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Thesis for the degree of Philosophiae Doctor

Trondheim, November 2016

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Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfilment of the requirements for the degree of Philosophiae Doctor.

The work was carried out at the Department of Marine Technology at NTNU, in Trondheim, Norway. Professors Harald Ellingsen and Ingrid Bouwer Utne from the Department of Marine Technology at NTNU were the main supervisor and co-supervisor, respectively.

NTNU funded the doctoral work. Norwegian Shipowners' Association Fund and Anders Jahre's Grant provided partial funding for attendance to conferences during the research period.

The target audience of this work include researchers and practitioners interested in the following areas: energy efficiency and emissions of fishing vessels, Norwegian fisheries, energy efficiency gap in shipping, LNG-powered vessels, Bond Graph method, institutional interactions between environmental regulations, and systems engineering.

Sepideh Jafarzadeh

Trondheim, 2016

Summary

Operation of fishing vessels is energy demanding. On one hand, fuel costs and preference of customers for buying "green" seafood products challenge economic feasibility of fisheries. On the other hand, environmental concerns and regulations further complicate the situation. All these call for an improved environmental profile within fisheries. This PhD study aims at contributing to the research body by focusing on energy efficiency and emission reduction within fisheries.

The topic of emission reduction spans across several disciplines. Different factors, such as vessel characteristics, regulations, and social aspects affect fuel consumption and air emissions of fishing vessels. As a result, this PhD study is interdisciplinary. Since the focus is on several disciplines rather than one specific area, systems thinking has dominated this study. In this way, the focus is on "the big picture" and various factors and interactions that affect energy consumption and emissions rather than on one specific factor.

First, this study focuses on reducing the air emissions indirectly by increasing energy efficiency of vessels. To set a baseline, it statistically analyses energy efficiency of Norwegian fisheries in recent years. Then, through literature review and focus groups, this study investigates barriers that prevent the adoption of energy-efficient measures that are cost-effective. A framework is also offered to assist ship owners and operators in alleviating these barriers. Then, the study focuses on increasing the knowledge of ship owners and operators about the energy efficiency of their vessels and available measures in order to facilitate their adoption. In this regard, the power system of a fishing vessel is modelled and simulated to study energy consumption for various operations.

Second, this study explores the possibility of fuelling fishing vessels by liquefied natural gas (LNG) and reducing emissions directly. In this regard, this study reviews the literature to identify pros and cons of using LNG on fishing vessels. Then, the systems engineering approach is used to increase the knowledge of ship owners, naval architects, and crew on safety and financial aspects of using LNG. The aim is to assist these stakeholders to make better-informed decisions when assessing the suitability of LNG.

The main contributions of this thesis are as follows:

- The analysis of energy efficiency in Norwegian fishing fleet,
- Providing a framework for overcoming the barriers to energy efficiency in shipping,

- Investigating interactions between environmental regulations in shipping and fishing,
- Making a decision-making support that advises on fuel consumption of vessels and effectiveness of energy-efficient measures, and
- Clarifying the technical aspects of LNG-fuelled systems, their potential implementation costs, and the expertise and training needed for operating them in a safe manner.

The results of this study show the benefit of taking a holistic view on the topic of energy efficiency and emission abatement in fisheries. In this way, "the big picture" is not lost due to focusing on a single aspect. This approach has the benefit of investigating the problem from different angles and identifying different influential elements. In addition, it highlights the interactions among these elements and their possible effects on the overall environmental performance. Such interactions may be overlooked by focusing on specific aspects.

Acknowledgments

No piece of research is feasible without direct and indirect input from others. This contribution stemmed from the existing knowledge and found its way in collaboration with other people.

I would like to start with expressing my gratitude to my supervisors, Harald Ellingsen and Ingrid B. Utne. Thanks to Harald and his family, Anne and Kari, for hosting me during my first days in Norway. It was such a perfect Norwegian start: a cabin trip. My research started with getting to know what multe (cloudberry) is and hunting for it. I am indebted to you for making me feel at home. Harald also gave me the freedom to be independent and explore the areas I found interesting. Thanks for giving me the opportunity to attend the London School of Economics and Political Science (LSE) to learn about environmental economics. Although it did not directly relate to my research, it widened my view about the economic consequences of environmental decisions. Ingrid once told me that a good PhD is a finished PhD. She always followed up my progress and provided guidance when most needed. Ingrid, you will always be my role model when it comes to organization and sticking to deadlines. Thank you for your patience and teaching me how to write scientifically. You kept reminding me that the whole PhD process, although at times frustrating, is more about learning to do research rather than contributing to science body.

