400	7400
Unconventional uranium[c]	34	n.a.		7100

[a]Reserves are those quantities that can be recovered in the future from known reservoirs under existing economic and operating conditions. [b]Resources are detected quantities that cannot be profitably recovered with current technology (reserves are not included). [c]Reserves and resources are based on once-through fuel cycle operation.

Box 3-4 Shale gas production

Shale gas is gas trapped in the pore spaces of sedimentary rock, in vertical fractures in the rock and adsorbed onto mineral grains and organic materials. Recent growth in production of shale gas is the result of new technology that creates extensive artificial fractures around horizontal well bores (Rogner H-H et al., 2012). The development has been concentrated in North America, but there are also shale gas resources in other parts of the world (Vello A. Kuuskraa et al., 2013).

With increased exploration and production there arise questions regarding the nature of shale gas development, its potential environmental impacts and the ability of the current regulatory structure to address this development. The environmental impacts associated with shale gas development occur at the global and local levels. These impacts generate environmental concerns involving water issues, greenhouse gas emissions, induced earthquakes and human health (Wang et al., 2014).

Hydraulic fracturing includes high-pressure injection of large quantities of water and chemicals to split rock apart and release the natural gas. It can be a challenge to protect water resources in areas of hydraulic fracturing. The amount of water used could be reduced by recycling the used water, but this is challenging due to contaminants. Another problem connected to the water use is the potential for water contamination because many of the chemicals used are toxic and carcinogenic. There is also a risk of methane contamination of groundwater (Wang et al., 2014).

The life cycle greenhouse gas emissions associated with the use of shale gas are still debated, particularly those associated with methane leaks during well completion and extraction. There are authors who argue that the use of shale gas is better for the climate than coal and oil, but other authors argue that shale gas may be worse than coal (Wang et al., 2014).

3.4.2 Renewable Energy Sources

The Earth’s largest energy source is the sun, with an annual input of 3,900,000 EJ. This amount is so large that the average radiation striking the Earth’s surface in one hour is approximately equal to all the energy consumed by all humans in one year. The annual flow of solar energy each year is larger than all fossil and uranium reserves and resources that are presently known. 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. The annual flows of renewable energy and their technical potentials are shown in Table 3-3, below.

Biomass was the primary energy source used by humans before the nineteenth century, and it is still the primary energy source used in the least-developed countries.[33] Biomass is biological material derived from agricultural crops, forest products, aquatic plants, crop residue, animal manure and waste. The annual flows of biomass are large, considerably larger than current global energy consumption, but harvesting large factions of the available biomass would result in severe adverse impacts on biodiversity, resilience and the Earth's ecosystems. The question, therefore, is how much utilisation is ecologically sustainable and socioeconomically desirable. Berndes et al. (2003) reviewed 17 studies that yielded estimates of the potential global biomass supply; the resulting estimates ranged from less than 100 EJ per year to greater than 400 EJ per year in 2050. The future availability of land and the yields of energy crop production are very uncertain and a major source of the broad range in the estimates. The global technical potential ranges between 160 and 270 EJ per year, according to Rogner H-H et al. (2012). Of this potential, dedicated energy crops represent 44-133 EJ, crops residues 49 EJ, manure 39 EJ, municipal solid waste 11 EJ and forestry 19-35 EJ. This estimated range is lower than previous estimates and is primarily based on lower expectations of the potential for growing dedicated energy crops (Rogner H-H et al., 2012). However, it should be stressed that these types of estimates are highly uncertain. These potentials can be compared to the world's primary bioenergy production of approximately 55 EJ 2012 (REN21, 2013) and the world's biofuel production of approximately 11 EJ in 2011 (U.S. Energy Information Administration, 2014).

There is a potential for the shipping industry to use wind, solar and wave power directly. The shipping industry could also potentially use electrofuels produced from renewable sources. Electrofuels are discussed in Box 3-2.

Table 3-2 Renewable energy flows, potentials and utilisation (Rogner H-H et al., 2012). The data are expressed as energy inputs. Considerable amounts of energy may be lost when converting it to useful energy carriers, such as electricity, heat or fuels; these losses depend on the specific technology.

	Utilisation 2005 [EJ]	Technical potential [EJ/year]	Annual flows [EJ/year]
Biomass, municipal solid waste, etc.	46.3	160-270	2200
Geothermal	2.3	810-1545	1500
Hydro	11.7	50-60	200
Solar	0.5	62,000-280,000	3,900,000
Wind	1.3	1250-2250	110,000
Ocean[a]	-	3240-10,500	1,000,000

[a]Ocean energy refers to the kinetic energy carried by waves, tides and currents and the potential energy stored in ocean salinity and temperature differences.

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[33] The traditional use of biomass is associated with the inefficient use of animal dung, wood, charcoal and crop residues for domestic cooking and heating.

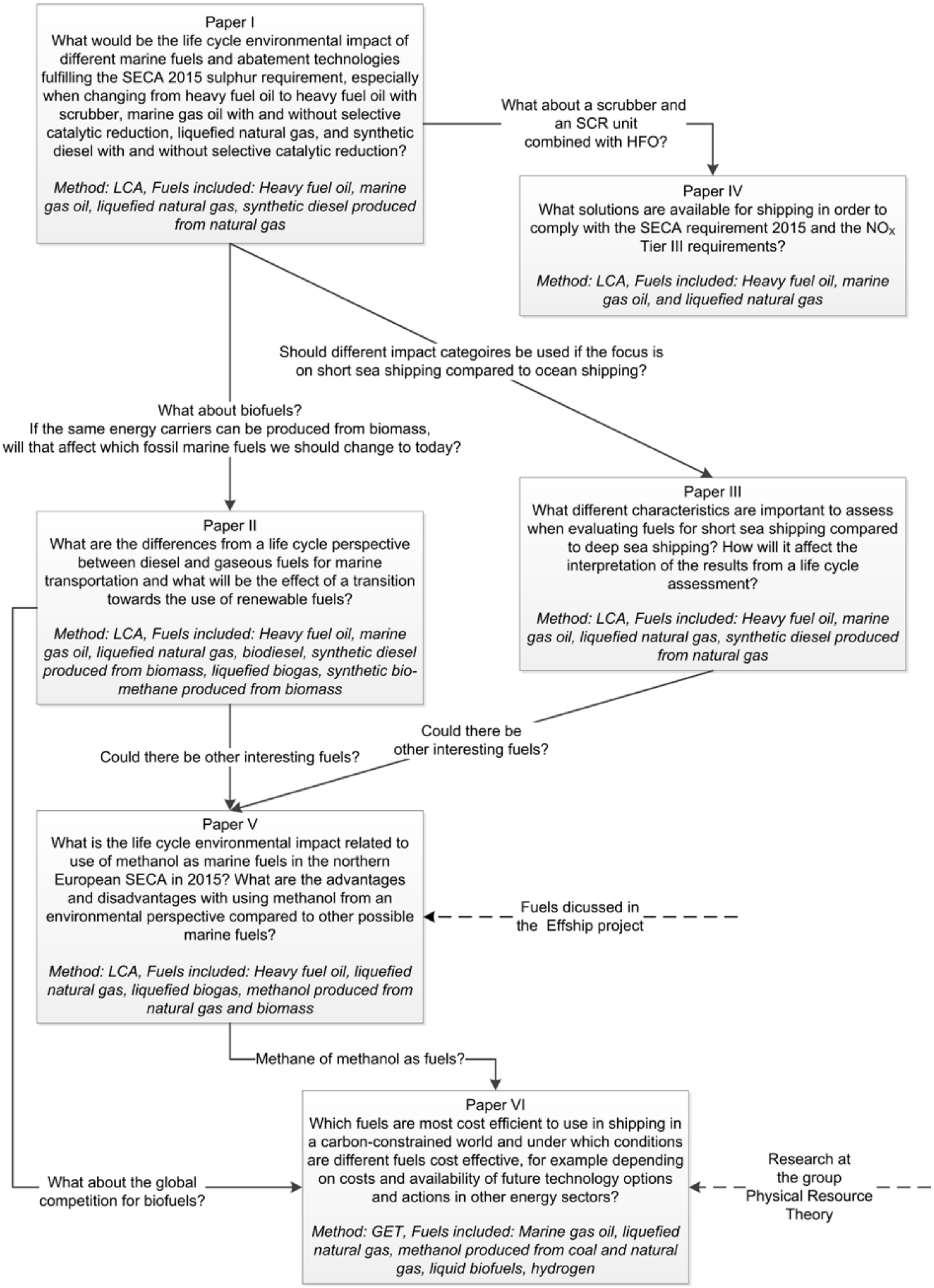

Figure 4-1 Overview of the papers included in this thesis and the questions linking them. Dashed lines represent inspiration gained from outside sources.

4 Methods

This study involved two different methods: LCA and global energy systems modelling. LCA is a well-established method for assessing the environmental performance of fuels. This was therefore the first choice of method for comparing the environmental performance of various marine fuels. During this study, questions were raised regarding the ways in which other energy sectors would impact the fuel choices of the shipping sector. The shipping sector is a relatively small energy consumer but is also a global industry. The fuels' environmental performance, based on the LCAs, were therefore complemented with use of the GET model, developed by the Physical Resource Theory group at Chalmers University of Technology. The papers included in this thesis and the questions linking them are shown in Figure 4-1.

4.1 Life Cycle Assessment of Marine Fuels

This section describes the general aspects of the five papers based on LCAs of marine fuels. It will also describe the modelling of choices in the LCA results presented in section 5.2.

4.1.1 Goal and Scope

The studies investigating the life cycle performance of marine fuels share a number of aspects in common, even though the specific questions addressed in the studies differ. They all share the common goal of assessing the environmental performance of possible future marine fuels and comparing them to existing fuels. The LCAs are geographically limited to ship operations in the northern part of Europe but do include the entire fuel cycle, from the raw material extraction to the combustion in marine engines, excluding the production of capital goods (e.g., ships, terminals, exhaust abatement technology, etc.). In a screening LCA by Johnsen and Magerholm-Fet (1998), the fuel life cycle was shown to be responsible for the largest proportion of the environmental impact associated with a ship's life cycle. The northern part of Europe in one of the first areas to be subjected to the 0.1 wt. % sulphur limit in marine fuels beginning in 2015 and is therefore the natural geographic region to include in an assessment of alternative marine fuels.

The studies also have a short time horizon and are intended to be applicable to the period 2010-2025 (with slight variations among the studies). This timespan was selected so that the assessments would be applicable when the stricter environmental regulations enter into force and for a few years into the future afterward. Three potential future energy carriers (diesel, methane and methanol) produced from natural gas and biomass were included, resulting in a total of 10 investigated fuels (Table 4-1). The specific modelling choices of the various studies are explained in the appended papers.

The functional unit in all of the studies was one tonne of cargo transported one km using a ro-ro vessel, except in Paper II, in which the year-round ferry operation between the island Gotland and the Swedish mainland was used instead. In this thesis, the values are expressed in units of MJ of fuel combusted in four-stroke diesel engines to allow for comparison with other assessments easier and to render the data independent of different storage requirements onboard different vessels. The results do not take into account that different amounts of fuels may be needed for the same transport work, due to the different storage requirements of the various fuels. The benefit of this choice is that readers of this thesis can use the data and adopt it to specific vessels and their specific energy requirements. The use of fuels with lower energy densities and larger fuel storage requirements will not necessarily reduce the transport work per unit of energy consumed. There will also be differences between the energy requirements of various types of scrubbers. The negative aspect of this choice is that the results might be misleading in situations in which the choice of fuel has an impact on the amount of energy needed for specific transport work. The results of this thesis may also be considered as complementing the results presented in the appended papers.

Table 4-1 Summary of fuels investigated in this work.

Abbreviation	Full name	Energy carrier	Primary energy source
HFO	Heavy fuel oil	Diesel	Crude oil
MGO	Marine gas oil	Diesel	Crude oil
GTL	Synthetic diesel	Diesel	Natural gas
RME	Rapeseed methyl ester	Diesel	Biomass (i.e., rapeseed)
BTL_w	Synthetic biodiesel	Diesel	Biomass (i.e., willow; forest residues were also assessed in Paper II)
LNG	Liquefied natural gas	Methane	Natural gas
LBG_{ar}	Liquefied biogas	Methane	Biomass (i.e., agricultural residues, manure and municipal organic waste)
LBG_w	Liquefied biogas	Methane	Biomass (i.e., willow; forest residues were also assessed in Papers II and V)
$MeOH_{ng}$	Methanol	Methanol	Natural gas
$MeOH_w$	Methanol	Methanol	Biomass (i.e., willow; forest residues were also assessed in Paper V)

4.1.2 Environmental Impact Categories

A number of environmental impact categories were included in the various studies, all at the midpoint level (discussed in section 2.3.1), including climate change, energy use, acidification, eutrophication, photochemical ozone formation, particulate matter formation and land use. The characterisation factors used in the first four studies are those of Guinée (2002) and the CML (2010), and the factors used in the last paper (Paper V) are those of IES (2012). In Paper III, characterisation factors from published articles were also included. Additional details can be found in the specific papers. The characterisation factors for the results presented in section 6.2 are shown in Table 4-2. The impact category *total extracted energy* is also included in this thesis, and the characterisation factors are based on the energy content (i.e., the lower heating value) of the primary energy sources.

Table 4-2 Characterisation factors for the included impact categories of the results presented in section 6.2 (IES, 2012).

Impact categories	**Climate change**			**Particulate matter**	**Photochemical ozone formation**	**Acidification**	**Marine eutro-phication**
Unit	kg CO_2-eq. /kg			kg $PM_{2.5}$- eq. /kg	kg C_2H_4- eq. /kg	mole H^+- eq. /kg	kg N- eq. /kg
	100 yr	20 yr	500 yr				
CO_2	1	1	1	0	0	0	0
CH_4	25	72	7.6	0	0.0101	0	0
N_2O	298	289	153	0	0	0	0
NO_X[a]	0	0	0	0.0072	1	0.74	0.092
SO_2	0	0	0	0.0611	0.0811	1.31	0
NH_3	0	0	0	0.0667	0	3.02	0.389
PM_{10}	0	0	0	0.2278	0	0	0
NMVOC	0	0	0	0	1	0	0
CO	0	0	0	0	0.0456	0	0
CH_2O	0	0	0	0	0.877	0	0
C_2H_6	0	0	0	0	0.208	0	0
C_3H_8	0	0	0	0	0.297	0	0

[a] NO_X includes nitrogen monoxide (NO) and NO_2 and is calculated as NO_2.

CO_2 emissions from combustion of biomass use is in this thesis considered “carbon neutral” over its life cycle because combustion of biomass releases the same amount of CO_2 as was captured by the plant during its growth.[34] By contrast, fossil fuels release CO_2 that had been locked up for millions of years.

4.1.3 Description of the fuel chains

The life cycles of the evaluated fuels are described briefly in the following section. There are certain information overlaps associated with the descriptions in the section concerning present and possible future marine fuels, but the focus here is to provide a more detailed description of the life cycles of the fuels selected for evaluation in this work. A simplified flowchart of the fuel chains is shown in Figure 4-2.

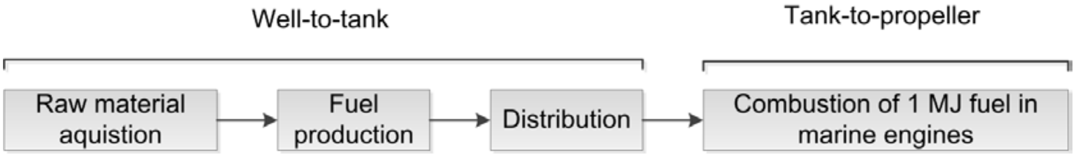

Figure 4-1 A simplified flowchart of life cycle of the assessed marine fuels.

4.1.4 Raw Material Extraction and Fuel Production

Three types of raw materials for fuel production were considered in this thesis: crude oil, natural gas and biomass. Each of these raw materials is described below.

Crude Oil as the Raw Material

Crude oil is extracted from onshore and offshore locations, and the characteristics of crude oil vary greatly, depending on the location of the oil field and the age of the production site. Typical crude oil contains 84.5% carbon, 13% hydrogen, 1-3% sulphur and less than 1% each of nitrogen, oxygen, metals and salts, but these amounts vary widely (Aitani, 2004). Crude oil can be transported either by pipeline or by a crude oil carrier from the extraction site to refineries.

After the removal of contaminants, the crude oil is distilled in atmospheric and vacuum towers to separate the crude into fractions, depending on their differences in boiling temperature. To obtain a larger share of lighter products, the heavier products are usually chemically modified by either thermal or catalytic cracking (Hocking, 2005). Many refinery processes may be used in the production of marine fuels, e.g., atmospheric distillation, vacuum distillation, thermal cracking, catalytic cracking, hydrocracking and coking. The set of refining processes used varies from one refinery to the next, and the feedstock for these processes also varies from one facility to the next and over time.

Gas oils are light, and heavy gas oil fractions and blends thereof, from straight-run and cracked origins, have a boiling range between 200 and 350°C. They are predominantly used as automotive diesel fuels and as domestic heating fuels, but *MGO* is also produced from this fraction (Alfke et al., 2007). *HFO* consists of various mixtures of residual oils from the distilling and conversion processes in the refinery. These products are used as marine bunker fuels, in power stations and in industrial furnaces. The HFOs can be blended with gas oils to adjust the density, viscosity and sulphur content (Alfke et al., 2007).

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[34] There is a debate if biomass combustion can actually be regarded as “carbon neutral” and how emissions of CO_2 from biomass should be treated, for more information on this see for example Whitman and Lehmann (2011), Johnson (2009) and Rabl et al. (2007).

Natural Gas as the Raw Material

Natural gas is extracted both offshore and onshore and may or may not be associated with oil. Its energy requirements and pollution associated with its extraction vary with the location and method of extraction. After extraction, the gas is separated from water, acidic gases, nitrogen and other hydrocarbons (Sevenster and Croezen, 2006). The treatment processes for the gas depend on the raw gas quality and the required standards for the processed gas.

Natural gas is transported from the site of extraction by pipeline or is liquefied on site. In the case of remote gas fields, it is also possible to transport the gas by CNG carrier (Beronich et al., 2009). Before the gas is transported by pipeline or CNG carrier, it is compressed to approximately 70 bar, but the initial pressure might be greater than 200 bar in subsea pipelines. Due to losses caused by friction, the gas is compressed along the pipeline to maintain the pressure (Sevenster and Croezen, 2006). There is also leakage of methane during pipeline transport, which is difficult to quantify. The methane emissions from the long-distance pipeline network in Russia are approximately 0.6% of the gas delivered (Lechtenböhmer et al., 2007). Today, natural gas imports to Europe come primarily from Africa, the Middle East, Russia and Norway (Schori and Frischknecht, 2012).

The processing of *LNG* is essentially the same as that of natural gas. If LNG is produced at the extraction site, the processing and liquefaction steps can be integrated, and the undesired hydrocarbons can be removed during the liquefaction process. The heavier hydrocarbons condense at higher temperatures than methane and are removed. The liquefaction process transforms natural gas into LNG by cooling it to -162 ºC. There are variations in liquefaction plant designs, and various processes use different refrigeration cycles and different types of refrigerants (Tusiani and Shearer, 2007). Ethane is usually added back into the methane after liquefaction. LPG and gasoline are typical by-products of this process. The liquefaction efficiency varies from one plant to the next. In state-of-the-art liquefaction plants, the liquefaction process reportedly used approximately 7.9-8.7% of the natural gas, whereas the average plant consumed 10.3% (in a range of 9.9-12.9%) in 2006 (Sevenster and Croezen, 2006).