I also would like to thank my co-authors. Thank you Eilif Pedersen for introducing me to Bond Graph method. Eilif always started with drawing a propeller shaft and an engine on a blank paper and continued with clearing my thoughts. Thanks Svein A. Aanondsen for fruitful discussions on energy efficiency of fishing vessels. Thanks to Emilio Notti and Antonello Sala in National Research Council of Italy, Institute of Marine Sciences, Fisheries Section (CNR-ISMAR) for answering my questions on their article and our collaboration. It was a relief in the time I was struggling to access such confidential data. Thank you also for my visit in Ancona. Thanks Nicola Paltrinieri for showing interest in my systems engineering approach to decision-making. Without your support and safety knowledge, the article would not shape.

I am also thankful to other professors, researchers, and PhD candidates who shed light on the concepts out of my expertise. Harald Valland increased my knowledge on engines. Dag Myrhaug clarified some sampling and statistical issues. Sverre Steen was approachable when I knocked on his office door with basic questions on propellers. Cecilia Haskins at the Department of Production and Quality Engineering at NTNU provided valuable suggestions on my systems engineering approach. Erwin

A. M. Schau at the European Commission took the time to answer my emails and explain his approach to evaluating energy efficiency. Anette E. Persen in the Directorate of Fisheries not only provided datasets on energy consumption of fishing vessels, but also answered my never-ending questions in detail. Dag Standal in SINTEF Fisheries and Aquaculture clarified the quota system in Norwegian fisheries. Dag Stenersen and Per M. Einang in MARINTEK increased my knowledge about liquefied natural gas (LNG). Hannes Johnson in Chalmers University of Technology and his blog introduced me to energy efficiency gap. Edgar McGuinness proofread one of my papers. Kevin K. Yum helped me with Bond Graph method. Different reviewers and editors also contributed to my work by providing feedback on my articles. I am afraid that I have left out some. Thank you all for your invaluable input.

I appreciate the assistance of administration staff, librarians, and technical staff, especially Jannike Gripp, Renate Karoliussen, and Astrid E. Hansen. They made my life much smoother than it could otherwise be. I also am grateful to the Department of Marine Technology at NTNU for funding my research. Thanks to Norwegian Shipowners' Association Fund and Anders Jahre's Grant for partially funding my attendance to conferences.

A warm thank you to all my friends at the Department of Marine Technology, especially those in Marine Systems. Without your company, loads of coffee breaks, and discussions on canteen food quality I would have less motivation to wake up in the morning and come to my office. Many thanks to my officemates, who soon became my friends: Daniel de Almeida Fernandes, Kevin K. Yum, Sandro Erceg, Jungao Wang, and Øystein Sture. I will never forget our naggings and discussions about PhD life, politics, food, music, travel destinations, and jokes. Thanks to my friends, who are spread around the world from warm, polluted Tehran to cold, clean Trondheim. We did not work together, but our café gatherings, parties, telephone calls, and long messages made my days.

I am indebted to my beloved family. Thanks to my father for his interest in books and newspapers. If he had not taken me to book exhibitions, and if he had not taught me how to bind newspapers together to make a sort of encyclopedia, I probably would never choose the PhD path. Thanks to my mother for all the games that we played on the way to school. They made my school time much more fun. Maman, thanks for letting me sit in your classes while you taught. They formed some of my best memories. Loads of thanks to my sisters: Sahar always put things in perspective and made me see PhD accomplishable. Sara believed in me more than I did. Finally, I should thank Nick for being there for me. You were the best support I could ask for.

Sepideh Jafarzadeh

Trondheim, 2016

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Nomenclature

Acronyms

AIS	Automatic Identification System
BC	Black carbon
CH_4	Methane
CO_2	Carbon dioxide
CPUE	Catch per unit of fishing effort
ECA	Emission control area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EGR	Exhaust gas recirculation
EMIP II	Energy Management in Practice II
EU	European Union
FUI	Fuel use intensity
GHG	Greenhouse gas
GT	Gross tonnage
GWP	Global warming potential
HFO	Heavy fuel oil
IAPP	International Air Pollution Prevention
IEA	International Energy Agency
IMO	International Maritime Organization
LCA	Life cycle assessment
LNG	Liquefied natural gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MBSE	Model-based systems engineering
MDO	Marine diesel oil
MGO	Marine gas oil
MOE	Measure of effectiveness
NO	Nitric oxide
N_2O	Nitrous oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
NOK	Norwegian Krone
OECD	Organization for Economic Cooperation and Development
PM	Particulate matter
R&D	Research and development
SCR	Selective catalytic reduction
SE	Systems engineering
SECA	Sulphur emission control area
SEEMP	Ship Energy Efficiency Management Plan
SO_x	Sulphur oxides

Bond Graph symbols

0	0-junction
1	1-junction
C	Capacitance
E(t)	Energy
e(t)	Effort variable
f(t)	Flow variable
GY	Gyrator
I	Inertia
MGY	Modulated gyrator
MTF	Modulated transformer
m	Transformer modulus
P(t)	Power
p(t)	Momentum
q(t)	Displacement
R	Resistance
r	Gyrator modulus
S_e	Effort source
S_f	Flow source
TF	Transformer
t	Time
Φ	A single valued function

1 Thesis structure

This doctoral thesis is written in the format of a collection of articles, commonly known as a compilation thesis. The thesis consists of two parts:

- Part I, which interrelates the articles and presents the research results in a coherent entity.
- Part II, which consists of the articles forming the backbone of this thesis.

The articles are stand-alone and can be read in any order. Although one may prefer to skip Part I and start with reading Part II, I suggest otherwise.

2 Publications

This thesis includes the following publications, the full texts of which are presented in Part II:

Article I:

Jafarzadeh, S., Ellingsen, H., Aanondsen, S.A., 2016. **Energy efficiency of Norwegian fisheries from 2003 to 2012**. Journal of Cleaner Production 112, Part 5, 3616-3630.

Contribution of authors:

I (the first author) and the second author initiated the research idea. I identified the state of the art and research gaps. On the basis of these, I defined the research approach. I obtained datasets for the years of interest and cross-related them on the basis of regulatory changes. I analysed the data statistically and presented them in a meaningful way using R language. The second and third authors provided feedback on the analysis. The third author provided additional fuel price data for comparison. I wrote the manuscript, and the co-authors supervised the work.

Article II:

Jafarzadeh, S., Utne, I.B., 2014. **A framework to bridge the energy efficiency gap in shipping**. Energy 69, 603-612.

Contribution of authors:

I initiated the research idea. The second author introduced me to Energy Management in Practice II (EMIP II) project. I identified state of the art, was involved in workshops with the participants in EMIP II project, designed the framework, and wrote the manuscript. The second author assisted in developing the research approach, was involved in the EMIP II project and in the workshops, refined the manuscript and provided feedback on the approach and arguments.

Article III:

Jafarzadeh, S., Ellingsen, H., 2016. **Environmental regulations in shipping: interactions and side effects**, ASME 2016 35^{th} international conference on ocean, offshore and Arctic engineering (OMAE2016). ISBN: 978-0-7918-4998-9. Paper No. OMAE2016-54646. Busan, South Korea.

Contribution of authors:

I initiated the research idea, reviewed the available information, and wrote the manuscript. The co-author supervised the work.

Article IV:

Jafarzadeh, S., Pedersen, E., Notti, E., Sala, A., Ellingsen, H., 2014. **A bond graph approach to improve the energy efficiency of ships**. ASME 2014 33^{rd} international conference on ocean, offshore and Arctic engineering (OMAE2014). ISBN: 978-0-7918-4551-6. Paper No. OMAE2014-24026. San Francisco, California, USA.