It is also possible to use the natural gas to produce liquid fuels, e.g., *synthetic diesel* (also called GTL) and methanol. To produce synthetic diesel, the processed natural gas is further processed in a Fischer-Tropsch diesel production unit. It is most efficient to produce GTL near the natural gas reservoir because the same distribution infrastructure for liquid fuels can be used. The Fischer-Tropsch process primarily consists of three steps: synthesis gas generation, carbon synthesis and upgrading. Syngas is produced via methane reforming and non-catalytic partial oxidation. The syngas is then converted to synthetic crude by carbon synthesis and then further refined into the desired products, e.g., diesel (Jaramillo et al., 2008). Fuel combustion, vents and fugitive emissions are sources of air emissions from a Fischer-Tropsch conversion plant. The primary fuel combusted in Fischer-Tropsch plants consists of fuel gases generated during the Fischer-Tropsch conversion and upgrading (Marano and Ciferno, 2001). The efficiency of GTL production is in the range of 61-65%, and there is the potential to increase this efficiency to 63-67% (Edwards et al., 2013a)

Methanol is currently primarily produced by methanol synthesis following the production of synthesis gas from natural gas. The production of methanol consists of three primary steps: (1) production of synthesis gas, (2) synthesis of methanol and (3) processing of crude methanol. During the period 1830-1923, before a method for producing methanol from synthesis gas was discovered, the primary source of methanol was from dry distillation of wood (Fiedler et al., 2000). The conversion of synthesis gas into methanol and water is an exothermal process that takes place at temperatures of approximately 220-280°C and at pressures of approximately 40-110 bars using the catalysts presently available (Höhlein et al., 2006). The crude methanol leaving the reactor is a mixture of methanol (≈90 wt. %), water (≈8 wt. %), dissolved gases and traces amounts of by-products. The composition of the crude methanol depends on the gas feed, reaction conditions and type and lifetime of the catalysts (Olah et al., 2009). The distillation of crude methanol is an energy-intensive separation process and represents a large part of the cost of methanol production (Höhlein et al., 2006).[35] The heat needed for distillation can be supplied by steam or possibly by waste heat from a reformer unit, depending on the setup of the methanol plant. Höhlein et al. (2006) reported efficiencies for various methanol plants using various sources in the range of 62-70% and an energy demand of 29-32 GJ per tonne of methanol produced. The natural gas consumption can vary greatly between new and old methanol plants, from less than 30 GJ to greater than 40 GJ per tonne produced (Methanex, 2013). If the distillation step is not required or reduced, then the result may be greater energy efficiency and less costly production, making methanol with a higher water content a potential marine fuel.

Biomass as the Raw Material

Biomass includes a wide range of products and by-products from forestry and agriculture and from municipal and industrial waste streams. It thus includes trees, arable crops, algae and other plants, agricultural and forest residues, effluents, sewage sludge, manure, industrial by-products and the organic fraction of municipal solid waste. The environmental impacts associated with the use of biomass as a feedstock for fuel production depends on the source of the biomass. Residues and wastes are generally associated with lower environmental impacts in comparison to dedicated crops. The environmental impacts are associated with the collection, the farming and harvesting and the transportation of biomass. Six types of biomass are included in this work: rapeseed, willow, forest residues, agricultural residues, manure and municipal organic waste.

Biofuels are usually categorised as first or second generation. First-generation biofuels are primarily produced from food crops, such as grains and oil seeds. These first-generation biofuels include rapeseed methyl ester (RME) and ethanol. The sustainability of first-generation biofuels is debated. The issues raised include the competition with food production for land, the limited production potential and the questionable environmental performance (Sims et al., 2008). It is argued that second-generation biofuels can avoid many of the concerns facing first-generation biofuels, although they still face economic and technical challenges (Naik et al., 2010). Second-generation biofuels are produced from lingo-cellulosic materials, such as forest residues. A typical example of a second-generation biofuel is synthetic biodiesel.[36]

This study includes both first- and second-generation biofuels. *RME* is a first-generation fuel of diesel quality. The production starts with the cultivation and collection of rapeseed, which may be dried before oil extraction to obtain the optimal water content. Subsequently, the oil is extracted. To extract the oil, the rapeseed is crushed and the oil extracted using steam and hexane. It is also possible to extract the oil using only mechanical pressure. The by-product is rapeseed meal, which is a high-protein product that can be used as animal feed. Rapeseed oil is then used as a raw material for the production of RME, a type of fatty acid methyl ester (FAME). FAME, usually called biodiesel, is produced by transesterification of vegetable oils. During transesterification, the vegetable oil reacts

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[35] One of Methanex's plants uses 4.5 GJ of natural gas per tonne of methanol produced for distillation, which represents approximately 10% of the overall energy consumed by the methanol plant. This plant uses steam as a heating medium in distillation, and at least part of this is in addition to the heat available from the reformer unit (Methanex, 2013).

[36] Also called biomass-to-liquid (BTL).

with an alcohol (usually methanol) in the presence of a catalyst, forming methyl ester and glycerol[37] as by-products (Gerpen, 2005).

A second-generation biofuel of diesel quality can instead be produced via gasification followed by Fischer-Tropsch synthesis, i.e., *synthetic biodiesel*. Gasification is a process under development and thus far is not commercially viable. A wide variety of biomass resources can be used as feedstock, including wood, agricultural waste, black liquor, organic waste and sludge. Cleaner feedstocks result in cleaner synthesis gas. For example, clean wood provides synthesis gas with relatively low levels of contaminants. The biomass needs to be pre-treated prior to gasification. The type of pre-treatment necessary will depend on the technology used in the gasification. Reactors involving a fluidised bed or entrained flow are the two primary gasification reactor designs considered for the production of fuels (Hellsmark, 2010). The pre-treatment can, for example, involve the large-scale grinding of the biomass into a fine powder, torrefaction or fast pyrolysis (Hellsmark, 2010). The gasification pressure can be varied, either oxygen or air can be used as the medium, and the heating can be achieved directly (by partial oxidation of the feedstock) or indirectly (through a heat exchange mechanism).

Methanol can also be produced from biomass via gasification, after which it is classified as a second-generation biofuel. Biomass-to-methanol production can reach an efficiency of 55%, according to Olah et al. (2009). One potential route to methanol is via black liquor gasification, but additional biomass is needed in the pulp and paper mill to compensate for the heat loss. This process can have a conversion efficiency of 66% (Edwards et al., 2011a).

Gaseous biofuels, or *liquefied biogas*, are produced using two different methods: anaerobic digestion of biomass (first-generation biofuel) and gasification of biomass followed by methanation (second-generation biofuel). Methanation is the process that converts synthesis gas to methane. The raw materials considered for anaerobic digestion in this thesis are agricultural residues, manure and municipal organic waste.

4.1.5 Fuel Distribution and Storage

The characteristics of the fuel affect how it is transported and stored. It is possible to divide the fuels into two categories: liquid fuels and cryogenic fuels. The cryogenic fuels are methane-based fuels that are distributed and stored under cryogenic conditions, i.e., cooled sufficiently to maintain a liquid form. The rest of the fuels are considered to be liquid fuels.

Most of the fuels under evaluation are *liquid* at standard temperature and pressure. The distribution of these fuels can use the existing distribution pathways for oil products, such as pipelines and product tankers. The environmental impact due to their transport originates from fuel combustion and potential risks of oil leakage and spills.

LNG, defined as a *cryogenic liquid*[38], is stored and transported below -162 °C. The absorption of heat from the surroundings continuously occurs because the tanks cannot be perfectly insulated. The absorbed heat evaporates liquid at the surface, which is called boil-off gas (BOG). BOG is generated during the entire LNG supply chain. LNG is stored in atmospheric storage tanks both at LNG plants and receiving terminals. The BOG is usually compressed and exported back to the fuel system at LNG production plants, but it is either flared or sent to a regasification facility at receiving terminals. The BOG is also produced during loading and unloading of LNG. This BOG is usually also handled by the LNG plant or receiving terminal (Hasan et al., 2009). At Gasnor AS, the tubes used for loading LNG

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[37] Glycerol, or glycerine, is also discussed as a potential marine fuel: see Box 3-1.

[38] The cryogenic temperature range is defined as between -150 °C and absolute zero.

are filled with nitrogen before and after loading and unloading to minimise the leakage of methane (Kvittingen, 2009). Gasnor AS estimates that the boil-off during loading and unloading amounts to 0.2 %. This gas is then used for generating electricity, according to Kvittingen (2009).

Large vessels with insulated tanks of the membrane or moss types without external refrigeration, i.e., LNG carriers, are used for transporting the LNG. A significant amount of the transported LNG evaporates during the voyage. The BOG can be used as fuel or can be re-liquefied or burnt (Dimopoulos and Frangopoulos, 2008). The handling of the BOG affects the emissions and energy requirements during transport. A portion of the LNG, known as the heel, needs to be left in the tank to cool it during the return journey. The heel directly affects the revenue generated by the trip, and it also affects the boil-off rate during loading and unloading and the ballast voyage. A common practice is to use 5% of the total cargo capacity as the heel (Hasan et al., 2009).

4.1.6 Combustion of Fuels in Marine Engines

The fuels assessed in this thesis may be assigned to one of three categories based on their energy carrier: diesel, methane and methanol. The majority of modern marine engines are two-stroke or four-stroke diesel engines. Diesel engines can use fuel of diesel quality, although certain modifications may be required, depending on the type of diesel fuel used. Gas engines for marine applications have been developed, and it is possible to buy gas and DF engines on the market. These engines can use gaseous fuels containing methane as the energy carrier. There may be minor differences in methane content between different grades of LNG[39] and between LNG and LBG, which may also require modifications. Marine methanol engines have not yet been produced commercially, but various methanol engine concepts were evaluated as part of the Effship project.

Diesel Engines

Slow-speed diesel engines are two-stroke engines with a typical shaft power ranging between 8,000 and 800,000 kW, operating at 80 to 300 revolutions per minute. A two-stroke engine can reach a thermal efficiency of approximately 55%. Medium-speed diesel engines are four-stroke engines with a typical shaft power ranging between 500 and 35,000 kW, operating at 300 to 1,000 revolutions per minute. The thermal efficiency of a four-stroke engine is typically in the range of 40% to 50% (Woud and Stapersma, 2008). Exhaust emissions are affected by the fuel and combustion parameters, i.e., the temperature, oxygen concentration and residence time.

Marine diesel engines are currently fuelled by HFO or distilled fuels, but synthetic diesel is also a possible fuel. Synthetic diesel has not been tested in two-stroke diesel engines or in large four-stroke marine engines, as far as the author knows. There have, however, been emissions tests using synthetic diesel in truck engines and small marine engines.[40] Using GTL, emissions of particles, NO_X and CO were reduced by 33.5%, 5.2% and 19.5%, respectively, compared with conventional diesel in a test using an intercooled, turbocharged Euro III diesel engine (Wang et al., 2009). Similar reductions in NO_X and particle emissions were reported by Cerne et al. (2008) in a test using EcoPar (a synthetic diesel fuel produced from natural gas) in small marine engines. The particle and NO_X emissions decreased by 24% and 7%, respectively. Particle emissions are related to both the properties of the fuel (e.g., sulphur content) and the combustion characteristics, whereas the emissions of NO_X and CO primarily depend on the characteristics of the engine.

Biodiesels, according to the standard EN 14214:2008 (CEN, 2008), can also be used in marine diesel engines and can be blended with distillate fuels, according to Haraldsson (2010). Cerne et al. (2008)

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[39] See, for example, Kavalov et al. (2009).

[40] See, for example, Larsson (2007), Wang et al. (2009) and Cerne et al. (2008).

reported that the NO_X emissions were 9% higher but the particle emissions were 38% lower using RME in comparison with a diesel fuel with less than 50 ppm sulphur.[41]

Gas and Dual-Fuel Engines

The LNG-propelled ships in operation in Norway are equipped either with lean-burn SI gas engines or DF engines. This section will describe the primary types of gas and DF engines on the market now.

The lean-burn SI engines run only on gas; lean refers to a high air-fuel ratio. The extremely lean air-fuel mixtures lead to lower combustion temperatures and therefore lower NO_X formation. The engine operates based on the Otto principle, and the combustion is trigged by spark plug ignition. The gas is injected at low pressure. Rolls-Royce (specifically, its Norwegian subsidiary, Bergen Diesel) started the development of lean-burn gas-fuelled engines in the 1980s for land electrical power and cogeneration. It is also now used for the propulsion of a number of the LNG-fuelled ships in Norway. Its lean-burn combustion system is based on spark plug ignition in a pre-chamber where pure gas is mixed with the lean mixture in the cylinder, thus forming a rich mixture that is easily ignited. Combustion of the lean mixture in the cylinder is fostered by the ignition discharge from the pre-chamber (Doug, 2010). Wärtsilä has developed a similar lean-burn SI engine with a pre-chamber but currently has no intentions of using it for marine applications (Stenhede, 2010).

Dual-fuel engines can run in either gas mode or liquid-fuelled diesel mode. The engine is based on the lean-burn Otto principle in gas mode, but the lean air mixture is ignited by injecting a small amount of diesel fuel into the combustion chamber instead of using a spark plug. The injected diesel fuel is normally less than 1% of the total fuel, based on energy at full load (Haraldsson, 2011). The amount of pilot fuel injected is the same at all loads, resulting in a higher proportion of the pilot fuel at low loads. In diesel mode, the engine works according to the normal diesel cycle, with diesel fuel injected at high pressure just before top dead centre. Gas admission is activated, but pilot diesel fuel is still injected (Doug, 2010). Wärtsilä has recently developed a two-stroke lean-burn DF engine, based on their experience with the four-stroke DF engine, and it is expected to be ready for operation in 2015 (Nylund, 2013).

MAN has developed a new series of two-stroke dual-fuel engines (ME-GI Dual Fuel MAN B&W Engines). The series was developed specifically for LNG carriers but can also be used for other types of ships, such as LPG, ro-ro and container vessels. The working principle is similar to MAN’s traditional two-stroke engines, but the combustion process is based on a higher air surplus and a pressurised gas injection system, which injects pressurised gas at a maximum pressure of approximately 250 bar (Doug, 2010). MAN expects it to fulfil the Tier III NO_X requirements in combination with an exhaust gas recirculation system (Clausen, 2010). This engine can be classified as a gas diesel (GD) engine. GD engines run on various gas and diesel mixtures or, alternatively, on diesel. The engines use the diesel cycle, combusting a mixture of gas, diesel and air, and the gas is injected at high pressure. The conversion of existing diesel engines to natural gas operation can be performed by making small modifications (Doug, 2010). The emissions of NO_X are higher from this engine than from lean-burn SI and DF engines and cannot comply with the Tier III regulations without engine modifications or exhaust gas abatement technologies.

The methane slip, i.e., unburned methane emitted from gas and dual-fuel engines, is important to consider because it has a great impact on the GWP, due to the higher GWP of CH_4 than of CO_2 (IPCC, 2007, 2013). The engine methane slip has three primary causes: (1) gas in the intake port together with

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[41] A review of emissions tests using biodiesel and vegetable oil in marine engines is presented in Paper II.

scavenging,[42] (2) incomplete combustion and (3) crevices in the combustion chamber (Järvi, 2010). The methane emissions from measurements of installed marine and stationary engines and those provided by the engine manufacturers are presented in Table 4-3. The methane slip reported for lean-burn SI engines and four-stroke lean-burn DF engines are in the range of 1.4-4.1% and 2.4-7%, respectively, at full load. The emissions of methane can be very high at low engine loads, as shown in Table 4-3. Engine manufacturers are working to reduce the methane slip because this waste is not desirable from an engine efficiency or environmental standpoint. The methane slip reported from Wärtsilä's engine is a great deal lower than that from DF engines installed on ships operating in Norway. The lower methane slip from Wärtsilä's gas engines is due to certain engine conditions and engine developments. According to Järvi (2010), primary methods have the potential to reduce the methane slip by more than 30%, and a combination of primary and secondary methods, i.e., various after-treatment methods, yields a possible reduction of more than 90%.

Table 4-3 Methane emissions from marine and stationary gas engines [g CH_4/MJ LNG (wt. % of fuel input)][a]

Methane emissions from engines installed on ships operating in Norwegian waters (Nielsen and Stenersen, 2010):				
Engine load	25%	50%	75%	100%
Lean-burn SI engines	2.8-2.3 (13-11%)	0.9-1 (4.1-4.7%)	0.8-0.9 (3.7-4.5%)	0.7-0.9 (3.2-4.1%)
Dual-fuel engine[c]	3.2 (15%)	2.2 (11%)	1.5 (8%)	1.4 (7%)
Methane emissions from Wärtsilä's gas engines (100% load, nominal speed) (Hattar, 2010):				
Lean-burn SI gas engine				0.3 (1.4%)[b]
Dual-fuel engine (gas mode)				0.5 (2.4%)[b]
Gas diesel engine				0.04 (0.2%)[b]
Methane emissions from MAN's gas engines (Bäckström, 2010):				
Engine load		50%	75%	100%
ME-GI dual-fuel MAN B&W engine[d]		0.11(0.5%)[b]	0.08 (0.4%)[b]	0.06 (0.3%)[b]
Methane emissions from marine gas engines reported in Sustainable Shipping (Macqueen, 2013):				
Engine load	25%	50%		100%
Bergen C26:33L	0.75 (3.6%)			0.60 (2.9%)
Best dual-fuel engine	3.2 (15%)	1.03 (4.9%)		0.90 (4.3%)
Methane emissions from stationary and reciprocating gas engines in the United States. (U.S. EPA, 1996, 2000):				
Four-stroke lean-burn gas engines				0.5 (3%)
Dual-fuel engines				0.3 (3%)
Two-stroke lean-burn gas engines				0.6 (1%)

[a]It is assumed that LNG has a lower heating value of 48 MJ/kg in the calculations. A portion of the original data is reported as kWh without any information regarding engine efficiency. In those cases, the engine efficiency has been assumed based on information from similar engines and loads. [b]Emissions of hydrocarbons. [c] The measurements are from one offshore supply vessel. [d] Two-stroke engine, complies with NO_X Tier II requirements.

Methanol-Fuelled Engines

Apparently, the literature contained only one study of methanol-fuelled marine engines before 2013: that by Nakamurahk et al. (1992). One reason for not considering methanol in marine engines might be that methanol is typically an Otto fuel, whereas diesel engines have been dominant in marine applications. Methanol has a cetane number of three and will therefore not ignite reliably in a diesel engine (Fiedler et al., 2000). Methanol can, however, be used in DF engines in which diesel fuel is injected as an ignition source (pilot fuel). Various engine concepts, primarily the premixed dual-fuel concept and the methanol-diesel concept, in which methanol is used were evaluated as part of the Effship project.

In the DF concept, the gas valve on a DF gas engine is replaced or the engine is supplemented with a methanol injector. Premixed methanol and air are ignited using a small pilot fuel diesel spray. Certain

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[42] Removal of spent gases from an internal combustion engine cylinder and replacement by a fresh charge or air.

modifications in terms of ignition energy or preheating of the combustion air may be needed because the heat of vaporisation is higher for methanol and the output will be limited by knocking. The NO_X emissions are expected to be in the range of those of a DF engine running on LNG (Fagerlund and Ramne, 2013). Concerns include possible high concentrations of formaldehyde in the exhaust gas and corrosion of the fuel inlet and the cylinder liner surface (Fagerlund and Ramne, 2013).

In the methanol-diesel concept, the methanol is injected at high pressure and is ignited using a small amount of pilot diesel. This concept is similar to the gas-diesel concept but requires modification of the fuel injection system. The NO_X emissions are expected to be either in the range of Tier II or Tier III (Fagerlund and Ramne, 2013). The emissions of hydrocarbons, formaldehyde and CO are expected to be lower than those produced by the DF concept (Fagerlund and Ramne, 2013).

4.1.7 Exhaust Abatement Technologies

Possible measures to reduce SO_2 emissions include scrubbing and switching to low-sulphur fuels, whereas a number of options are available to reduce shipping-related NO_X emissions.[43] SCR technology offers the highest reduction potential and is the only NO_X abatement technology discussed in this work.

Scrubbers

In shipping, scrubbers are used for sulphur reduction and can be divided into wet scrubbers, in which sulphur oxides are absorbed by water, and dry scrubbers, in which sulphur oxides react with and bind to a solid substance. Scrubbers can also remove particles and NO_X from the exhaust gas to a certain extent. The technology is well proven in land-based applications, such as in power plants, which most often use dry scrubbing. The alkalinity[44] of seawater makes it suitable for use in a wet scrubber. This technology has been developed and installed on a few ships. There are two types of wet scrubbers for onboard exhaust gas scrubbing: open (seawater) scrubbers and closed (freshwater) scrubbers. It is also possible to use a combination of these, e.g., closed in harbours and sensitive areas, such as the Baltic Sea, and open when crossing the open ocean (Bosch et al., 2009). In an open system, seawater with natural alkalinity is used to capture the sulphur oxides. The amount of sulphur oxides captured depends on the alkalinity of the water. In the Baltic Sea, where the alkalinity is low compared with the open sea, a great deal more seawater is needed to capture the same quantity of sulphur oxides. When SO_2 is absorbed by the seawater it becomes acidic. The acidic water is then neutralised by reactions with bicarbonates and other substances in the seawater, which results in a release of CO_2. Approximately 1.2 g of CO_2 is released for every g of SO_2 dissolved in the seawater (Williams, 2010). It may prove necessary to use closed-loop scrubbers in sensitive areas to avoid excessive environmental loads due to discharge of acidic scrubber water into the environment.

The additional fuel consumption resulting from the use of scrubbers is reportedly 2-3% of the engine output, according to the U.S. EPA (2011), and 1.4%, according to Hansen (2012). In a closed system, the water is instead re-circulated with the continuous addition of alkali, normally caustic soda. The documented operational experience with closed-loop scrubbers for marine applications is thus far very limited.

Lövblad and Fridell (2006) estimated the reduction of PM by mass from use of scrubbers to 25%. Recent results from measurements on-board a ro-ro vessel equipped with a wet scrubber operating in open mode showed a 75% reduction of PM by mass, 91% reduction of the total number of particles, but only a 57% reduction of the number of solid particles (Fridell and Salo, 2014).

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[43] For a more detailed overview of various NO_X abatement technologies, see Magnusson (2014).

[44] Alkalinity is the quantitative capacity of an aqueous solution to neutralize an acid.

SCR

With the SCR technique, NO_X is reduced to nitrogen and water over a solid catalyst using ammonia as the reducing agent. The ammonia is usually supplied from a water solution of urea, which is sprayed into the exhaust. The urea then decomposes and forms ammonia.

The use of SCRs is much more extensive in heavy-duty vehicles than in marine transportation (Magnusson, 2014). Nevertheless, SCRs have been installed on more than 500 vessels around the world (IMO, 2013c). Although SCR systems can be installed on any type of engine, a minimum exhaust gas temperature is needed for efficient operation. This temperature is normally approximately 300 °C, but it depends on the sulphur content of the fuel (Bosch et al., 2009). The majority of the existing installations are on four-stroke engines, but there have also been installations on two-stroke engines. This difference may mean that the SCR needs to be installed upstream of the turbocharger on two-stroke engines, where the exhaust gas temperature is higher. Several general technical concerns have been raised regarding the use of SCRs in marine installations (IMO, 2013b). First, the SCR cannot operate optimally and therefore cannot reach the desired NO_X reduction at low operating temperatures, e.g., engine loads below 25%. Second, the deterioration of the catalyst due to poisoning and fouling by soot, ash and ammonium sulphates results in lower NO_X reduction efficiency. Finally, a slip of ammonia may occur when the reaction between NO_X and ammonia is incomplete, releasing ammonia to the air. Ammonia slip can be caused by, for example, an exhaust gas temperature that is too low, catalyst deterioration or urea dosage that has not been tuned properly (Fridell and Steen, 2007). Placing an oxidation catalyst downstream of the SCR can reduce the ammonia slip (Bosch et al., 2009).

4.1.8 Summary of Data Choices

Data were collected from free LCA databases, scientific journals, reports from industry and academia and from personal communication with industry representatives. Except for scientific journals, this study was limited to information that is freely available. The broad scope of the studies has limited the collection of primary data. The results of the studies were compared to similar studies of other types of transportation.

The results presented in sections 5.1 and 5.2 are primarily based on Paper V. However, not all of the fuels under investigation in this thesis are included in Paper V; the characteristics of these fuels were therefore modified to match the assumptions and data used in Paper V (see Table 4-4). The source of electricity used in the biofuel chains is assumed to be the average European electricity mix, whereas the source of electricity used in the natural gas production is assumed to be the average of the source country of the natural gas, which is Norway in this thesis. The data for the European and Norwegian electricity mixes are from IEA (2013a) and IEA (2013b), respectively, whereas the data for the cradle of the electricity are from Baumann and Tillman (2004).

Table 4-4 Summary of the data and assumptions of the LCA results presented in sections 5.1 and 5.2.

	Raw material acquisition and fuel production	Distribution	Combustion	Combustion with exhaust abatement
HFO	1 wt. % sulphur content, based on data from the ELCD core database version II (2010b). *(Paper V)*	Distr. 250 nautical miles (nm) using a product tanker, MSD engines, fuelled with HFO. *(Paper V)*	MSD engines based on Cooper and Gustafsson (2004) and NTM (2008). *(Paper V)*	Scrubber: 2% increased energy use, SO_2 emission equivalent to 0.1 wt. % S in the fuel, PM reduced 25%. SCR: Tier III NO_X emissions (0.28 g/MJ), 0.0029 g NH_3/MJ, 0.86 g urea/MJ fuel, urea trans. and prod. (Andersson and Winnes, 2011). *(Paper IV)*
MGO	Based on data from ELCD core database version II (2010a). Sulphur content set to 0.1 wt. %. *(Paper I)*	Distr. 250 nm using a product tanker fuelled with MGO.	MSD engines based on Cooper and Gustafsson (2004) and NTM (2008). *(Paper I)*	Tier III NO_X emissions (0.28 g/MJ) due to SCR, 0.0029 g NH_3/MJ, 0.80 g urea/MJ fuel, urea trans. and prod. (Andersson and Winnes, 2011). *(Paper IV)*
LNG	Natural gas extraction data from Schori and Frischknecht (2012). The liq. based on data from Edwards et al. (2007a) (liq. eff. of 93%). *(Papers I and V)*	Distr. from North Sea to Gothenburg (350 nm) using an LNG tanker with DF engines. *(Paper V)*	DF engines with 4% methane slip. *(Paper V)*	-
GTL	The same data for natural gas extraction as for LNG are used.	Distr. in Norway (350 nm) using a chemical tanker, MSD engines, fuelled with MGO.	MSD engines *(Paper I)*	Tier III NO_X emissions (0.28 g/MJ) due to SCR, 0.0029 g NH_3/MJ, 0.80 g urea/MJ fuel, urea trans. and prod. (Andersson and Winnes, 2011).
$MeOH_{ng}$	Based on data from Schori and Frischknecht (2012) and Strömman et al. (2006), adjusted to average natural gas with 1.5 vol. % CO_2. *(Paper V)*	Distr. from Norway (350 nm) using a chemical tanker, MSD engines, fuelled with MGO. *(Paper V)*	DF engines *(Paper V)*	-
RME	Based on data from Bernesson (2004) for medium scale RME prod. and allocation based on energy content. *(Paper II)*	Distr. 200 km using a truck with semi-trailer (NTM, 2010) and 500 nm using a chemical tanker, MSD engines, fuelled with MGO.	MSD engines *(Paper II)*	Tier III NO_X emissions (0.28 g/MJ) due to SCR, 0.0029 g NH_3/MJ, 0.89 g urea/MJ fuel, urea trans. and prod. (Andersson and Winnes, 2011).
LBG_{ar}	Based on data from Börjesson and Berglund (2006), Berglund and Börjesson (2006) and Johansson (2008), assuming biomass produced from manure (1/3), agricultural residues (1/3) and municipal organic waste (1/3). *(Paper II)*	Distr. 200 km using a truck and semi-trailer (NTM, 2010) and 500 nm using an LNG tanker, DF engines, fuelled with LBG_{ar}.	DF engines with 4% methane slip. *(Paper V)*	-
LBG_w	Based on data by Börjesson (2006) for willow cultivation and trans. and by Karlsson and Malm (2005) and Johansson (2008) for LBG_w prod. *(Papers II and V)*	Distr. 200 km using a truck and semi-trailer (NTM, 2010) and 500 nm using an LNG tanker, DF engines, fuelled with LBG_w. *(Paper V)*	DF engines with 4% methane slip. *(Paper V)*	-
BTL_w	Data for willow cultivation and trans. from Börjesson (2006) and Jungbluth et al. (2008) for BTL prod. *(Paper II)*	Distr. 200 km using a truck and semi-trailer (NTM, 2010) and 500 nm using a chemical tanker, MSD engines, fuelled with MGO.	MSD engines *(Paper II)*	Tier III NO_X emissions (0.28 g/MJ) due to SCR, 0.0029 g NH_3/MJ, 0.73 g urea/MJ fuel, urea trans. and prod. (Andersson and Winnes, 2011)
$MeOH_w$	Data for willow cultivation and trans. from Börjesson (2006). Data for methanol prod. are from CPM (2013). *(Paper V)*	Distr. 200 km using a truck and semi-trailer (NTM, 2010) and 500 nm using a chemical tanker, MSD engines, fuelled with MGO. *(Paper V)*	DF engines *(Paper V)*	-

4.2 Global Energy Systems Modelling

The other tool used in this thesis is the GET model, developed by the Physical Resource Theory research group at Chalmers University of Technology. This model has been used to assess the transition to CO_2-neutral energy technologies in the transportation sector. In this thesis, the model was specifically used to assess the fuel choices in the shipping sector. The goal of the work was to investigate, based on a global cost-minimisation perspective, which factors will affect future shipping sector fuel choices and propulsion technologies between the present and 2050. In this thesis a new version of the the model, GET-RC 6.2, was developed and used. The new version was developed from the GET-RC 6.1 model (extensively described by Gran et al (2013)). Taljegård (2012) performed initial work with developing the model. The following discussion describes the most important modifications that were performed to develop a detailed model specific to the shipping industry.

4.2.1 Modifications of the GET Model

An overview of the energy system model is shown in Figure 4-3. The shipping sector is modified to include three ship modes (short sea, deep sea and container) instead of two (see Table 4-5). The selection of three vessel categories is a compromise between a detailed and an approximate representation. Although this is a crude division of ships, it still captures two important aspects: (i) historically, the number of container vessels has increased considerably faster than that of other vessel types and (ii) the relationship between the tank capacity and size of the engine is specific to different types of ships.

Table 4-5 Generic types of maritime transport vessels included in the model.

Vessel types	Short sea	Deep sea	Container
Description	Ships used in short sea shipping; mostly passenger vessels, ferries and offshore vessels, <15,000 dwt	Larger ships suitable for intercontinental trade, > 15,000 dwt	All types of container vessels
Engine power (kW)	2400	11,000	23,000
Voyage range full speed (days)	7[a]	30[b]	15[b]
Tank capacity (m^3 fuel oil[c])	90	1830	1920
Tank capacity (GJ)	3500[d]	71,300[d]	74,600[d]
Life time (years)	30	30	30

[a]Based on the time it takes to travel from Marseille to Rotterdam (Stopford, 2008), assuming a speed of 20 knots, times 1.5 (to account for backup tank capacity). [b]Based on the time it takes to travel from Long Beach to Shanghai at 13.6 and 23 knots (Stopford, 2008) for the ocean-going and container vessels, respectively, times 1.5 (to account for backup tank capacity). [c]Fuel oil is represented by data for MGO. [d]Based on higher heating value (HHV).

Six marine fuel options are included in the model: crude oil-based fuels, LNG, synthetic fuels produced from coal or natural gas, biofuels and hydrogen. The LNG route is not treated separately in previous versions of the GET model but is treated in the same manner as that of CNG. For shipping, the discussion is primarily focused on LNG and not CNG, as CNG would require 2-3 times more storage space, depending on the degree to which the CNG is compressed (Sinor, 1991). The crude oil-based fuel category is represented by MGO and is called *fuel oil* in the model. It is assumed that the cost associated with MGO is the same as the costs of HFO combined with a scrubber. The synthetic fuels produced from coal or natural gas are called *fossil methanol* in the model. The costs and efficiency of methanol production are used for this category, and they are assumed to represent a broad range of synthetic fuels produced from coal or natural gas. The *biofuels* category represents all types of fuels of biogenic origin, but the costs are those associated with bio-methanol. *Hydrogen* represents both compressed and liquefied hydrogen, which are assumed to be similar in cost. Liquefied hydrogen is assumed to be the form used on vessels.

The technological efficiencies of the internal combustion engine (ICE) and the fuel cell (FC) for ships and the cost of various ships using various drivelines and fuels were incorporated into the model. The cost of infrastructure was separated into costs of road transport and shipping. The possibility of including the methane slip from LNG engines as a CO_2-equivalent was also added, even though the models only take into account CO_2 emissions. Hybrid ships (e.g., ships with dual-fuel engines) or the retrofitting of ships are not possibilities included in the model.

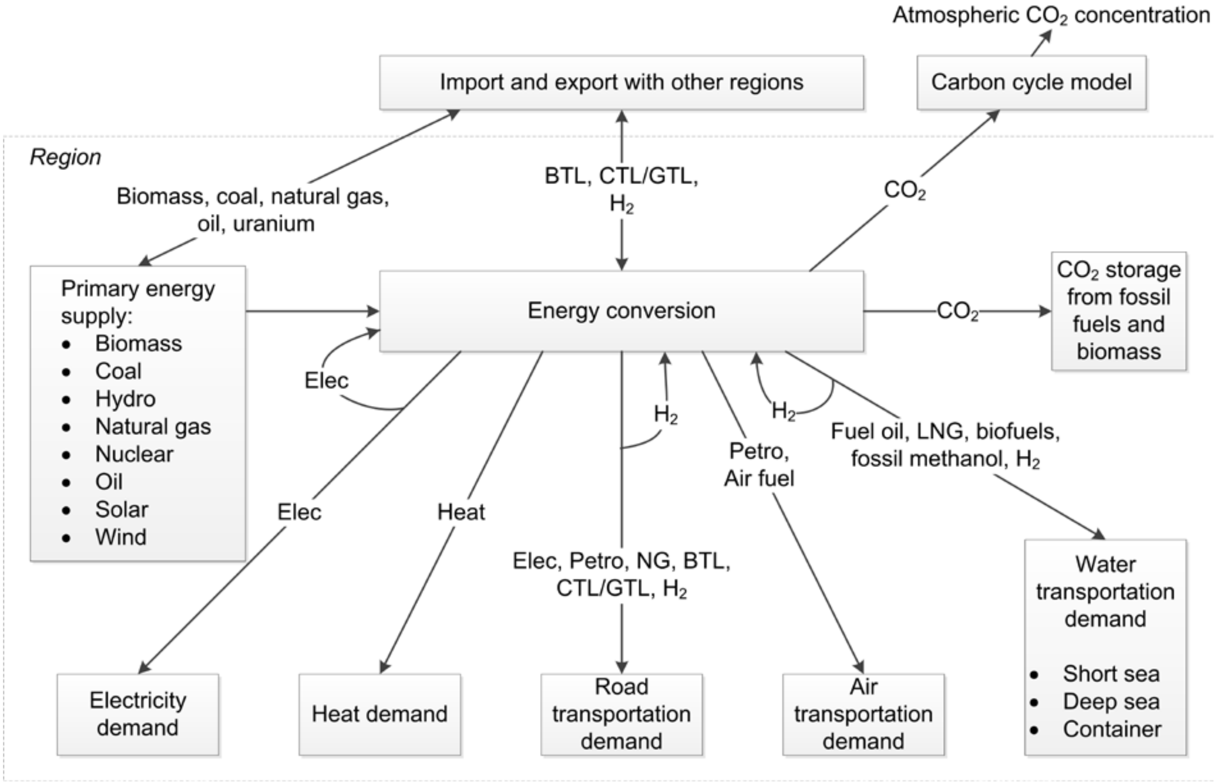

Figure 4-2 The basic flowchart of supply and fuel choices in GET-R 6.2. Abbreviations: H_2 (hydrogen), Elect (electricity), Heat (low- and high-temperature heat for the residential, service and industrial sectors), NG (natural gas) , LNG (liquefied natural gas), Petro (diesel and gasoline) and air fuel (synthetic fuels for aviation). Note that electricity and hydrogen can loop back to the energy conversion module, allowing the use of electricity to generate heat and allowing the use of hydrogen to generate both heat and electricity.

4.2.2 Inputs Representing the Shipping Sector in the Model

Demand from water transportation is an input to the model. However, this future demand is inevitably very uncertain. Buhaug et al. (2009) estimated the world fleet's fuel consumption for the period 1990-2007, based on the number of ships, average installed power, operating days at sea and the specific fuel consumption of individual ship categories. This estimate is used as a basis for projecting the world fleet's fuel consumption until 2100. It is assumed that the shipping energy demand will grow 0.8% faster than GDP. This assumption is based on the historically strong correlation between GDP and world seaborne trade (UNCTAD, 2013). A projection of GDP growth is included in the GET model based on the IIASA/WEC ecologically driven demand scenario "C1" (IIASA/WEC, 1995). However, the water transportation demands of the various ship types are differentiated to compensate for the rapid growth of container shipping (Buhaug et al., 2009). The water transportation demand of container shipping is assumed to grow 2% faster than GDP until 2050 and 1% faster thereafter.

Other new input data representing the shipping sector are associated with the efficiency of the propulsion system and the cost of the propulsion and fuel storage systems. An engine efficiency of 40% for reciprocating ICEs is assumed in the model, independent of the fuel used, and an efficiency of

45% is assumed for fuel cells. The assumed costs of propulsion and fuel storage are summarised in Table 4-6 below. The data are derived from published sources (Andersen et al., 2011; Danish Maritime Authority, 2012; Germanischer Lloyd, 2012; JJMA and BAH, 2002; Ludvigsen and Ovrum, 2012; Nielsen and Schack, 2012; Verbeek et al., 2011) and from discussions with stakeholders.

Table 4-6 Detailed costs of various fuels and vessel types, divided into propulsion system and storage system costs.