Contribution of authors:

I and the last author initiated the research idea. I modelled the system, simulated it, and wrote the manuscript. The second author supervised the modelling and provided feedback on the results and arguments. The third and fourth authors provided data input for analysis. The third author provided feedback on the use of data and results.

Article V:

Jafarzadeh, S., Ellingsen, H., Utne, I.B., 2012. **Emission reduction in the Norwegian fishing fleet: Towards LNG?** The 2^{nd} international symposium on fishing vessel energy efficiency (E-Fishing), Vigo, Spain.

Contribution of authors:

I and the second author initiated the research idea. I reviewed the available information and structured them. I wrote the manuscript. The second and third authors supervised and gave feedback on the work.

Article VI:

Jafarzadeh, S., Paltrinieri, N., Utne, I. B., Ellingsen, H. **LNG-fuelled fishing vessels: a systems engineering approach**. (Accepted for publication in Transportation Research Part D: Transport and Environment)

An earlier version of this article was presented in the 12th international marine design conference (IMDC2015): Jafarzadeh, S., Paltrinieri, N., Ellingsen, H., 2015. Decision-making support for the design of LNG-propelled fishing vessels, 12th international marine design conference (IMDC2015). ISBN: 978-4-930966-04-9. Paper No. 9-A-2. Tokyo, Japan.

Contribution of authors:

I initiated the research idea. The research idea was further evolved through inputs from the second and third authors. I gathered data, carried out modelling, and performed cost analysis. I wrote the manuscript, except for Sections 2.3 and 4.4.2, which were written in collaboration with the second author. The third author assisted in developing the research approach, refining the manuscript and provided feedback on the approach and arguments. The second and fourth authors provided feedback on the work.

Part I

Main Report

3 Introduction

Global fisheries contributed to approximately 1.2% of worldwide oil consumption in 2000. This value is presumably an underestimate, given that energy inputs for the provision of fuel, vessels, and fishing gears are not considered (Tyedmers et al., 2005). In Norwegian waters[1], fishing vessels contributed to approximately 10.2% of fuel consumption of ships in 2013 (DNV GL, 2015). Considering the shares of passenger ships (22.3%) and offshore supply vessels (15.7%), fishing vessels were the third most fuel consuming shipping segment in Norway.

Fuel is one of the primary costs associated with fishing, and its proportion varies among fisheries (Sumaila et al., 2008). Different factors, such as target species, the status of fish stocks, fish quotas, harvesting methods, the distance to fishing grounds, fleet age/condition, and fuel subsidies/taxes affect fuel consumption and fuel cost. Larger vessels in general are more dependent on fuel prices because fuel is a larger proportion of their operational costs. For small vessels, labour is more than half of the operational costs (STECF, 2013). However, there are some exceptions: for example, purse seiners and pelagic trawlers are energy efficient (Parker and Tyedmers, 2015; Schau et al., 2009) and more flexible in response to fuel prices, despite their large sizes (Table 1).

In 2013, fuel and lubrication oil accounted for approximately 14% and 13% of the operational costs for an average Norwegian demersal and pelagic vessel, respectively (Directorate of Fisheries, 2015). The high share of labor costs in Norway (i.e., approximately 39% and 34%, respectively (Directorate of Fisheries, 2015)) might have overshadowed the share of fuel costs. Moreover, the majority of the Norwegian fishing fleet is formed by small vessels, which can bias the results. For example, the corresponding value for Norwegian cod trawlers in 2012 ranged from 13–41% (with the average of 22%), while the overall value for the fleet was 10% (my calculations based on the dataset received from the Directorate of Fisheries) (Table 1).

Seafood consumers and other relevant stakeholders are becoming aware of the environmental consequences of fishing, and they increasingly request environmental information to select green seafood products. Therefore, the environmental impacts of seafood products may influence the market shares (Fet et al., 2010). Conventional fishery research has addressed the direct environmental effects of fishing, such as decreasing the size of target fish stocks, the effects on bycatch stocks, ghost fishing, and the effects of bottom trawlers on the seabed. Until recently, the indirect environmental effects of fishing have been underestimated, and they are related to

[1] Norwegian waters include the Norwegian economic zone, fishery protection zones around Svalbard and Jan Mayen, the Loop Hole (i.e., Smutthullet) in the Barents Sea, and the Banana Hole (i.e., Smutthavet) in the Norwegian Sea (DNV GL, 2015).

the use of fossil fuels, antifouling substances, and refrigerants on fishing vessels, among other things (Schau, 2012; Winther et al., 2009).

Global fisheries emitted approximately 134 million tonnes of carbon dioxide (CO_2) in 2000 (Tyedmers et al., 2005). This value is presumably an underestimate as it only reflects emissions from energy use and excludes greenhouse gas (GHG) emissions from refrigerants on board (FAO, 2012). In addition, fishing vessels emit sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) (Lin and Huang, 2012). As a part of its efforts to limit adverse health and environmental impacts of shipping, the International Maritime Organization (IMO) has enforced regulations to control SO_x, NO_x, GHG, and PM emissions. In addition, some countries impose additional regulations to control emissions further.

The large amount of fuel consumption combined with the associated fuel costs, environmental concerns, and emission regulations call for an improved environmental profile within fisheries, which motivates the work in this thesis.

The remainder of Part I of this thesis is organized as follows: Section 4 presents the regulations imposed on emissions of air pollutants from ships. Section 5 presents the available measures for compliance with these regulations. Section 6 gives an overview of the relevant research background. Section 7 presents the research questions that form the basis for this study. Section 8 sets forth the research objectives. Section 9 explains the research methodology and some thoughts on the research approach. Section 10 presents the research methods. Section 11 states the contributions from different articles. Section 12 discusses the findings. Section 13 presents the conclusions. Finally, Section 14 suggests future work.

Table 1. Share of fuel cost for different fisheries

Fishery, year	Fuel cost/ operational costs (%)	Source
Italian fishing fleet, 2011	38	(STECF, 2013)
54 fishing fleet segments in Europe (aggregated), 2008	29	(Cheilari et al., 2013)
European demersal/beam trawlers, 2008	50	(Cheilari et al., 2013)
European artisanal fleet, 2008	5	(Cheilari et al., 2013)
Commercial fisheries in Hong Kong, 2007	60	(Sumaila et al., 2007)
Australian abalone harvested by divers, 2012	3	(Parker et al., 2015a)
Australian Torres Strait prawn harvested by bottom trawlers, 1993–2008	51	(Parker et al., 2015a)
Norwegian shrimp trawlers, 1980–2005	35 *	(Schau et al., 2009)
Average Norwegian demersal vessels, 2013	14	(Directorate of Fisheries, 2015)
Average Norwegian pelagic vessels, 2013	13	(Directorate of Fisheries, 2015)
Average Norwegian cod trawlers, 2012	22	This thesis
Average Norwegian vessels, 2012	10	This thesis

* Fuel cost/operational revenues (%)

4 Environmental regulations

In 1997, the Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted to control air pollution from ships. These regulations entered into force in 2005. MARPOL Annex VI, among other things, aims at a progressive reduction in SO_x, PM, and NO_x emissions globally and more stringently in designated emission control areas (ECAs). The Baltic Sea and North Sea are Sulphur ECAs (SECAs). North American and United States Caribbean Sea areas are ECAs for NO_x in addition to SO_x. In 2011, MARPOL Annex VI was revised to control GHG emissions (DNV GL, 2014; IMO, 2013b, 2015a). In some countries, there may be additional regulations to control these emissions further.

After pointing out adverse health and environmental impacts of different emissions, this section elaborates on the relevant environmental regulations for the fishing fleet.

4.1 SO_x regulations

Bunker fuel is rich in sulphur. When an engine burns fuel, the remaining sulphur converts into SO_x, which is an acidic gas. The emissions of SO_x cause irritations to eyes, nose, and throat and can result in breathing difficulties. From an environmental perspective, it contributes to acid rain, which can adversely affect plants, aquatic animals, and infrastructure (Cullinane and Cullinane, 2013).