Propulsion system[a]	**Short sea vessel cost**		**Deep sea vessel cost (kUSD)**		**Container vessel cost (kUSD)**	
	ICE/FC (USD/kW)	**Storage tank (USD/GJ)**	**ICE/FC (USD/kW)**	**Storage tank**[b] **(USD/GJ)**	**ICE/FC (USD/kW)**	**Storage tank**[a] **(USD/GJ)**
Fuel oil ICE	700	30	600	25	500	25
Methanol ICE	720	50	620	40	520	40
LNG ICE	1015	110	870	80	725	80
H_2 ICE	1015	300	870	225	725	225
Fuel oil FC	4000	30	4000	25	4000	25
Methanol FC	4000	50	4000	40	4000	40
LNG FC	400	110	4000	80	4000	80
H_2 FC	4000	300	4000	225	4000	225

[a] Fuel oil ICE, methanol ICE, LNG ICE, H_2 ICE are internal combustion engines powered by fuel oil, methanol (fossil methanol and biofuels), liquefied natural gas and liquefied hydrogen, respectively. Fuel oil FC, methanol FC, LNG FC, H_2 FC are fuel cells powered by fuel oil, synthetic fuels (fossil methanol and biofuels), liquefied natural gas and liquefied hydrogen, respectively. [b] A factor of 0.75 has been used for ocean-going and container ship storage tanks because they have larger storage tanks relative to short sea ships, which produces a scaling effect due to a lesser need for material per unit of energy.

Based on data presented in the literature, the liquefaction costs for LNG are between 150-400 USD/kW (Cornot-Gandolphe et al., 2003; Engelen and Dullaert, 2010; Jensen, 2004), and the liquefaction efficiency is assumed to be 93% (Edwards et al., 2011b). The investment cost for LNG production is assumed to be 300 USD/kW in the model.

The infrastructure cost is separated into the costs of shipping and other transportation sectors. The distribution cost of oil is assumed to be 10 Euros per tonne (Danish Maritime Authority, 2012). The distribution cost of LNG is estimated to be 4.7 USD/GJ, which is based on an estimate of the distribution cost in the North European LNG Infrastructure Project (Danish Maritime Authority, 2012). The distribution cost of methanol produced from coal and natural gas is assumed to be twice that of oil because methanol's energy density is half that of oil. However, because methanol from biomass has to be transported longer distances on roads (biomass sources are usually produced at smaller scales and located far from ports), it is assumed that methanol from biomass has a distribution cost of 1.80 USD/GJ compared to 0.6 USD/GJ for methanol produced from natural gas. The fuel cost of hydrogen is based on the transport of hydrogen in pipelines, which is assumed to be similar to liquefaction and distribution in liquid form.

5 Results and Discussion

This chapter presents and discusses the result of the appended papers in a holistic way. This section begins with the life cycle inventory results of the evaluated marine fuels, followed by their life cycle environmental performance. The last part of the chapter assesses the possible marine fuels from a global perspective, considering the global competition for energy sources and a global stabilisation of greenhouse gases.

5.1 Life Cycle Inventory Results

The life cycle inventory results for all of the assessed marine fuels in appended Papers I-V are compiled in a consistent manner in this chapter. The resource uses and environmental flows are summarised in Tables 5-1 (from well to tank) and 5-2 (from tank to propeller). These emissions have impacts on a number of environmental issues, which are considered in the next section (section 5.2). Certain conclusions, however, may be readily drawn from Tables 5-1 and 5-2.

Table 5-1 The environmental flows for the evaluated fuels in the base case from well to tank (raw material acquisition, fuel production and distribution) per MJ of fuel used.

	HFO	**MGO**	**GTL**	**RME**	**BTL$_w$**	**LNG**	**LBG$_{ar}$**	**LBG$_w$**	**MeOH$_{ng}$**	**MeOH$_w$**
Primary energy sources [MJ/MJ fuel]										
Natural gas	0.058	0.063	1.6	0	0.068	1.1	0.088	0.10	0.51	0.061
Crude oil	1.0	1.1	0.0057	0.28	0.033	0.0011	0.063	0.036	0.024	0.046
Other fossil fuels	0.009	0.010	7.3E-5	0	0.17	1.1E-4	0.22	0.26	2.3E-4	0.15
Biomass	0	0	0	2.0	2.2	0	2.0	1.5-	0	2.0
Renewable fuels	0.0014	0.0016	8.2E-6	0	6.2E-6	1.6E-5	0.0006	0.0006	3.3E-5	2.9E-5
Emissions to air [g/MJ fuel]										
CO_2	6.7 (8.3)	7.1 (8.6)	20 (21)	14 (15)	18 (20)	8.3	25	27	20	17
CH_4	0.072 (0.074)	0.078 (0.080)	0.0057 (0.0073)	0.010 (0.012)	0.048 (0.049)	0.033	0.17	0.18	0.011	0.042
N_2O	1.6E-4	1.7E-4	0.0007	0.087	2.3E-4	1.7E-4	2.8E-4	3.3E-4	2.9E-4	2.2E-4
NO_X	0.021(0.025)	0.023 (0.026)	0.035 (0.038)	0.053 (0.057)	0.043 (0.046)	0.010	0.071	0.053	0.047	0.060
SO_2	0.039 (0.043)	0.041 (0.044)	0.0011 (0.0046)	0.023 (0.027)	0.049 (0.052)	8.3E-4	0.062	0.073	0.0021	0.048
NH_3	7.4E-5 (0.0014)	7.7E-5 (0.0014)	2.0E-6 (0.0013)	0.091 (0.092)	5.6E-5 (0.0012)	7.7E-7	7.0E-5	8.3E-5	5.1E-6	5.1E-5
PM_{10}	0.0011 (0.0017)	0.0011 (0.0016)	4.4E-4 (9.7-04)	0.0029 (0.0035)	0.012 (0.013)	3.2E-4	0.016	0.018	5.7E-4	0.011
NMVOC	8.2E-5 (0.0015)	8.1E-5 (0.0014)	0.0018 (0.0030)	0.0073 (0.0087)	0.0065 (0.0076)	6.9E-4	0.0094	0.0087	0.0109	0.0143
CO	0.0092 (0.0099)	0.0098 (0.011)	0.0092 (0.0099)	0.0062 (0.0069)	0.0073 (0.0079)	0.0027	0.0076	0.0096	0.0063	0.025
CH_2O	5.6E-6	6.2E-6	3.2E-8	0	2.5E-8	6.2E-8	6.2E-8	6.2E-8	0.0028	1.2E-7
C_2H_6	0.0037	0.0042	3.8E-4	0	1.7E-5	0.0058	4.3E-5	4.3E-5	4.4E-4	8.0E-5
C_3H_8	0.0067	0.0077	1.3E-4	0	3.0E-5	0.0023	7.7E-5	7.7E-5	2.5E-4	1.4E-4

[a] Data in parentheses represent values if abatement technologies are used to comply with the 0.1 wt. % S and NO_X Tier III regulations, including urea production and transport for use in the SCR. The increased energy use of the scrubber is not reflected in these results because this is presented per MJ. Abbreviations: HFO (heavy fuel oil), MGO (marine gas oil), RME (rapeseed methyl ester), BTL$_w$ (synthetic diesel produced from willow), LNG (liquefied natural gas), LBG$_{ar}$ (liquefied biogas from residues), LBG$_w$ (liquefied biogas from methanation of willow), MeOH$_{ng}$ (methanol produced from natural gas) and MeOH$_w$ (methanol produced from willow).

MGO is associated with a higher energy use and more CO_2 emissions from well to tank relative to HFO. HFO is associated with the highest emissions from tank to propeller. The lowest tank-to-propeller NO_X emissions are associated with LNG, LNG$_{ar}$ and LBG$_w$, followed by MeOH$_{ng}$ and MeOH$_w$. The tank-to-propeller NH_3 emissions are higher with SCR technology than without. The tank-to-propeller emissions are generally higher than the well-to-tank emissions.

The values presented in Tables 5-1 and 5-2 represent a base case, but because many factors are uncertain, a number of alternative cases were evaluated in Papers I, II, IV and V. The data for a few of the fuels are updated from the values presented in certain papers. For example, more up-to-date data are used for the extraction of natural gas for producing LNG and GTL versus the data used in Paper I. Paper I evaluated the use of SI engines, whereas the other papers evaluated the use of DF engines. There were several smaller changes in data and modifications of the modelling as this thesis evolved. These differences did not change the overall conclusions, which are shown to be robust in the appended papers. The data used in this thesis are summarised in Table 4-4 in chapter 4.

Table 5-2 The environmental flows associated with the fuels under evaluation in the base case during combustion in marine engines per MJ of fuel used.

	HFO	**MGO**	**GTL**	**RME**	**BTL$_w$**	**LNG**	**LBG$_{ar}$**	**LBG$_w$**	**MeOH$_{ng}$**	**MeOH$_w$**
Emissions to air [g/MJ fuel]										
CO_2	77	73	73	0	0	54	0	0	69	0
CH_4	4.5E-4	4.5E-4	4.5E-4	4.5E-4	4.5E-4	0.63	0.79	0.79	0	0
N_2O	0.0035	3.5E-3	0.0035	0.0035	0.0035	0	0	0	0	0
NO_X	1.6 (0.28)	1.5 (0.28)	1.5 (0.28)	1.6 (0.28)	1.4 (0.28)	0.11	0.11	0.11	0.28	0.28
SO_2	0.69 (0.047)	0.047	9.1E-5	2.6E-4	8.9E-5	5.6E-4	5.8E-4	5.8E-4	0	0
NH_3	3.0E-4 (0.0029)	3.0E-4 (0.0029)	3.0E-4 (0.0029)	3.0E-4 (0.0029)	3.0E-4 (0.0029)	0	0	0	0	0
PM_{10}	0.093 (0.070)	0.011	0.011	0.0068	0.0084	0.0043	0.0043	0.0043	0.0043	0.0043
NMVOC	0.056	0.058	0.058	0.058	0.058	0	0	0	0	0
CO	0.13	0.13	0.13	0.13	0.13	0	0	0	0	0
C_2H_6	0	0	0	0	0	0.12	0	0	0	0
C_3H_8	0	0	0	0	0	0.047	0	0	0	0

[a] Data in parentheses represent values if abatement technologies are used to comply with the 0.1 wt. % S and NO_X Tier III regulations. HFO is combined with a scrubber and an SCR unit; MGO, GTL, RME and BTL$_w$ are combined only with SCR units. Abbreviations: HFO (heavy fuel oil), MGO (marine gas oil), RME (rapeseed methyl ester), BTL$_w$ (synthetic diesel produced from willow), LNG (liquefied natural gas), LBG$_{ar}$ (liquefied biogas from residues), LBGw (liquefied biogas from methanation of willow), MeOH$_{ng}$ (methanol produced from natural gas) and MeOH$_w$ (methanol produced from willow).

5.2 Life Cycle Environmental Performance of Marine Fuels

The life cycle environmental performance of the present and possible future marine fuels evaluated in this work are presented in the following sections. First, marine fuels are considered without any exhaust abatement technologies, followed by the result for the same fuels when combined with various types of abatement technologies for complying with the 0.1 wt. % sulphur and the NO_X Tier III regulations. A special section is also dedicated to the impact of various types of LNG engines and the methane slip. This section ends with a discussion of the implications of the expected changes in refinery production between 2015 and 2020 due to the stricter sulphur regulations in marine fuels.

5.2.1 Marine Fuels Used Without Exhaust Abatement

Three types of energy carriers (fuels of diesel quality, methanol and methane-based fuels) produced from three different raw materials (crude oil, natural gas and biomass) are evaluated using LCA. The results of the LCAs are summarised in Figure 5-1. The impact of using HFO is represented by the dashed line in Figure 5-1. All of the fuels are better than HFO regarding nearly all of the assessed impact categories. This finding implies that a change to any alternative marine fuel will be positive overall regarding the environmental impacts associated with shipping.

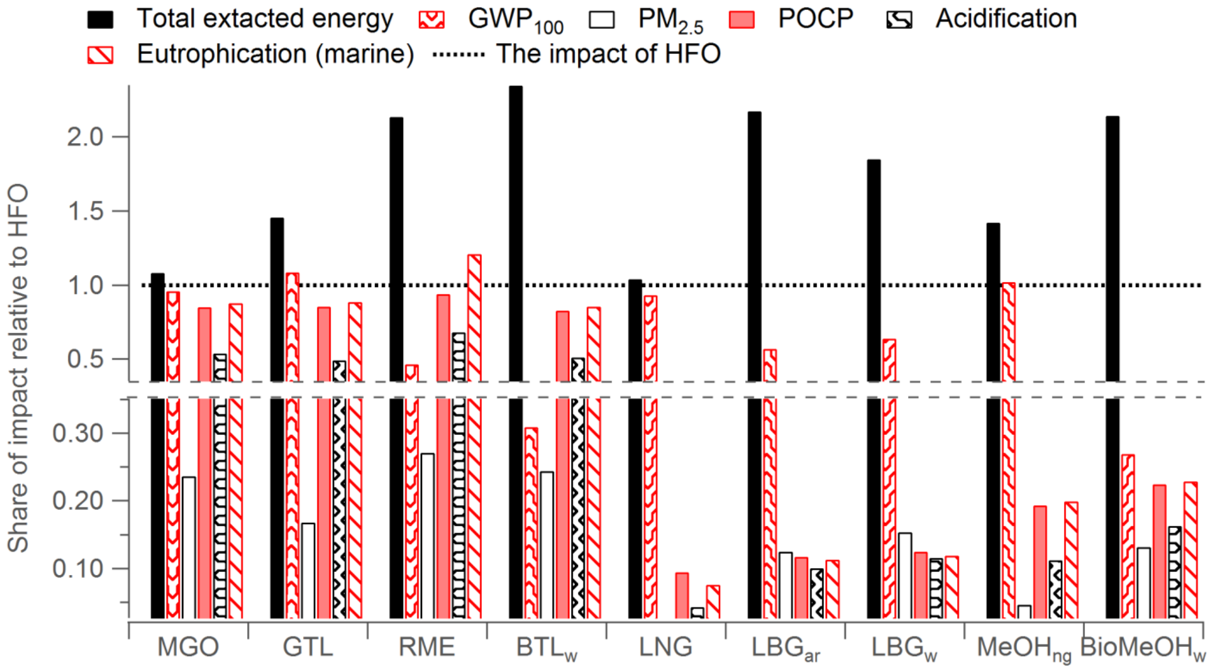

Figure 5-1 Summary of all investigated impact categories for all fuels compared to the environmental impact of HFO as marine fuel (represented by the dashed line). Abbreviations: HFO (heavy fuel oil), MGO (marine gas oil), RME (rapeseed methyl ester), BTL$_w$ (synthetic diesel produced from willow), LNG (liquefied natural gas), LBG$_{ar}$ (liquefied biogas from residues), LBG$_w$ (liquefied biogas from methanation of willow), MeOH$_{ng}$ (methanol produced from natural gas), MeOH$_w$ (methanol produced from willow), GWP$_{100}$ (Global warming potential over a time horizon of 100 years), PM$_{2.5}$ (particulate matter formation) and POCP (photochemical ozone creation potential).

The life cycle environmental performance is observed to correlate with the type of energy carrier and the type of primary energy source used. The biomass-based fuels generally have a lower impact in terms of climate change than the fuels that are based on crude oil and natural gas, but the opposite applies to the total amount of extracted energy. The crude oil-based fuels are associated with the lowest amount of total extracted energy. The methane-based fuels display the lowest photochemical ozone formation, particulate matter formation, acidification and eutrophication potential. The methanol-based fuels fall between the methane-based fuels and the fuels of diesel quality.

The impacts of the energy carrier and the primary energy source were also illustrated in Paper II, which assessed a possible transition to the use of biofuels in shipping by comparing two types of energy carriers: diesel and methane. The Swedish ferry transport to and from the island Gotland was used as a case study. Currently, this route is serviced by ro-pax ferries using HFO with 0.5 wt. % S combined with SCR units. The “diesel route” involved the use of MGO, followed by a gradual transition toward RME and finally a full transition to BTL, whereas the “gas route” involved the use of LNG, followed by a gradual shift to LBG$_{ar}$[45] and a full transition to LBG$_{fr}$ (LBG produced from forest residues).[46] The gas route displayed better overall environmental performance that the diesel route.

The results presented in Figure 5-1 are the base case, but as mentioned earlier, these results were evaluated using different sensitivity analyses in the appended papers. Two routes for LNG distribution were considered in Paper I, i.e., Norway and Qatar. Paper V considered transport of LNG and methanol produced from natural gas with a starting point of either Norway or Algeria. In the results presented in this thesis, it is assumed that the natural gas-based fuels are distributed from Norway. This is likely one of the shortest possible distribution routes. The difference in distribution has an impact on the result. In the LCA, the climate impact was shown to be 5% higher for LNG distributed

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[45] LBG$_{ar}$ is designated as LBG in Paper II.

[46] LBG from forest residues (LBG$_{fr}$) is designated as LB-CH$_4$ in Paper II.

from Qatar instead of Norway (Paper I). However, there were no significant effects on the acidification and eutrophication potentials. In Paper V, both the transport distance and the data for natural gas extraction were changed. The GWP_{100} was 6% higher for natural gas from Algeria than for natural gas from Norway for both LNG and methanol, whereas the local and regional environmental impact categories were lower for LNG and higher for methanol. This disparity was due to the lower emissions produced during natural gas extraction in Algeria compared to Norway, based on the data used, and because methanol transport was assumed to use MGO, whereas the LNG distribution was assumed to use boil-off and was therefore associated with lower emissions (Brynolf et al., 2014).

Two important aspects of fuels are their impact on climate change and their energy use (represented by the impact category total extracted energy). These aspects are compared in Figure 5-2. The bio-based fuels are associated with lower emissions of greenhouse gases and higher levels of total extracted energy. However, the energy use of fossil energy is lower than that of the other evaluated fuels. The types of primary energy sources used to produce several of the evaluated fuels are shown in Figure 3 of appended Paper II.

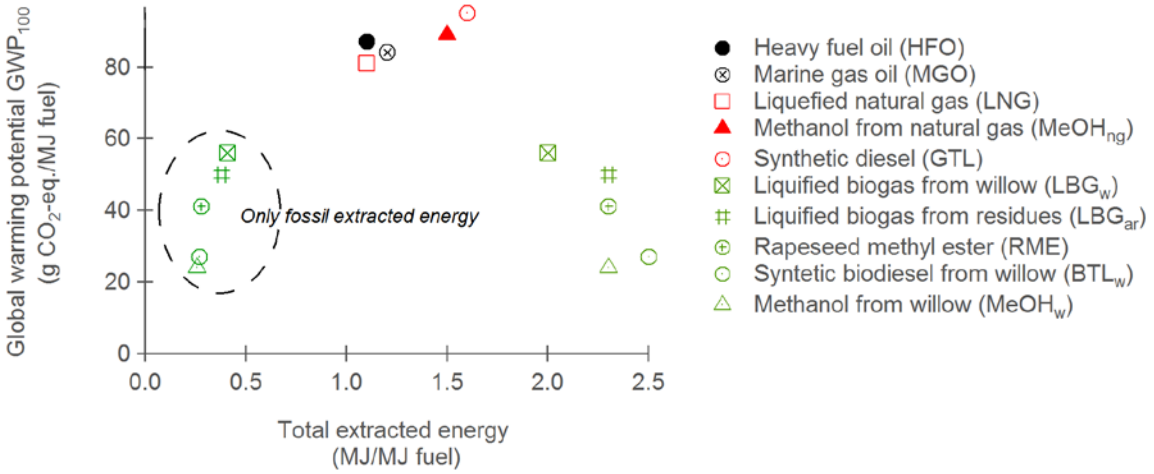

Figure 5-2 Global warming potential versus total extracted energy of the evaluated fuels.