SO_x regulations set following stepwise limits for sulphur contents of fuel oils. Commencement dates are shown inside the parentheses (IMO, 2014c):

- Global sulphur limitations
    - Global cap from 4.5%[1] to 3.5% (1.1.2012)
    - Global cap from 3.5% to 0.5% (1.1.2020- A feasibility review in 2018 may postpone this to 2025.)
- Sulphur limitations in SECAs
    - Limitation from 1.5% to 1.0% (1.7.2010)
    - Limitation from 1.0% to 0.1% (1.1.2015)

These regulations apply to all ships. Vessels of 400 gross tonnage (GT) and above require an International Air Pollution Prevention (IAPP) Certificate to show their compliance with these regulations. This certificate shows whether the ship uses fuel oil with a sulphur content that does not exceed the applicable limit value as documented by bunker delivery notes or uses an approved equivalent arrangement.

[1] The sulphur limits are expressed in % m/m, which is percent by mass.

Flag States may establish other measures to ensure compliance of smaller vessels (DNV, 2008; Hop, 2016; IMO, 2013b, 2014a).

There may be additional regulations in some regions. For example, the European Union (EU) has introduced stricter sulphur limits for marine fuel. While regarding MARPOL Annex VI the latter global cap is subject to a review in 2018, the EU is firmly bound to implementation in 2020. Besides, in Europe passenger ships sailing outside SECAs have to respect a sulphur limit of 1.5%, which was set in 2005. Ships in the EU ports should use fuels with maximum 0.1% sulphur if they do not use shore-side electricity. This requirement, which came into force in January 2010, applies to any ship type with any use of fuel (e.g., in auxiliary engine) (T&E, 2015). Within the Regulated California Waters (i.e., 24 nautical miles of the Californian coastline), the sulphur content is not allowed to exceed 0.1% since January 2014 (DNV GL, 2014).

In Norway, fishing in distant waters is exempt from SO_x tax. However, fishing in Norwegian coastal waters (i.e., within 250 nautical miles ashore) is subject to SO_x tax. The tax rate depends on the sulphur content of the fuel. In 2016, the tax rate starts from 0.133 Norwegian Krone (NOK) per liter for mineral oils with 0.05–0.25% sulphur and increases up to 2.13 NOK/L for mineral oils with 3.75–4.00% sulphur. Liquefied natural gas (LNG) fuel is exempt from this tax (Norwegian Directorate of Taxes, 2016).

4.2 NO_x regulations

Nitrogen is a natural element in the atmosphere and is also found in the chemical structure of some fuels. During the fuel combustion process, NO_x, which is a collective term for nitric oxide (NO) and nitrogen dioxide (NO_2), is produced. NO_x is formed in three ways:

- Thermal formation, as a result of the reaction between atmospheric nitrogen and oxygen at high temperatures,
- Fuel formation, as a result of the reaction between nitrogen in the fuel and oxygen, and
- Prompt formation, as a result of complex reactions of hydrocarbons and atmospheric nitrogen.

The largest component of NO_x is formed through the thermal formation. Long-term exposure to NO_x can cause respiratory problems. From an environmental perspective, it contributes to acid rain and photochemical smog (Cullinane and Cullinane, 2013; LR, 2012b, 2015).

MARPOL Annex VI imposes three tiers of control to regulate NO_x emissions. These tiers are based on ship construction date. NO_x cap within each tier depends on engine speed (Table 2) (IMO, 2014b).

Table 2. Nitrogen oxides (NO_x) limits (based on IMO (2014b))

Tier	Ship construction date	NO_x cap (g/kWh)		
		n* < 130	130 ≤ n < 2000	n ≥ 2000
I	1.1.2000	17.0	$45 \times n^{-0.2}$	9.8
II	1.1.2011	14.4	$44 \times n^{-0.23}$	7.7
III**	1.1.2016	3.4	$9 \times n^{-0.2}$	2.0

* 'n' represents rated speed of engine in rpm.
** Only applies to emission control areas (ECAs). Outside ECAs, Tier II holds.

These regulations apply to marine diesel engines of over 130 kW output power other than those used solely for emergency purposes. These regulations are applicable irrespective of the tonnage of the ship onto which such engines are installed. Vessels of 400 GT and above require an Engine IAPP Certificate to show their compliance with these regulations. Flag States may establish other measures to ensure compliance of smaller vessels (DNV, 2008; Hop, 2016; IMO, 2014b).