The various fuels are associated with different proportions of greenhouse gas emissions (Figure 5-3). Nitrous oxide (N_2O) contributes a great deal to the GWP associated to use of RME. This contribution is due to the use of fertilisers during the agricultural production of rapeseed. The methane-based fuels are associated with a great deal of CH_4 emissions to the atmosphere and thus display a large overall climate impact. The various greenhouse gases exhibit different lifespans in the atmosphere, and their impacts on climate change depend on the time horizon considered. The global warming impact over 100 years is considered in LCAs, and this time horizon is recommended in the majority of LCA guidelines. In Figure 5-3, the GWPs for 20- and 500-year horizons are also shown. A time horizon of 20 years instead of 100 years results in a significant impact from the methane-based fuels because of their high methane emissions, which causes these fuels to be those with the greatest climate impact. Methane has a short duration in the atmosphere (approximately 12 years (IPCC, 2013)), and its effects relative to CO_2 decrease as longer time horizons are considered.

The shipping industry needs to reduce its emissions of greenhouse gases significantly in the future to bear its share of the burden of stabilising atmospheric greenhouse gases (Anderson and Bows, 2012). In this thesis, only the bio-based fuels of diesel and methanol quality are associated with a significant reduction in greenhouse gas, regardless of the time horizon considered. It should also be noted that the contribution of land use changes to the climate is not included in the graph below. This issue is discussed in section 6.1.2.

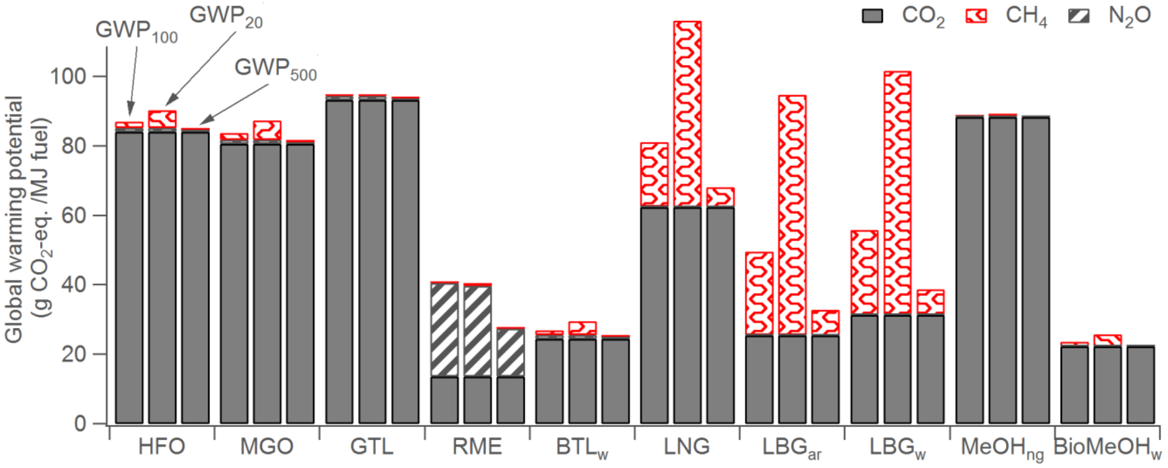

Figure 5-3 Global warming potential for the evaluated fuels based on 100-, 20- and 500-year time horizons. Abbreviations: HFO (heavy fuel oil), MGO (marine gas oil), RME (rapeseed methyl ester), BTL$_w$ (synthetic diesel produced from willow), LNG (liquefied natural gas), LBG$_{ar}$ (liquefied biogas from residues), LBG$_w$ (liquefied biogas from methanation of willow), MeOH$_{ng}$ (methanol produced from natural gas) and MeOH$_w$ (methanol produced from willow).

The local and regional environmental impacts are closely associated with the emissions of NO$_X$ during the life cycle (Figure 5-4). LNG is the fuel with the lowest NO$_X$ emissions over its life cycle (see Tables 5-1 and 5.2) and is also the fuel with the lowest local and regional environmental impact. LBG$_{ar}$ and LBG$_w$ are associated with higher emissions during raw material acquisition and fuel production, causing their impacts to be slightly higher in the life cycle assessments. The methanol-based fuels follow the methane-based fuels as the fuels with the lowest impacts. The selection of engine technology and the associated emissions of NO$_X$ can cause the methanol-based fuels to be less favourable or potentially similar to the methane-based fuels. In this thesis, it is assumed that the methanol engines comply with the Tier III regulations. Depending on the engine concept, the methanol engines are expected to be associated with emissions of NO$_X$ in the range of Tier II to Tier III regulations (Fagerlund and Ramne, 2013), but this needs to be verified during actual operation. HFO has a very high impact associated with acidification and particulate matter formation potential due to its high sulphur content (1 wt. %) relative to the other evaluated fuels.

Paper III focused on short sea shipping and its characteristics. Local and regional environmental impacts were the environmental criteria that were considered important in this segment of the shipping industry. LNG was the fuel that scored best against these criteria. In Paper III, various characterisation factors for the local and regional impacts were considered, and it was found that the conclusions were robust in terms of all of the factors under consideration. The NO$_X$ emissions were also emphasised as a strong indicator of the local and regional environmental impacts.

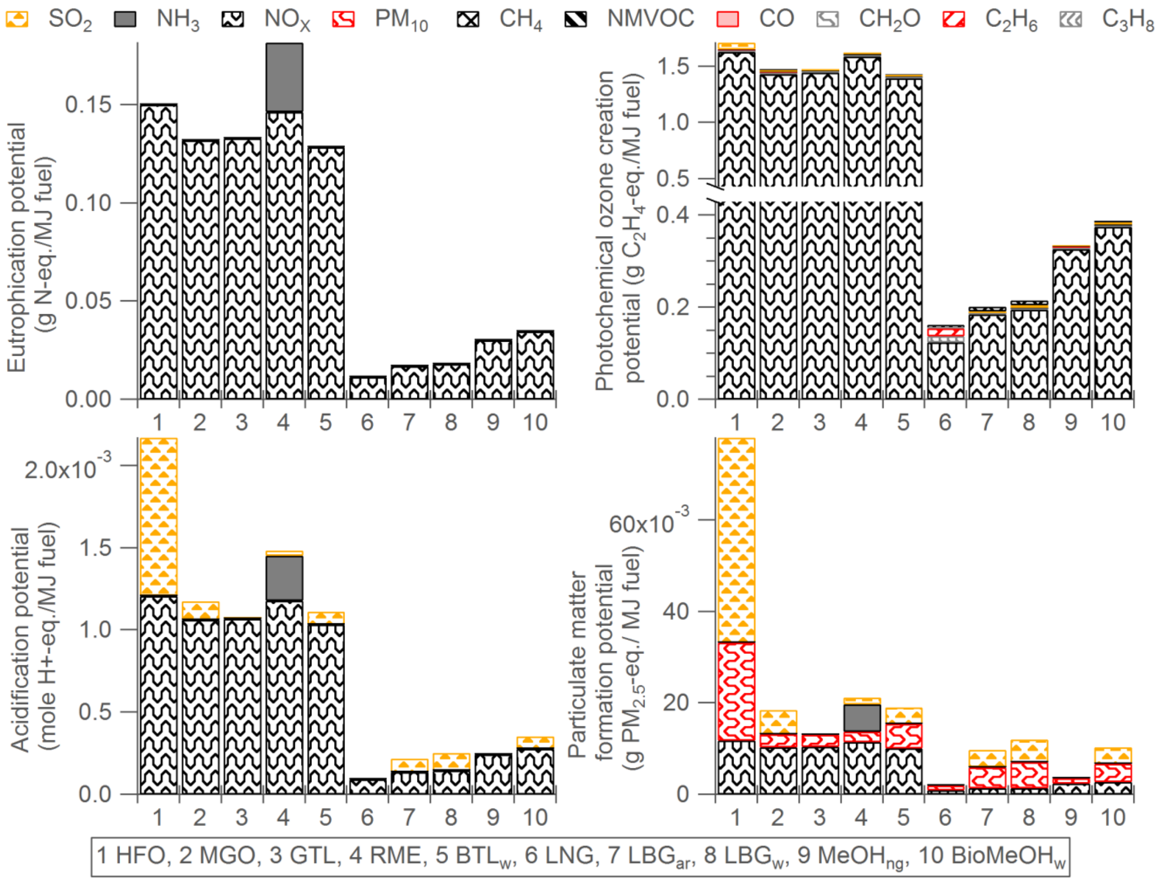

Figure 5-4 Local and regional environmental impacts associated with the evaluated fuels. Abbreviations: HFO (heavy fuel oil), MGO (marine gas oil), RME (rapeseed methyl ester), BTL_w (synthetic diesel produced from willow), LNG (liquefied natural gas), LBG_{ar} (liquefied biogas from residues), LBG_w (liquefied biogas from methanation of willow), $MeOH_{ng}$ (methanol produced from natural gas) and $MeOH_w$ (methanol produced from willow).

5.2.2 Marine Fuels Combined With Exhaust Abatement

Two exhaust abatement technologies are also included in the analysis: open scrubbers and SCR units. The diesel-based fuels can comply with the strictest environmental regulations in force when combined with scrubbers and/or SCR units. These exhaust controls result in a small increase in energy use, except in the case of HFO, and a 2-5% increase in GWP (Table 5-3). The extra energy requirement associated with the use of a scrubber is assumed to be 2%, but this is not shown in the results because the results are presented per MJ of fuel combusted.[47]

The local and regional environmental impacts of the fuels and exhaust abatement options differ from those of the results from the use of fuels without any exhaust abatement (see Figure 5-5). The emissions of NO_X are particularly reduced, causing the impacts associated with the other emissions to be more pronounced. LNG is still the fuel with the lowest overall local and regional environmental impacts. However, RME is shown to be worse than HFO in three of the four investigated categories.

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[47] A fuel quantity of 1.02 MJ would be needed to perform the same transport work as 1 MJ of the other alternatives.

Table 5-3 Life cycle global warming impacts of the evaluated fuels over a 100-year time horizon: a comparison of the results without exhaust abatement technology and the results of all fuels complying with the 0.1 wt. % S and NO_X Tier III regulations (g CO_2-eq./MJ)[a].

	No exhaust abatement	Compliance with 0.1 wt. % sulphur and NO_X tier III	Increase
HFO	87	89 (91)[b]	2% (5%)[b]
MGO	84	85	2%
GTL	95	96	2%
RME	41	42	4%
BTL_w	21	22	7%
LNG	79		
LBG_{ar}	50		
LBG_w	51		
$MeOH_{ng}$	89		
$MeOH_w$	18		

[a]Abbreviations: HFO (heavy fuel oil), MGO (marine gas oil), RME (rapeseed methyl ester), BTL_w (synthetic diesel produced from willow), LNG (liquefied natural gas), LBG_{ar} (liquefied biogas from residues), LBG_w (liquefied biogas from methanation of willow), $MeOH_{ng}$ (methanol produced from natural gas) and $MeOH_w$ (methanol produced from willow). [b]Includes the 2% increased energy use to run the scrubber.

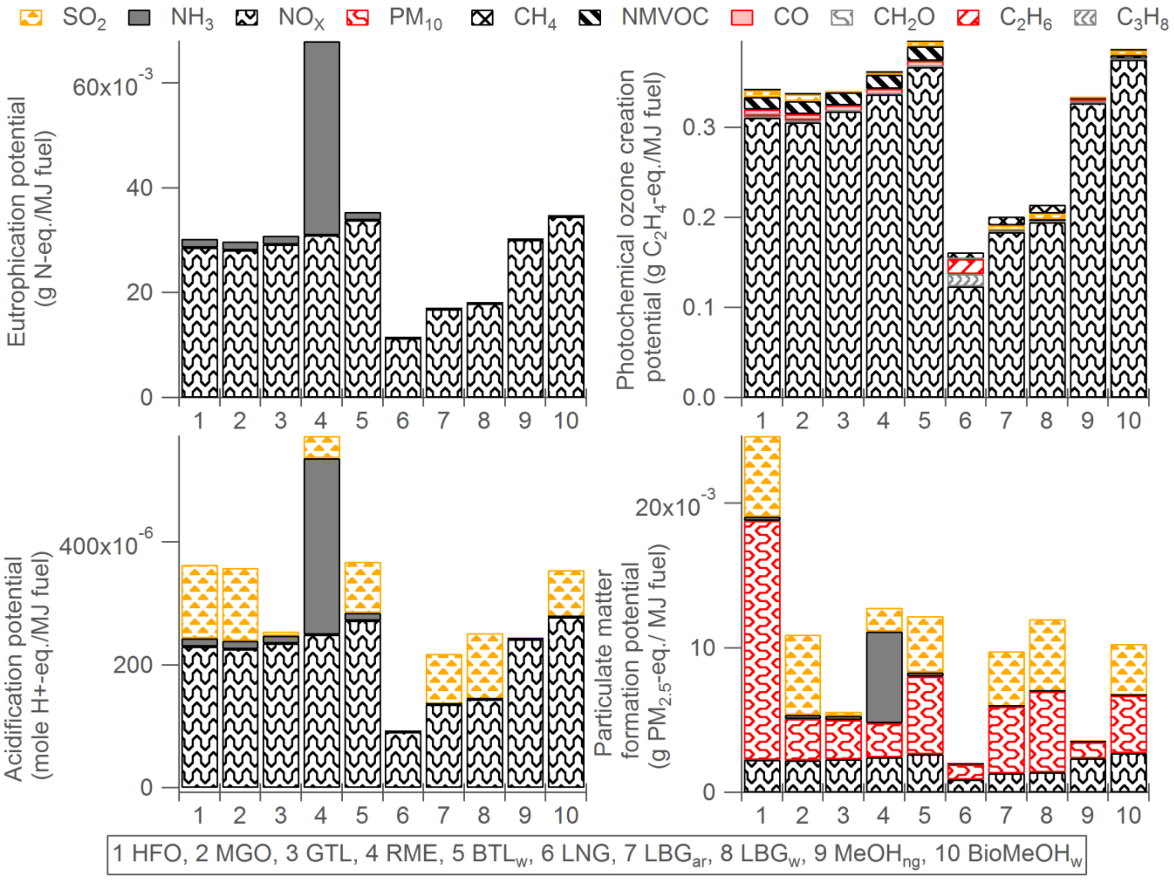

Figure 5-5 Local and regional environmental impacts associated with the evaluated fuels that comply with the 0.1% sulphur and NO_X Tier III requirements. The use of HFO is combined with a scrubber and an SCR unit, and the uses of MGO, GTL, RME and BTL are combined with SCR units. Abbreviations: HFO (heavy fuel oil), MGO (marine gas oil), RME (rapeseed methyl ester), BTL_w (synthetic diesel produced from willow), LNG (liquefied natural gas), LBG_{ar} (liquefied biogas from residues), LBG_w (liquefied biogas from methanation of willow), $MeOH_{ng}$ (methanol produced from natural gas) and $MeOH_w$ (methanol produced from willow).

The SCR technology is demonstrated to be an effective way to reduce NO_X emissions from marine engines. However, the potential ammonia slip from the SCR could pose a problem. Ammonia is used as the reducing agent in the SCR and is usually supplied in the form of a water-based solution of urea. The urea then decomposes to ammonia in the SCR. The use of SCR units will increase the emissions of ammonia slightly, even if handled using best practices, and ammonia contributes to three of the evaluated impact categories of local and regional environmental problems, as shown in Figure 5-5. The impact of the urea dosage was investigated in Paper IV, and the results indicated that a significant over-dosage of urea could counteract the benefits of reducing NO_X emissions, if no ammonia oxidation catalyst was fitted. A catalyst oxidising the ammonia to nitrogen would prevent the undesirable effects of ammonia slip.

5.2.3 Carbon Footprint of LNG Dependent on Engine Choice and Methane Leakage

The implications of methane leakage in the life cycles of methane-based fuels were evaluated in the appended papers, and methane leakage was shown to have a significant impact on the results. Methane is a strong greenhouse gas, and even small releases will have an impact on the methane-based fuels' GWP, particularly when considering short time horizons because methane has a short duration in the atmosphere (IPCC, 2007). There is also large uncertainty associated with the actual methane slip from gas engines during operation, and there are only a few published measurements of these emissions (see Table 4-3). The methane slip also observed to differ depending on the type of engine used and when the engine was produced. The first LNG engines used in Norway were shown to have significant methane slip, particularly at low loads (Nielsen and Stenersen, 2010).

To illustrate the potential impacts of these uncertainties, three types of engines are compared in Figure 5-6A: four-stroke SI engines, four-stroke DF engines and two-stroke GD engines. The LNG two-stroke GD engine displays the lowest GWP_{100} per MJ of combusted fuel. Figure 5-6 shows the impact per MJ of combusted fuel and therefore does not consider the efficiency of the engine. This finding implies an even lower climate impact from LNG burned in a two-stroke GD engine than the impact from the other engine choices due to its higher efficiency.

The actual amount of methane that can be emitted in the LNG fuel chain and still result in a lower climate impact associated with use of LNG than for the traditional fuels, such as HFO and MGO, has varied slightly among the appended papers. This amount depends on several aspects, including whether only the increased methane leakage is compared to the base case and whether the comparison is based on a case without methane leakage during the life cycle. This factor also depends on the specific data used in the appended papers. For example, in this thesis and in Paper V but not in Papers I-IV, LNG is assumed to contain constituents in addition to methane. In this work, it is assumed that a 4 wt. % slip from the engine will consist of approximately 3.1 wt. % methane, 0.6 wt. % ethane and 0.2 wt. % propane (the base case, which is based on average Norwegian natural gas). Figure 5-6B shows the total amount of methane leakage that can occur in the life cycle for LNG to remain the fuel with the lowest GWP_{100} of all the fossil fuels compared in this study (3%) and the amount that will cause LNG to be the fuel with the highest GWP_{100} of all the evaluated fuels (7%). The leakage of methane included in this work, from the raw material acquisition to the delivery into the marine engines, represents approximately 0.2 wt. %.

In Paper I, increased methane leakage in the fuel chain was considered, and it was concluded that an increased leakage of approximately 2% would assign LNG the same GWP_{100} as MGO and HFO (this study thus already included a leakage of slightly more than 2% in the LNG life cycle). Paper IV investigated the amount of methane slip that the LNG engines could emit and still display a lower GWP_{100} than the use of HFO with a scrubber and an SCR unit and the use of MGO with an SCR unit. The methane leakage occurring before the combustion in marine engines in the life cycle was thus included in the data. In Paper IV, it was concluded that a methane slip of 4% or more from the engines would cause LNG to be the alternative with the highest GWP_{100}.