In 2012, the Gothenburg Protocol was revised to set, among other factors, NO_x ceilings for 2020. Norway ratified this protocol (UNECE, 2014). To comply with the Gothenburg Protocol, Norway introduced a NO_x tax in 2007. The NO_x tax applies to different sectors, including domestic shipping and fishing. In 2008, the Norwegian state and 14 business organisations reached a NO_x agreement for the 2008–2010 period. Later, the same members and an additional business organisation signed a NO_x agreement for 2011–2017. As a part of the agreement, the involved parties cofounded a NO_x fund, and they pay a smaller amount to the NO_x fund instead of the tax when emission-reducing measures are implemented. The fund supports NO_x-reducing measures in addition to covering administrative costs. The Norwegian Fishermen's Association, the Norwegian Fishing Vessel Owners' Association, and the Norwegian Seafood Federation are among the cooperating organisations (EFTA Surveillance Authority, 2011; Høibye, 2012; NHO, 2013; Åsen, 2013).

4.3 GHG regulations

Gases that trap heat in the atmosphere are called GHGs. The combustion of fossil fuels produces various GHG emissions, such as CO_2, methane (CH_4), and nitrous oxide (N_2O). In general, emissions of CO_2 are a function of the carbon content of the fuel. CH_4 can be produced when the hydrocarbons in fuels are not completely combusted. The CH_4 content of the fuel, the engine type, the amount of non-combusted hydrocarbons passing through the engine, and post-combustion emission controls influence CH_4 emissions. N_2O is produced during fossil fuel combustion when nitrogen in the air or fuel is oxidized in the high temperature environment of the engine. N_2O emissions are likely to be affected by fuel type and engine type (Jun et al., 2002; Smith et al., 2014).

$GWP_{x,T}$ stands for the global warming potential of substance x in time horizon T. GWP is a relative measure of the amount of heat a GHG traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question (i.e., x) to the amount of heat trapped by a similar mass of CO_2. GWP is calculated over a specific time interval (i.e., T), commonly 20, 100 or 500 years. GWP is expressed as a factor of CO_2 whose GWP is standardized to 1 (Goedkoop et al., 2009). CO_2 is the primary direct GHG emitted from navigation (Smith et al., 2014). However, CH_4 is estimated to have a GWP of 28–36 times that of CO_2 for a 100-year timescale. N_2O has a GWP of 265–298 over 100 years (EPA, 2015).

Climate change has different effects on human health. Some direct effects are heat waves; whereas, infectious diseases and social and economic disruption are among its indirect effects. Climate change can also affect ecosystem diversity, for example, through loss of species (Goedkoop et al., 2009).

MARPOL Annex VI aims at reducing GHG emissions via improving energy efficiency. In general, energy efficiency refers to using less energy to produce the same amount of service or useful output. Energy efficiency is a generic term, and there is no single measure to quantify it. Different indicators may be used to show energy efficiency. Most indicators show the ratio of useful output to energy input. The issue then becomes how to precisely define useful output and energy input. However, IMO uses an indicator that shows the reverse: it shows the environmental impacts of energy input per useful work done in shipping. In other words, if this indicator increases, the efficiency reduces and vice versa. MARPOL Annex VI offers two tools for enhancing energy efficiency: the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) (Ekanem Attah and Bucknall, 2015; IMO, 2013a). Their effectiveness, however, is under scrutiny (Devanney, 2011; Johnson et al., 2013).

The EEDI is a technical measure that sets minimum energy efficiency levels per capacity mile for new builds. It is a formula to calculate CO_2 emissions per transport work (i.e., tonne-nautical mile) at a specific operating point. The actual EEDI of a vessel must be below a prescribed baseline value for the corresponding ship type and size. By tightening the baseline values gradually, EEDI is expected to stimulate the adoption of energy-efficient equipment and designs (IMO, 2015a). EEDI does not apply to fishing vessels currently, but it may apply in the future (Bazari and Longva, 2011; Hop, 2016). Some ships, such as fishing vessels are not designed for cargo transportation. In such cases, transport work is not appropriate to express their service. Therefore, the unit in which EEDI is measured needs modification to address some ship types and sizes (Buhaug et al., 2009).