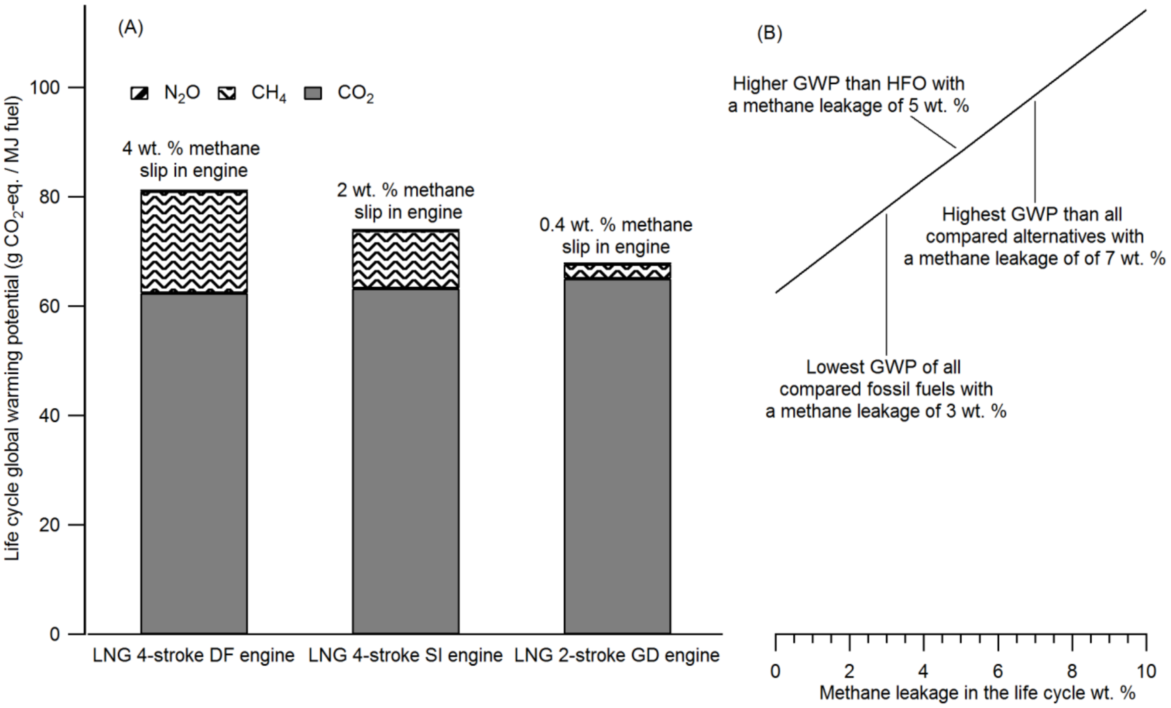

Figure 5-6 The climate performance of LNG burned in various types of engines and the impact of the methane leakage during the life cycle. The data are presented per MJ of combusted fuel, and the results therefore do not indicate that the two-stroke GD engine is more efficient than the four-stroke engines.

5.2.4 Implications of Expected Changes in Refineries 2015 and 2020

The emissions and energy use from refineries are expected to change in 2015 and 2020 (or 2025), when the new sulphur regulations come into effect and increase the demand for low-sulphur fuels. This demand will cause changes in the refinery processes, and the data used in this work are not applicable to these changes. Bredeson et al. (2010) assessed factors driving refinery CO_2 intensity and found that the most important factor is the hydrogen content in the products relative to the hydrogen content in the crude oil. Refinery energy use increases for heavier crude oil and for increased conversion of residual products into transportation fuels. The conversion of residual products into more distillate fuels is one likely outcome of the reduced sulphur content requirement in marine fuels.

The changes in European refineries due to the upcoming regulations were investigated in a study by Avis and Birch (2009). They estimated that the total CO_2 emissions from European refineries will increase by approximately 4.5% and 2.5% in 2015 and 2020, respectively, relative to a baseline scenario without any regulation of the sulphur content in marine fuels. If all of the increased CO_2 emissions in European refineries in 2015 were allocated to the production of MGO, the result would be an increase of 7 g CO_2/ MJ MGO. Using the same approach for 2020 (i.e., allocating the increased CO_2 emissions in 2020 to the expected use of bunker fuels, including MGO) results in an increase of 2 g CO_2/MJ during the production of bunker fuels, such as MGO and HFO. These figures can only be used as indications on the ways that the changes in refinery production will impact the CO_2 emissions associated with marine fuels, and more detailed assessments (including all emissions from refineries) are recommended. If the energy use and CO_2 emissions increase, then the other emissions from the refineries can also be expected to increase, but no such estimates were found in the literature.

5.3 Comparison with other LCAs of Fuels

As summarised in section 3.1 there are some studies in which the life cycle impacts of marine fuels and exhaust abatement technologies were evaluated. The results of these studies[48] are compared with the results of this thesis. Because there have been few studies of biofuels in shipping, the results of this work are also compared to selected studies of other transportation modes in section 5.3.2.

5.3.1 Comparison with other LCAs of Marine Fuels

Using the TEAMS model, Winebrake et al. (2007) compared the life cycle performance of six marine fuel pathways: those of HFO, conventional diesel, low-sulphur diesel, CNG, Fischer-Tropsch diesel made from natural gas and biodiesel made from soybeans. Winebrake et al. (2007) presented the results from the model in three case studies; the results for the container vessel are used for comparison with the work presented in this thesis. The lowest life cycle emissions of greenhouse gases are associated with the residual fuel closely followed by conventional diesel, whereas the greatest life cycle emissions are from the Fischer-Tropsch diesel. The conclusion that the climate impact is greatest for the Fischer-Tropsch diesel is supported in this work. The CNG fuel chain produces slightly more greenhouse gas emissions than the fuel chain of conventional diesel. It is not possible to directly compare the CNG fuel chain with the LNG fuel chain studied in this thesis because their production processes differ. CNG occupies more space than LNG but is more energy efficient to produce. In the study by Winebrake et al. (2007), the life cycle emissions of NO_X of CNG are by far the lowest, and the total life cycle emissions of SO_2 are the lowest for CNG, low-sulphur diesel and GTL. This finding is also consistent with the results from the work presented in this thesis.

In this work, the larger well-to-tank emissions of climate gases from MGO relative to HFO are offset by lower tank-to-propeller emissions, resulting in a slightly lower GWP for MGO than for HFO (by 2-4%). Corbett and Winebrake (2008) studied the emissions trade-off between residual fuels (e.g., HFO) and distilled fuels (e.g., MGO) by modifying the TEAMS model. Their results indicate the opposite relationship between HFO and MGO and suggest that the CO_2 emissions will increase slightly (less than 0.5% for the best estimate) with distilled fuels in comparison to residual fuels. These differences between the models could be caused by differences in the allocation of the impacts from the refining process. Corbett and Winebrake (2008) used refinery efficiencies based on data by Wang et al. (2004). The differences may also result from the fact that this study uses data from an average European refinery, whereas Corbett and Winebrake (2008) used data from a typical United States refinery. However, neither the work in this thesis nor the work by Corbett and Winebrake (2008) indicate that there is a large difference between the environmental impacts of distillate and residual fuels. Both approaches consider the refinery to be in a steady-state condition without considering changes in refinery production in relation to the forthcoming stricter regulations of sulphur content in marine fuels. This change in refining was discussed in section 5.2.4.

Verbeek et al. (2011) estimated well-to-propeller greenhouse gas emissions for LNG at between 78.4 and 92.6 for three pathways of LNG in the Netherlands; the corresponding reference values used for HFO, MGO and diesel (EN590 10 ppm S) were 87.5, 87.1 and 88.8 respectively. The three LNG pathways investigated were LNG from Qatar, domestic LNG and LNG produced in the Netherlands from pipeline gas originating in Russia. The LNG derived from pipeline gas from Russia was the alternative associated with the greatest greenhouse gas emissions. Verbeek et al. (2011) assumed a methane slip of 2.6 wt. %, whereas a 4 wt. % methane slip is used as a base in this thesis. The study concluded that the GWP_{100} for LNG fuel chains is approximately 10% lower than that of the diesel fuel chain. They also suggest that lowering the methane emissions from marine engines is one method

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[48] Except for the master theses.

for further improving the GWP_{100} of LNG. These conclusions are supported by the results of this thesis, even if the figures are not identical.

Lowell et al. (2013) estimated that the life cycle greenhouse gas emissions for the eight investigated pathways were in the range of 72-93 g CO_2-eq./MJ. This range can be compared to the figure of 81 g CO_2-eq./MJ used as the base case in this work and an estimated range of 73-96 g CO_2-eq./MJ presented in Papers I and Paper V. The study by Lowell et al. (2013) was based primarily on United States data. The data for natural gas extraction, processing and liquefaction, for example, were based primarily on those of Skone (2012). The imported LNG pathways involved LNG produced in Trinidad and Tobago and transported to the United States. in large LNG carriers on a 20-day trip. The other pathways involved LNG produced in the United States. Another critical assumption included the methane slip during combustion in gas and dual-fuel engines. The methane slip was assumed to be 4 g/kWh in the LNG engines, representing approximately 1-2 wt. % of the fuel input. This value is in the same range as those of the methane slip used in Paper I but is lower that the methane slip (4%) assumed in the base case presented in this thesis. The study by Lowell et al. (2013) used a value of approximately 88 g CO_2-eq./MJ for HFO and MGO for comparison with LNG. The overall results are consistent with the results of this thesis.

Ma et al. (2012) concluded that a scrubber system used with HFO has the potential to reduce the energy use and greenhouse gas emissions during the fuel life cycle compared with the use of low-sulphur marine fuels. This statement is not supported by this work. However, the changes in refinery production due to the sulphur regulations are not considered. It is possible to estimate the effect of the refinery changes on the results. Based on the data by Avis and Birch (2009), the increased CO_2 emissions associated with MGO production due to changes in refinery production can be estimated at 7 g/MJ MGO in 2015 (see section 5.2.4). Adding this figure to the assessment in this thesis and also the CO_2 emissions formed in the oceans by the release of scrubber water (1.5 g/MJ HFO), results in a GWP_{100} of 90.7 and 90.3 for MGO and HFO with a scrubber respectively, indicating a small benefit associated with the use of HFO with a scrubber.

5.3.2 Comparison with other LCAs of Transportation Fuels

In Table 5-4, the life cycle greenhouse gas emissions found in this study are compared with the results of the European well-to-wheel study presented by Edwards et al. (2013a). The well-to-tank emissions from the European well-to-wheel study are compared to this work by adding the greenhouse gas emissions from combustion in marine engines used in this work. The values for the fossil fuels are lower in this work. This discrepancy can be partly explained by the fact that the European well-to-tank study included fuel distribution via truck of approximately 500 km. The distribution for shipping differs and is performed by tankers, which are more energy efficient. Furthermore, the final step in the distribution process, from port to the ro-ro-vessel via a bunker ship, is not included in the work presented in this thesis. It was, however, considered in Papers I and II. The last distribution step was excluded from latter studies because it did not affect the relative results between the fuel alternatives.

The values for the biofuels are (with the exception of RME) lower in the European well-to-wheel study than in this thesis. Part of this difference may be caused by different handling of the distribution of biofuels. In this work, the biofuels are assumed to be distributed first by land to the nearest port and then by ship.

Malça and Freire (2011) assessed a large number of LCAs of FAME fuels in Europe and found large variations in the results. The greenhouse gas intensity, for example, was in a range of 15-170 g CO_2-eq./MJ fuel. The important factors that contributed to the difference in the results were the treatment of the co-products and the land use modelling. The JEC well-to-wheel study presented greenhouse gas intensity results for RME in the range of 30-60 g CO_2-eq./MJ (Table 5-4). The figure for RME production used in the base case presented in this thesis is from Bernesson (2004) and is equal to 39.7 g CO_2-eq./MJ. These data are thus in the lower range of the estimates for FAME fuels.

Table 5-4 Greenhouse gas balances of selected pathways in the European well-to-wheel study (g CO_2-eq./MJ) (Edwards et al., 2013b).

	Well-to-tank (best estimate)	**Well-to-tank (range)**	**Well-to-propeller[a] (indicative values)**	**Well-to-propeller (this work)**
Diesel	15.4	13.8-17	89.4-93.4 (74-78)	84-87
LNG, road (GRLG1)	19.4	18.7-20.6	91.4 (72)	81
Biogas from municipal waste	14.8	11.3-18.1	32.8 (18)	
Biogas from liquid manure (closed storage)	-69.9	-71.3 to -68.8	-51.9 (18)	50
Biogas from liquid manure (open storage)	-45.2	-46.6 to -44.2	-27.2 (18)	
Synthetic methane	3.3	2.2-4.1	21.3 (18)	56
RME (meal as AF, glycerol as chemical) (ROFA1)	53.9	46.0-59.8	53.9 (0)	41
RME (meal and glycerol to biogas) (ROFA4)	37.3	29.7-44.3	37.3 (0)	
GTL (GRSD1)	23.4	20.5-27.3	96.4 (73)	95
BTL (WFSD1)	7.0	5.3-19.6	7.0 (0)	27
MeOH from natural gas (GRME1)	24.9	23.7-26.8	93.9	89
MeOH from wood (WFME1)	6.6	5.2-18.8	6.6 (0)	24

[a] Added values of g CO_2-eq./MJ emitted when fuels are combusted in marine engines; the values added are in parenthesis.

5.4 Cost-effective Marine Fuels in a Carbon-Constrained World

The environmental performance of the marine fuels assessed in this work are presented from a life cycle perspective, and the results are compared to those of other studies. It is now time to adopt a different systems perspective to assess which marine fuels are the most cost-effective in terms of the global stabilisation of CO_2 emissions and global competition for primary energy sources. The LCA indicated that biofuels may be one way to reduce the climate impact of shipping, but are they also a globally cost-effective solution for shipping?

The global energy systems model GET-RC 6.2 is used to investigate various cost-effective fuel and propulsion technology options for shipping. Two base scenarios that differ in the concentration of CO_2 in the atmosphere are considered. These scenarios involve global stabilisations at 400 and at 500 ppm atmospheric CO_2 and assume that carbon capture and storage (CCS) is available as a large-scale CO_2 emission mitigation technology (see Figure 5-7). The fuels produced from natural gas are found to be the primary substitutes for crude oil-based fuels within the next few decades. Biofuels, hydrogen and fuel cells are not shown to be cost-effective fuel choices in the base scenarios. LNG is introduced in 2020 in both base scenarios, although oil is phased out slightly earlier in the scenario with the 400 ppm CO_2 target due to increased pressure to reduce CO_2 emissions in the energy system. LNG alone is the most cost-effective replacement for oil until 2050 in the 400 ppm scenario (see Figure 5-7A). In the base scenario with the CO_2 target of 500 ppm, a combination of LNG and fossil methanol are the most cost-effective alternatives until 2050 (see Figure 5-7B). Less natural gas is needed to produce LNG than to produce methanol, and the associated CO_2 emissions are lower with LNG. These factors cause LNG to be more advantageous when assuming the lower CO_2 stabilisation targets.

A Monte Carlo analysis of the two base scenarios (i.e., achieving global CO_2 stabilisation at 400 and at 500 ppm), with and without CCS, was performed. In the simulation, 13 parameters were varied (see Table 2 in appended Paper VI), a uniform distribution was assumed, and 700 iterations were run (a larger number of iterations did not change the result). The impact of the availability of CCS was analysed because previous studies have shown that CCS has a significant impact on cost-effective fuel choices in the transportation sector (Grahn et al., 2009b) and because it is very uncertain whether CCS will be an accepted mitigation technology.

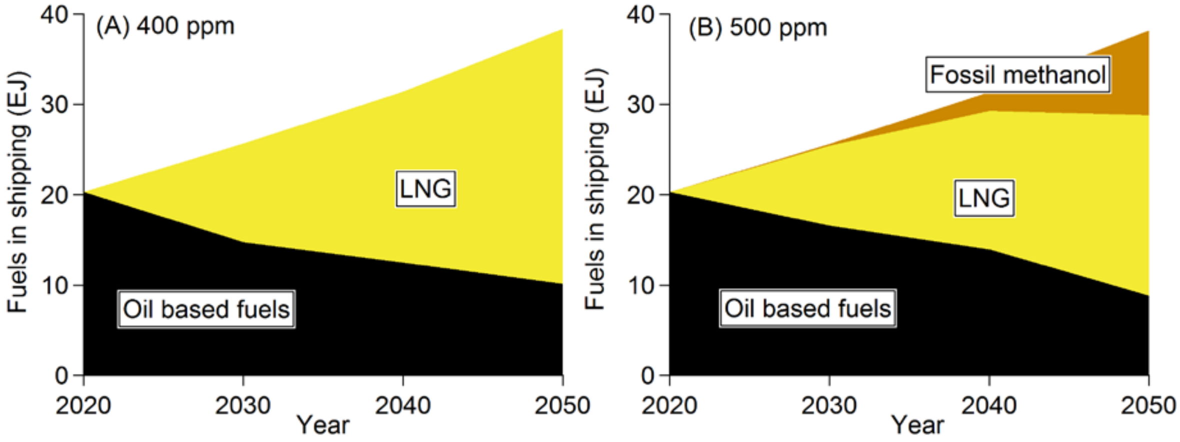

Figure 5-7 Global secondary energy use for shipping in the two base scenarios involving a CO_2 concentration of (A) 400 ppm and (B) 500 ppm, with carbon capture and storage as a large-scale technology option for CO_2 reduction.

An early switch from oil to alternative fuels was shown to be cost-effective during the next few decades in the majority of the model runs. Natural gas-based fuels, LNG and fossil methanol, seem to be the most cost-effective alternative fuels in the shipping sector to 2050. Biofuels were shown to rarely play a major role in the shipping sector due to their limited supply and competition for bioenergy from other energy sectors. The majority of bioenergy is instead used in the stationary energy sector, particularly in the heat sector. To render biofuels a large share of the marine fuels (more than 40%), the bioenergy supply potential must exceed 200 EJ (Figure 5-8). The Monte Carlo analysis with a CO_2 stabilisation target of 400 ppm without the availability of CCS produced the largest share of biofuels in the majority of the runs, while a CO_2 stabilisation at 500 ppm with CCS resulted in few runs with a large share of biofuels in shipping.

The primary insight obtained from the study was that it is cost-effective to start the phase out of oil from the shipping sector during the next few decades. The natural gas-based fuels (LNG and fossil methanol) are the most likely replacements through 2050, whereas biofuels never play a major role in the shipping sector due to their limited supply and competition for bioenergy from other energy sectors. Moreover, the availability of CCS, the primary energy supplies, the future CO_2 stabilisation level and the technology costs, such as the LNG tank, affect the marine fuel choices significantly. It is difficult to identify one fuel choice as the single optimal choice through 2050. However, LNG appears to be the most cost-effective option in the majority of model runs.

The model evaluates the fuel choices and technologies that are cost-effective to use until 2100, even though the period after 2050 was not assessed in Paper VI. The fuel options associated with low-carbon emissions will be essential beyond 2050, when almost no emissions will be allowed in any energy sector if the ambitious CO_2 stabilisation levels are to be met, i.e., even the natural gas-based fuels must be replaced in the shipping sector. The model indicates that hydrogen will be the primary cost-effective option after 2050, but the present model does not include fuels other than biofuels that could be used to significantly reduce the CO_2 emissions.

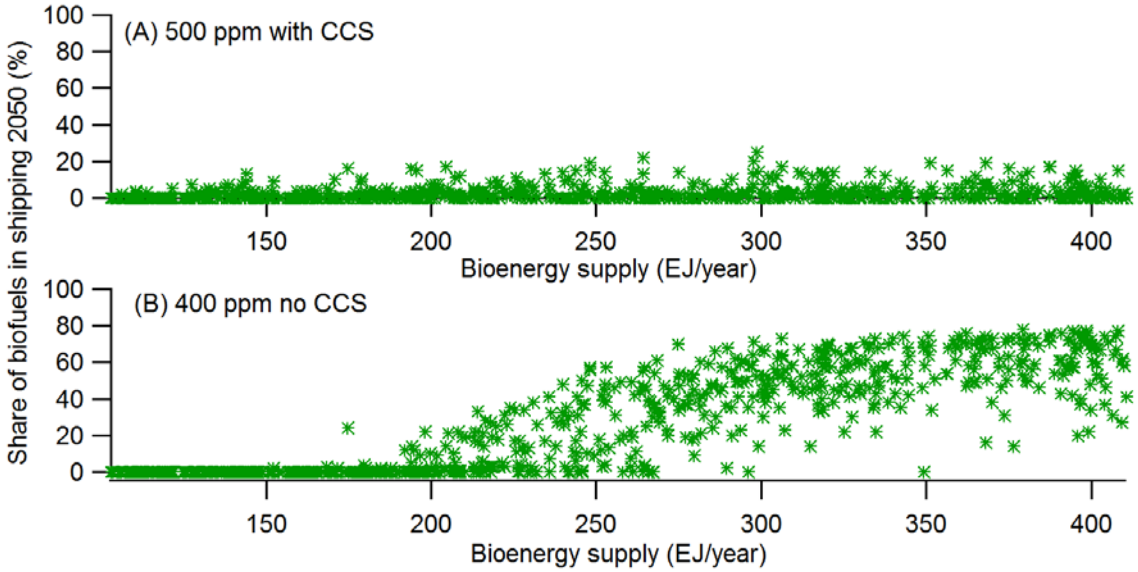

Figure 5-8 A Monte Carlo analysis with 700 iterations in which 13 parameters (the potential energy supply, cost of ship technologies and size of the methane slip) are varied. The share of biofuels in the shipping sector in 2050 is plotted against the potential yearly bioenergy resources meeting a CO_2 concentration of (A) 500 ppm with carbon capture and storage (CCS as a large-scale mitigation technology) and (B) 400 ppm without the availability of CCS.

6 Systems Assessment for Evaluation of Marine Fuels

The two primary methods used in this thesis are LCA and energy systems modelling. Both are based on a systems approach and are thoroughly discussed in this chapter. The chapter starts with an evaluation of the methodological choices used in the LCAs (Papers I-V). This evaluation is followed by a discussion of LCA as a tool for environmental assessment of marine fuels. The chapter ends with a discussion of the methodological choices used in the GET model (Paper VI) and its utility in the environmental assessment of marine fuels.

6.1 Methodological Choices in the LCAs

Three methodological choices that have an impact on the results are the choice of the functional unit, the choice of the impact categories and the allocation methods. Other important aspects are the data sources and the manner in which the robustness of the results is evaluated. These issues are discussed in this section.

6.1.1 The Choice of a Functional Unit

The unit used for comparison in an LCA, the functional unit, was chosen to be one tonne of cargo transported one kilometre using a ro-ro vessel, as in Papers I, III, IV and V. The unit used in Paper II consisted of one year of ro-pax ferry service. In this thesis, the results are presented as impact per 1 MJ of combusted fuel to make the comparison with other studies easier. The choice of presenting the values in units of MJ of combusted fuel can be misleading when incorporating abatement technologies. As an example, the use of a scrubber will increase the fuel consumption, but this increase will not be evident if the impact is measured in MJ of fuel combusted. The same problem is present if one wishes to account for reduced cargo capacity and there is a consequent increase in energy use per amount of transport work. However, the benefit of presenting data in units of MJ of fuel combusted is that it is applicable to various types and sizes of vessels as long as similar engine types are used.

The choice of a ro-ro vessel has an impact on the assumed storage requirements of the fuels. The results would change marginally if other vessel types, other vessel sizes and other types of combustion engines were considered. A 4% reduction in cargo capacity was used for the methane- and methanol-based fuels. However, this figure is rather uncertain and depends on the specific vessel and whether the engine is retrofitted or installed during a newbuilding project. A 4% reduction in cargo capacity was observed when retrofitting a container feeder vessel in Norway (Gullberg and Gahnström, 2011).

The choice was also made to assume the use of four-stroke engines for propulsion. Certain emissions would have been different if two-stroke engines were chosen instead. Two-stroke engines are more efficient than four-stroke engines, although they are associated with slightly higher NO_X emissions. The emissions profiles of the two-stroke LNG engines are thus far uncertain, but they exhibit less methane slip and higher emissions of NO_X than the four-stroke lean-burn engines.

It was also assumed that the engine efficiency[49] was the same for all fuels. There is little available information regarding the efficiencies of marine engines running on different fuels. Certain data suggest that gas and dual-fuel engines will be more efficient than diesel engines. For example, a position paper from Det Norske Veritas reports a 12% higher efficiency of the 4-stroke gas engine compared to a 4-stroke diesel engine (Ludvigsen and Ovrum, 2012). However, another study reports nearly the same engine efficiency when using HFO, MGO, LNG and methanol in a marine four-stroke engine (Stenhede, 2013). The most reasonable assumption was to assume the same efficiency of the engines because the data are very limited. However, higher efficiencies of methane and methanol engines would have important impacts on the results, and a sensitivity analysis of these variations in efficiency is recommended.

If the selected functional unit consists of one tonne of cargo transported one kilometre using a ro-ro vessel, as in Papers I, III, IV and V, then there is a need to estimate the load factor i.e., how much cargo the ship is carrying in relation to the cargo capacity. The load factor can be assumed to be independent of the fuel used and will therefore not impact the comparison between the various fuels. However, it is important to take into account the load factor when comparing different types of vessels and different modes of transport. On a ro-ro vessel, there is a double load factor problem: the load factor of the vessel and the load factor of the trucks. The tonne of cargo represents trucks with an average amount of cargo. The question of load factor was not considered in detail because it does not have an impact of the relative comparison of the various fuels.

6.1.2 The Choice of Impact Categories and Characterisation Factors

The impact categories considered important in the assessment of marine fuels were climate change, toxicity, particulate matter formation, acidification, eutrophication, photochemical ozone formation, land use and resource depletion (section 2.2.1). Toxicity (i.e., human toxicity and eco-toxicity) was not assessed due to a lack of data. However, the rest of the impact categories were included in at least one of the appended papers.

The goal of this work was a holistic assessment of the environmental performance of marine fuels. It was therefore desirable to assess all impact categories associated with the use of fuel. Many environmental issues are important in shipping, including not only climate change but also local and regional environmental impacts, such as eutrophication, acidification and impacts on human health. Therefore, it is important to consider more impact categories than are common in the well-to-wheel studies of road fuels, which typically consider only energy use and GWP, e.g., Edwards et al. (2007b). The results also demonstrate that the impact on climate change could not be used as an indicator of all types of environmental impacts. Finding data with complete information regarding various elemental flows of the assessed fuels was therefore an important part of this work, but this step also limited the number of available data sources.

Various impact categories and characterisation factors were tested and evaluated throughout this work. This step was performed to investigate, for example, whether the choice of various characterisation factors for the same impact category would alter the results. These differences were also a result of the author’s increased knowledge of various available characterisation methods and their reliability and acceptance and the release of new LCA guidelines. In the initial studies, the impact categories and characterisation factors were based on those of Guinée (2002) and CML (2010). In Paper III, a number of characterisation factors were evaluated, including, for example, the specific characterisation factors for the exposure of vegetation and human beings to photochemical ozone that forms as a consequence

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[49] Engine efficiency is the relationship between the total energy contained in the fuel, in this thesis based on lower heating value, and the amount of energy in the form of work provided by the engine.

of emissions in and around the Baltic Sea. There was no change in the overall conclusions depending on which characterisation factors were used for the various impact categories. The midpoint characterisation factors from the International Reference Life Cycle Data System (ICLD) handbook (IES, 2012) were used in Papers IV and V and in this thesis. The overall conclusions regarding the environmental impact of present and future marine fuels during the five years of work were not observed to be sensitive to the specific characterisation factors used, with the exception of the choice of GWP time horizons. This choice was further evaluated in this study.

Land use was only taken into account in Paper II, which included the use of renewable fuels. Land use was only assessed from the occupancy perspective, i.e., the m^2 of agricultural land used per year. It is important to note that the greenhouse gas emissions associated with land use changes were not considered in this study.[50] There are many ways to include such changes in the results, but there is no standardised method. The raw materials considered for biofuel production in this work consist of rapeseed, manure, agricultural residues, municipal organic waste, willow and forest residues. The cultivation of three of these materials, including changes in soil organic carbon (SOC), was assessed by Brandão et al. (2011). They estimated changes in the SOC to be 880, -497 and 0 kg CO_2-eq. per hectare per year for rapeseed, willow and forest residues, respectively. This finding indicates an increase in the GWP for RME of approximately 22 g CO_2-eq./MJ and a decrease in the GWP of willow-based biofuels in the range of 5-7 g CO_2-eq./MJ if the changes in the SOC due to direct land use changes are considered. This change would cause RME to become the biofuel with the greatest life cycle climate impact. However, this finding is only based on one assessment, and a more detailed analysis would be needed before drawing any further conclusions.

It was also recognised that very few of the characterisation factors available took into account the environmental fate of emissions at sea. Even though the choice of characterisation factors was not shown to impact the overall results, it would still be interesting to investigate whether the development of specific characterisation factors associated with the local and regional environmental impacts from shipping emissions would alter this conclusion. Although most of the ship emissions occur within 400 km of land, it could also be interesting to observe how the results would change if the locations of the emissions were taken into account. Most of the emissions during the life cycle are caused by ship transportation, but portions of the emissions also occur on land, making it important to use characterisation factors that are applicable to both situations if possible.

6.1.3 Allocation Choices

The allocations associated with HFO and MGO production in refineries in the appended papers were based on the energy content of the fuel following each sub-process in the refinery. The data for HFO and MGO production used in this thesis were from the ELCD core database.[51] Another possible allocation method is a system expansion, which would include more processes inside the system boundaries. In the case of a refinery, the use of a system expansion would be complex and would lead to new allocation problems. This allocation method was not tested because sufficiently detailed data could not be found.

A detailed allocation of energy use in a typical American refinery in relation to petroleum products was performed in a study by Wang et al. (2004). Three allocation choices at the refining process

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[50] There are many impacts associated with land use in addition to occupancy and global warming potential. Land use, for example, can also be associated with soil degradation and loss of biodiversity. Other issues associated with land use include secondary land use and competition among various uses.

[51] See ELCD core database version II (2010b) and ELCD core database version II (2010c).

level[52] were compared with one another and with three allocation choices at the refinery level.[53] HFO is associated with 0.8-2.9% and gas oil with 4.6-5.1% of the total energy use at the refinery, based on the three different process level allocation methods (Wang et al., 2004). The percentages are higher if the mass is used as the base for allocation and lower if the economic value is used. The difference in the allocated energy use between HFO and gas oil is greater in the study by Wang et al. (2004) than in the ELCD core database. Approximately twice the amount of energy is allocated to gas oil relative to HFO in the study by Wang et al. (2004), whereas only approximately 14% more energy is allocated to light fuel oil in the ELCD core database. The allocation method used in the ELCD core database (according to the description) is referred to by Wang as an energy content-based approach at the process level. The study by Wang et al. (2004) implies that if a market-value-based process-level allocation method had been used for HFO and MGO, then the energy use and emissions per tonne of product would be slightly lower than the values in the ELCD core database. These differences between various allocation methods would likely have no significant impact on the final results of this thesis because the impacts from the refining represent only a small portion of the overall environmental impacts.

RME production is another system in which allocation is necessary because rapeseed meal and glycerol are by-products. The allocation is performed based on the energy content values in the base data presented in this work. Paper II included a sensitivity analysis in which three alternative allocation methods were considered. The allocation methods for the by-products were shown to have a significant impact on the results; the GWP_{100} of RME varied from the highest to the second lowest of all of the fuels compared in Paper II. Glycerol could also be used as a fuel, as discussed in Box 3-1. The use of glycerol would have an impact on which allocation methods that can be considered to be most appropriate.

6.1.4 Data Sources and Data Reliability

Two sources were used to gather the necessary data for the LCAs: (i) specific data, if possible, for marine transportation and (ii) data from published LCAs for the steps involving raw material acquisition and fuel production. The work has been limited to the use of secondary data, and no measurements were performed.

The marine transportation data were, to the degree possible, gathered from actual measurements during transportation. If such data were not available, then the values were estimated based on discussions with industry representatives and/or adopted from measurements obtained in studies of road transportation. Significant effort was expended on the data collection for this step because the emissions during the combustion of fuels in marine engines is very important for the life cycle environmental performance. For MGO and HFO, there are considerable data, and emissions factors have been compiled in various reports, e.g., those by Cooper and Gustafsson (2004) and NTM (2008). There are very few measurements of emissions from marine engine combustion of the alternative fuels investigated in this work. There have been laboratory emissions tests using methanol in an engine (Stenhede, 2013), and certain emissions tests have been performed using biofuels in smaller marine engines (see Paper II). Of the alternative fuels, the only fuels in actual use today are MGO and LNG. The only possible way to estimate the emissions from the other fuels was to use the results from the limited studies available and to consider the results from other types of engines using the same fuels. The methane slip from gas and dual-fuel engines is one factor that was observed to have a significant effect on the climate impact of the methane-based fuels (LNG, LBG_{ar}, LBG_{w}).

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[52] The allocation is performed after each process in the refinery.

[53] The allocation among the products is performed after they leave the refinery, i.e., the refinery is viewed as a black box.

There is also large uncertainty associated with the performance of exhaust abatement technologies. Various types of scrubbers may be used, but only one type was assessed in this work. The type assessed here is the open sea water scrubber, and it is debated whether this type of scrubber should be allowed everywhere because it efficiently transfers acid to the surface water (Hassellöv et al., 2013). In addition to reducing SO_2, the use of a scrubber is also assumed to reduce the emissions of PM by 25 % by mass in the LCAs whereas a later study demonstrated a reduction of PM by 75 % by mass (Fridell and Salo, 2014). These values should be further verified. It is also possible that the scrubber would affect the stability of the vessel, thereby affecting the cargo capacity, but this possibility was not considered. SCR is shown to be an efficient method for reducing NO_X emissions; this use is, for example, illustrated in Figure 1 in appended Paper IV. However, there are questions regarding its efficiency at low loads and the consequent lower exhaust gas temperatures. The LCAs assume fully operational SCR units, without considering the efficiency at low loads.

The majority of the data regarding the raw material acquisition and fuel production were gathered from previous LCA studies. However, the data were adapted to fit the goal and scope of the specific studies, when necessary. Data from the northern parts of Europe or Europe in general were used, when possible, to ensure that the data would be applicable to the selected system boundaries.

The problems with the assessment of biofuels were related to the discrepancy between various assessments of the same fuel, the availability of data, the allocation to by-products and great uncertainties because the current production of biofuels occurs primarily on a pilot scale, and much larger facilities would be necessary for the commercial use of biofuels. These problems are similar to those identified in previous biofuel assessments (Cherubini et al., 2009; Hillman, 2008; Malça and Freire, 2011; Plevin, 2010).

6.1.5 Evaluation of the Robustness of the Results

Section 2.2.3 discussed three methods, based on Finnveden et al. (2009), to address uncertainties in the LCAs: (i) the “scientific way”, (ii) the “social way” and (iii) the “statistical way”. A combination of these three approaches was used during the work in Papers I-V. Throughout the work, there was a continual effort to locate better data and to model the life cycles more appropriately. As an example, the data for natural gas extraction were updated in Paper V using more recent data, as were the data specific to two geographical regions, based on the study by Schori and Frischknecht (2012). There were also numerous discussions with stakeholders and industry representative regarding the data used.

The LCA results were evaluated using variation analysis, i.e., investigation of alternative cases and the effects of data choices and assumptions. This step was performed by the authors of Paper I to a certain extent and rigorously by the authors of Papers II and V. In Paper II, the electricity used in the baseline scenario was assumed to be the average electricity produced in Sweden, which would have been a typical choice in an attributional approach. The impact of using electricity produced from natural gas and electricity produced from biogas was evaluated during the variation analysis. The analysis indicated that the choice of electricity production did not affect the results significantly. The allocation methods were considered more important than the choice of electricity in this study. In Paper V, 20 alternate cases were considered, and the minimum and maximum values of these alternate cases were presented in the results. The primary results were shown to be robust, even if a significant change in the results was observed in a few of the cases, including the case involving a large amount of methane slip from the marine engines (8%) and the case involving low methanol production efficiency (57%).

6.2 LCA as a Tool for Environmental Assessment of Marine Fuels

This section will discuss which questions regarding the environmental assessment of marine fuels can be addressed using LCA and which questions can be better addressed using other methods and tools. It will also discuss the advantages of using LCA to assess the environmental performance of marine fuels.

During this work, various questions were raised but not pursued for which LCA could provide further guidance. Two such questions were whether the choice of allocation methods for HFO and MGO production could alter the results and whether considering the environmental impact of fuel infrastructure could affect the results. The diesel fuels and the gaseous fuels have different infrastructure requirements, and it is therefore also possible that the construction, maintenance and demolition of their corresponding infrastructure could impact the results. This possibility is particularly apparent because the differences between the gas and the diesel routes were not considered to be clear. These questions can be explored further using LCAs, but methodological considerations and the availability of data are obstacles.

Other questions were raised, and in these cases, LCA may not be the best tool for developing answers. For example, in the case of a vessel accident, how would the choice of fuel affect the outcome? Would one fuel be preferable to another in the case of a fuel spill? What are the risks of explosions? These are important questions to ask when evaluating various types of fuel for marine transportation, and suitable decision support tools for addressing these questions most likely include risk assessment or environmental risk assessment.

Another question concerns whether information regarding environmental life cycle performance provides sufficient guidance to make decisions. There are a number of other factors that are important to consider, including infrastructure requirements, maintenance, fuel availability and fuel prices. These considerations are not included in an LCA. One possible tool that could incorporate more aspects into such an assessment is an MCDA. This method is designed for multi-criterion problems in which “there is much information of a complex and conflicting nature, often reflecting different viewpoints and often changing with time” (Belton and Stewart, 2003). The question regarding which fuel to choose for marine transportation is clearly a problem of this type. A first attempt to assemble a set of criteria for evaluating marine fuels was presented in section 3.2., and these criteria were used to describe present and possible future marine fuels in a systematic way.

LCAs can be used to address questions related to the life cycle environmental performance of marine fuels but are less appropriate for addressing other aspects of the fuel choice. LCAs should therefore be complemented with other tools for comprehensive assessments. It is also possible that the results from an LCA will not have an effect on the final fuel choice decision but can still be used to support such a decision.

Nevertheless, important insights were gained by using LCAs for the assessment of marine fuels. It was possible to identify critical factors that significantly impact the overall results and to highlight areas of potential improvement, such as the methane slip and the emissions of NO_X from marine engines. The results also indicated that even if the direct emissions from marine engines are the most significant, changes in raw material extraction and fuel production can also alter the results. LCAs make it possible to compare various propulsion systems that provide the same service, even if there are other differences, such as vessel capacity. LCAs are also 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 support of such decisions.

6.3 Methodological Choices Associated with the Use of the GET Model

The GET model was upgraded to represent a more elaborately characterised shipping sector. Three types of ship categories were considered: short sea, deep sea and container vessels. It would also have been possible to include an even larger set of vessel types and sizes, such as the division used in the second IMO greenhouse gas study (Buhaug et al., 2009). This representation of the shipping industry was, however, considered to be too detailed compared to the way in which other sectors are modelled in the GET model. The use of three ship types did capture certain important aspects of shipping, such as the various relationships between the tank capacity and the size of the engine in different types of ships. The reason for considering container vessels as a separate category was due to the higher growth of this segment compared to other ship types during recent years. Even though three ship categories were selected, the results were nevertheless aggregated because only small differences were observed between ship categories.

During the refining of the model, data specific to the shipping sector were collected. These data were compiled from articles, reports and discussions with industry representatives to obtain the most reliable and accepted data possible. The data for the shipping sector also needed to be normalised with the data from other sectors used in the model. A large proportion of the data in the model was developed before 2003, when the model was first created. Different parts of the model were subsequently refined and the data updated. Different data for the same processes have also been used by different researchers in the Physical Resource Theory research group. It is difficult to estimate which data are most relevant because there are significant uncertainties in all of the data used. However, the approach was to reach a consensus among the energy systems modellers in the Physical Resource Theory group regarding which data were most relevant. The data were also compared with data used in similar global energy systems models.

To analyse the robustness of the results, a sensitivity analysis was performed by varying the assumptions, such as the shipping demand, the interest rate, the CO_2 stabilisation targets, the availability of different technologies, the resource supplies and the technology performance and costs. The resource supplies and certain technology costs and performance levels were shown to be capable of altering the results significantly, and a more systematic assessment of uncertainty was considered necessary. A Monte Carlo analysis in which important parameters were varied simultaneously was therefore performed. The shipping demand was not observed to affect the cost effectiveness of fuels and technologies used in shipping, and the interest rate was observed to have only a limited impact on the results by altering the costs of the technologies. Therefore, these parameters were not assessed further.

6.4 The GET Model as a Tool for Environmental Assessment of Marine Fuels

The GET model is a global model at a high systems level and includes only a simplified representation of reality. The GET model cannot be used to forecast the future development of the energy system, but it can provide insights regarding which fuels and technologies may be cost-effective to use and which factors have a significant impact on various choices. The model may be thought of as a theoretical tool for determining which fuels and technologies would serve best in various sectors from a perspective of global cost minimisation.

The GET model includes a number of simplifications and assumptions, which are mentioned in section 2.3.2. There are several examples of assumptions and simplifications that affect the model results and could be considered in future work using the GET model. For one, the model considers only global cost minimisation instead of regional- or sector-wide cost minimisation. In addition, it considers only CO_2 emissions and includes only a limited number of technologies.

The GET model assumes a common global goal of cost minimisation. Although this goal may be seen as the ideal goal, there are many other concerns and agendas that need to be considered. Another global strategy for the stabilisation of atmospheric CO_2 emissions could instead be based on equal burden sharing, which could be further evaluated using the model in the future. In reality, it is not clear or even likely that the world's decision makers will agree on a strategy of global cost minimisation. Opposing scenarios may be anticipated; for example, the countries that are party to Annex I of the Kyoto protocol may continue to bear obligations regarding emissions reductions that differ from those of non-Annex I countries (Anderson and Bows, 2011). Moreover, political will, energy security issues, country-specific interests and practical obstacles are all factors that will certainly have a major effect on future fuel and propulsion choices, in addition to the overall cost-effectiveness. However, the global results from the GET model may still be representative, in qualitative terms, of regions that behave uniformly with respect to policy, such as the European Union and North America. Furthermore, the model also provides insights into which solutions to aim for if global cost-effectiveness is desirable but perhaps not practically possible.

The GET model is limited in its evaluation by the fact that it takes into account only costs and CO_2 emissions. It could also have been interesting to use a similar type of model that included more climate gases, e.g., methane and N_2O, or one that involved the stabilisation of the monetary costs associated with a broader set of emissions, e.g., CO_2, NO_X and SO_2, instead of the stabilisation of atmospheric CO_2 concentration. Would it change which fuels that are cost-effective if a more holistic set of environmental impacts were included?

The model is also limited in that it includes only a certain set of technologies. During future work, the model could be used to evaluate the shipping sector beyond 2050 and to analyse the role of new types of fuel options. This modelling could include such technologies as low-emitting fuels currently in an early development phase, e.g., algae-based fuels and synthetic hydrocarbons produced from CO_2 and water. Such fuel options might be essential beyond 2050, when almost no emissions will be allowed in any energy sector if the world is to meet the ambitious CO_2 stabilisation targets.

The results of the GET model cannot answer all questions related to marine fuels. For example, it cannot answer the primary research question in this thesis, *what is the environmental performance associated with existing and potential future marine fuels?* The GET model nevertheless serves as an interesting complement to the LCA because it provides a new perspective, considers a longer time horizon and provides insight into the way in which the shipping sector competes with other sectors for the available primary energy sources.

7 Concluding remarks

This chapter summarises the main conclusions and the most important recommendations for policymakers, ship-owners and operators that were gained during the five years of work. It also represents an attempt to look forward by summarising important questions to continue to address in the future.

7.1 Main Conclusions

The environmental performance of existing and possible future marine fuels has been assessed in this work. It has been shown that there is a large potential to reduce the environmental impact from shipping through a change of fuels and/or through the use of exhaust abatement technologies. A switch to any of the alternative fuels investigated in this study reduces the overall environmental impact from marine fuels compared to use of HFO, even if the environmental impact associated with certain impact categories may increase. The alternative fuels discussed here include fuels of diesel quality (MGO, GTL, RME and BTL_w), methane-based fuels (LNG, LNG_{ar} and LBG_w) and methanol-based fuels ($MeOH_{ng}$ and $MeOH_w$). These fuels are produced from three types of primary energy sources: crude oil, natural gas and biomass. The use of exhaust abatement technologies (open scrubbers and SCR units) in combination with the fuels of diesel quality is shown to reduce the local and regional environmental impacts by reducing the emissions of NO_X and SO_2 from the engines, with only small increases in energy use and climate impact in the life cycle.

The life cycle environmental performance is shown to correlate with the type of energy carrier used and the type of primary energy source used. These are two factors that have a significant impact on the results. The biomass-based fuels generally have a lower impact regarding climate change compared to the fuels that are based on crude oil and natural gas, whereas the opposite pattern is observed in terms of the total extracted energy. The crude oil-based fuels are associated with the lowest total extracted energy. The methane-based fuels have the lowest impact in terms of photochemical ozone formation, particulate matter formation, acidification and eutrophication potential. The impact of methanol-based fuels lies between that of the methane-based fuels and the fuels of diesel quality. Two factors associated with the type of energy carrier are the NO_X emissions from the marine engines and the leakage of methane, particularly the methane slip from gas engines in the methane-based fuel life cycles. These factors were shown to be critical in the overall life cycle environmental performance.

The GET model provides a broad systems perspective in one respect; it includes all energy sectors. However, it is limited in its scope in that it considers only CO_2 emissions and global cost minimisation. The LCAs provide a holistic perspective in that they take into account the entire fuel life cycle and possibly all types of environmental impacts, although an LCA can be used to examine only one product or service at a time. The GET model demonstrates that costs and technology performance in other energy sectors have an impact on the cost-effectiveness of choices in the shipping sector; thus, the shipping sector cannot be studied in isolation. These methods provide different insights that are both contradictory and complementary. The GET model indicates that it is cost effective to phase out the use of oil-based fuels in the shipping sector, which would improve the overall environmental performance of the shipping sector, as indicated by the LCA results. Biofuels are one possible way to reduce the climate impact from shipping based on the LCA results, but they are seen as a cost-effective fuel in the shipping sector only if the yearly available bioenergy resources are greater than

200 EJ in combination with an atmospheric stabilisation of 400 ppm CO_2 in the GET model. Both the results of the LCAs and the GET model indicate that LNG is preferable to methanol produced from natural gas.

7.2 Implications for Policy

The assessment also highlighted three important regulatory aspects: the importance of reducing the NO_X emissions from marine engines to reduce the overall environmental performance, the need to regulate the methane slip from LNG engines and that a change of fuels is not necessarily a step toward reducing the impact of shipping on the climate. These aspects are important for assuring good environmental performance when introducing new fuels and exhaust abatement technologies in shipping.

1) First, emissions of NO_X contribute to various environmental issues, including acidification, eutrophication, particulate matter formation and photochemical ozone formation. NO_X emissions have also been shown to be the dominant constituent of the life cycle emissions and are responsible for the largest share of the environmental impact.
2) Second, the LNG slip, i.e., unburned methane, could be reduced via engine modifications or the use of oxidation catalysts. Limiting the LNG slip to 2 wt. % would ensure that LNG has a lower impact on climate change during its life cycle compared to HFO in the present situation.
3) Finally, the LCAs indicated that only the biofuels (of the studied fuels) have the potential to significantly reduce the impact of shipping on the climate. However, these fuels were only shown to be cost-effective in the GET model under a limited number of circumstances prior to 2050. Other fuels associated with low carbon emissions will likely be necessary in the shipping industry, if, for example, the EU target of reducing CO_2 emissions from shipping by 40% by 2050 is to be reached.

7.3 Possible Impacts on the Shipping Industry

The shipping industry needs to be proactive and to anticipate coming events. This anticipation is of special significance when taking into account the long life expectancy of vessels. It is therefore important in the long run to prepare for a future without oil and natural gas in shipping and in the short run to prepare for even stricter environmental regulations. The regulations regarding air emissions imposed on the shipping industry are not nearly as strict as those imposed on other transport modes and land-based industries. It is therefore realistic to assume that the regulations will become even stricter in the future.

The maximum sulphur content in road-based fuels is 10 ppm in Europe (European Commission, 2009b), which is 100 times lower than the ECA sulphur regulation in 2015. Even if further lowering of the sulphur levels in marine fuels seems unrealistic today, the impact on air quality and on abatement systems may change this situation in the future. Furthermore, the strictest regulation for heavy-duty diesel engines (Euro VI, January 2013) will limit the NO_X emissions to 0.4 g/kWh, which is significantly lower than the Tier III limits. In addition, the ECA regulations as of now do not include any quantitative emission standards regarding PM, yet these have been incorporated in the European standards for trucks, non-road machinery and inland waterway vessels. Specific levels regarding PM emissions may require the development of PM abatement technologies for marine engines.

When considering future marine fuels, it is important for ship-owners and operators to include a holistic set of criteria that takes into account whether their fuel can comply with even stricter environmental regulations and reduce emissions of greenhouse gases. If the shipping industry wants to bear its share of the burden of holding the increase in global temperatures below 2°C, then, Anderson and Bows (2012) conclude, “*nothing short of an immediate ‘Scharnow turn’ is necessary*”,[54] indicating the need for much more radical changes than were observed by using the GET model.

7.4 Which are the Future Marine Fuels?

There are many possible fuels that could contribute to more sustainable shipping in the future. However, there are also many remaining questions that will require answers before we know which fuels will be used in the future. There is also the possibility that shipping in the future will switch radically away from the use of stored energy in the form of fuels into only relying on intermittent energy, such as the wind and the sun.

Historically, the criteria regarding reliability, efficiency and cost have dominated the changes in marine fuels. These criteria might also be important characteristics in selecting future fuels. It could also be that new characteristics are important currently, such as various environmental criteria, including life cycle GWP and local and regional environmental impacts. During the twentieth century, we observed two fuel changes in shipping: one from coal to diesel and one from diesel to HFO. It is possible that further changes will be necessary during the twenty-first century. One possible future scenario for shipping would be a transition from HFO to MGO in 2020, followed by a shift to natural gas-based fuels. These natural gas fuels could consist of LNG or methanol.

DME, not assessed in this thesis, is another possible fuel. DME was first used in diesel engines as an ignition improver for methanol, but the test results were not satisfactory. This testing occurred in the 1980s, when DME production was considered expensive and methanol was under consideration as a fuel to reduce particulate emissions (Sorenson, 2001). DME is a colourless gas at room temperature and atmospheric pressure and is considered an alternative fuel in compression-ignition diesel engines. It is an oxygenated gas with a low auto-ignition temperature, which leads to low NO_X emissions and minimal soot (Müller and Hübsch, 2000). The production of DME is very similar to the production of methanol. The portions of its life cycle that differ are its distribution and its use in marine engines.

The assessments in this thesis suggest that LNG is preferable to methanol, but this might change in the future. Currently, large energy requirements are associated with methanol production from synthesis gas. However, methods to convert methane directly to methanol without the synthesis gas step may make the routes from methane to methanol more efficient and increase the attractiveness of methanol as a fuel. There is ongoing research regarding a number of processes that could produce methanol directly from methane, and there has been progress in this area during recent years (Olah et al., 2009). Another possibility for shipping is the use of methanol with a water content of approximately 10% (crude methanol), i.e., omitting the distillation step after methanol production and thus potentially saving energy and lowering costs. This omission could be an interesting method of differentiating the methanol used in shipping from other uses.

The type of natural gas used to produce such fuels as LNG, methanol and DME is also in question. The current major development of shale gas makes shale gas a potential source in the future. But before such development is further initiated, it is also important to evaluate if it is desirable. It is currently debated whether shale gas can be produced without significant environmental impacts.

Even if the shipping industry shifts to natural gas fuels, another fuel shift will most likely still be necessary for the shipping industry to reduce its climate impact. The third shift during the twenty-first

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[54] The Scharnow turn is a manoeuvre used to bring a ship or boat back to a point it previously passed through; it is one of the suitable manoeuvres used in a man overboard situation and described in IMO (1986).

century would likely be a shift to a low-carbon-emitting fuel, such as biofuels, hydrogen or electrofuels.

The biofuels that were investigated in this thesis are biodiesel, synthetic biodiesel, liquefied biogas and bio-methanol. Glycerol is a potentially interesting biofuel that was not investigated. Because glycerol is produced as a by-product in the production of first-generation biofuels, or FAME fuels, it is important to consider whether it will be a viable fuel in the long run, even if FAME fuels are no longer produced. There is also the question of whether it would work in marine engines.

The biofuels produced from synthesis gas display the lowest overall environmental performance, based on the LCAs presented in this thesis. The commercialisation of biomass gasification is important for further development of the use of these fuels.[55] It has been suggested that biomass will play an important role in the global effort to reduce greenhouse gas emissions. For example, EU Directive 2009/28/EC set a mandatory target for all member states to use a fuel mix with a minimum of 10% biofuels in the transport sector and an overall target of deriving 20% of energy from renewable sources in the EU by 2020 (European Commission, 2009a). Could this mandate also have implications for the use of biofuels in shipping? Even if biofuels are shown to have potential, their availability is limited, and biofuels are seen only as cost-effective fuels in the shipping sector if the yearly bioenergy supply exceeds 200 EJ in the GET model.

For a long time, hydrogen has been discussed as the future fuel for transport, but many issues remain regarding its production, infrastructure and storage, as a few examples. The use of hydrogen could be a potential long-term method for reducing the impact on climate change, if the hydrogen is produced from renewable resources or from non-renewable resources in combination with CCS. Hydrogen could also be used in shipping. A design concept for a zero-emissions container feeder vessel using liquid hydrogen as fuel to generate power with a combined fuel cell and battery system has been developed by the Germanischer Lloyd class society (Sames, 2012).

A potential future fuel category exhibiting low carbon emissions is electrofuels. These could be interesting in the future if large amounts of electricity are available at low cost. They also present an alternative method of producing methane and methanol versus the fuels evaluated in this study. This process could serve as a way to store intermittent energy and simultaneously supply renewable fuels to the shipping sector and other sectors that do not easily use electricity directly.

The fuel shifts during the twenty-first century need to be much faster than the fuel shifts during the twentieth century, which spanned approximately half a century, if shipping is to reduce its climate impact significantly. There is also the possibility of skipping the shift from HFO to MGO and instead shifting directly to natural gas-based fuels. This shift is occurring already. Fuel shifts are only part of the solution. There is also a need to continuously increase the energy efficiency in shipping during this century.

7.5 Future Work

The work in this thesis consists of many parts, and there are many additional questions that could be interesting to explore in the future. Five possible directions of further study are discussed below.

1) Development of a holistic set of criteria for evaluating future marine fuels
   A first attempt to perform an MCDA was included as part of the Effship project (Bengtsson et al., 2012) and partly presented in this thesis, specifically section 3.2 . This work included the

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[55] See for example Hellsmark (2010), who have studied the formative phase of this development in Europe.

initial steps in performing an MCDA. The use of an MCDA in a research project involved a learning process for all involved that improved the quality of work. The specific case study, i.e., that of comparing LNG and methanol, highlighted the importance of considering a holistic set of criteria. There are many important criteria in addition to environmental criteria when evaluating future marine fuels, and understanding these criteria better can be a step in identifying or selecting more sustainable shipping fuels. A possible continuation of this work would be to perform a full MCDA that also includes weighting of the criteria, involves stakeholders in various countries and explores their differences and similarities and compiles the work to develop a general set of criteria.

2) Assessment of cost-effective choices of energy carriers and energy-efficient propulsion technologies in shipping during the twenty-first century

   The modelling of global energy systems to increase the understanding of possible future marine fuels in a global perspective was initiated in this work. This work indicated that the fuel and technology choices in the shipping sector are affected by choices in other sectors. The work could be continued by investigating the role of fuels and technologies in shipping through 2100 by analysing the role of hydrogen, electrofuels, fuel cells and other technical solutions. It may also be important to investigate the impact of stricter CO_2 stabilisation targets for shipping. Furthermore, the differences between including the shipping sector in a global carbon reduction strategy with a 2°C target (the scenario that has been analysed thus far) and a proportional reduction of CO_2 emissions in the shipping industry in accordance with equal burden sharing could be interesting to investigate and understand.

3) Development of sustainable shipping scenarios through 2050

   The work in this thesis can be used as a basis for analysing various shipping scenarios through 2050 combined with back-casting of ways of arriving at various outcomes. This thesis provides insights regarding the fuels that are the most environmentally sustainable but not the manner in which to actually start using them in shipping. A scenario analysis could answer questions regarding ways to help shipping reach the EU CO_2 targets by 2050. Similar questions concern the manner in which the shipping industry should behave to be sustainable by 2050 and the paths that will make this goal achievable.

4) Development of guidelines for use of LCAs in shipping

   LCAs are a useful tool for evaluating the environmental impacts of products of goods and services, and the work in this thesis has shown that there is an increased interest in using LCAs in connection with shipping. Shipping is also a part of the life cycle of many types of products. However, thus far there are no guidelines regarding the method of modelling transportation by ships in the LCAs of products. The modelling of transportation by ships is often handled arbitrarily and by people without specific knowledge of shipping. This work could be used as a basis for developing guidelines and summarising data to be used in LCAs in which shipping is only a small part of the life cycle.

5) Detailed LCAs of specific fuels and pathways

   When new fuels or specific pathways for using marine fuels are suggested or considered, it will be important to evaluate the life cycle environmental performance of those alternatives. This work can be used as a base and be modified to evaluate the specific situation involving the new fuel or pathway. Such work could be important for identifying the primary environmental impacts and possibilities for improvement associated with specific fuels or pathways.

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