The SEEMP, which applies to fishing vessels of 400 GT and above (Hop, 2016), aims at improving the energy efficiency of ship operations. The SEEMP is a ship specific document to keep onboard the ship. It contains measures identified by the ship owner, which can improve efficiency, such as speed optimization and hull maintenance. This document is reviewed on a regular basis to check its impact on efficiency. An Energy Efficiency Operational Indicator (EEOI) can monitor the progress of the SEEMP (IMO, 2015a; LR, 2012a).

Additionally, the Kyoto Protocol covers domestic shipping. In 2012, the Doha Amendment to the Kyoto Protocol was adopted to reduce GHG emissions of involved countries, including Norway, during the new commitment period of 2013–2020 (UNFCCC, 2014).

Norwegian fishing vessels are either exempt from or refunded for basic tax on mineral oil (i.e., "grunnavgift" in Norwegian). Fishing in distant waters is also exempt from CO_2 tax in Norway. However, in 2016, fishing in Norwegian coastal waters is subject to 0.28[1] NOK per liter fuel for CO_2 emissions. LNG fuel is exempt from this tax (GFF, 2016; Norwegian Directorate of Taxes, 2016).

4.4 PM regulations

PM emissions from ships include three main types of particles (Di Natale and Carotenuto, 2015):

- Mineral ashes, which are usually between 200 nm and 10 μm,
- Sulphates and in minor fraction nitrates together with associated water, which are usually in micrometre range, and
- Soot particles, which are largely in the submicron (<1 μm) and ultrafine (<200 nm) range.

Sulphates account for 80% of emissions' weight. Including ashes, this percentage increases to 85%. However, considering the particles' numerical concentration, soot particles dominate the emissions. Among PM emissions, soot particles are the most toxic. Even in low doses, chronic exposure to soot particles may lead to respiratory pathologies, such as bronchitis and asthma. Besides, soot particles include black carbon (BC), which is an important climate-forcing agent. BC is created through incomplete combustion of carbon-based fuels (Di Natale and Carotenuto, 2015; Lack et al., 2012).

BC has a darkening effect when deposited on snow and ice. This effect reduces albedo (i.e., reflection coefficient), which enhances melting in the Arctic (Flanner et al., 2007). In 2012, fishing vessels were the main emitters of BC among Arctic ships (i.e., with a 45% share). Although these vessels have low speed during fishing, they need additional engine power to capture, process, and pack fish. Consequently, their fuel consumption and BC emissions increase. In the Arctic, the fishing activities and emissions are mainly coastal and highest along the Norwegian coast and around Faroe islands, Shetland islands, and Iceland (Winther et al., 2014).

To date, there are no specific regulations regarding PM emissions from shipping. However, SO_x regulations of MARPOL Annex VI indirectly reduce coarse particles, which are related to ashes and sulfur in the fuel. Recently, attention is growing on the role of PM, and in particular BC, on the Arctic climate. Eventually, IMO started a

[1] Upon bunkering, coastal fishing vessels pay 0.92 NOK/L for CO_2 tax. Later, they can be refunded for 0.64 NOK/L. Therefore, the net value paid is 0.28 NOK/L (GFF, 2016).

panel to investigate the amount of BC emissions and possible mitigation strategies (Di Natale and Carotenuto, 2015).

5 Regulatory compliance

This section gives an overview of different technical and operational measures for complying with the environmental regulations imposed on shipping (Section 4).

5.1 SO_x abatement

Norwegian fisheries mainly consume marine gas oil (MGO), which is a distillate fuel. MGO has a low sulphur content compared to heavy fuel oil (HFO), which is the residual oil from crude oil refineries. Worldwide, sulphur content of MGO ranges from below 0.1 to 1.5% (Vermeire, 2012). IMO monitors sulphur content of marine fuels. A sample of distillate fuels in 2014 (i.e., 37973 samples) had on average 0.12% sulphur content. Sulphur content of a sample of residual fuels in 2014 (i.e., 153719 samples) ranged from below 0.5 to above 3.5%. The average sulphur content for the sample was 2.46% (IMO, 2015b). As mentioned in Section 4.1, the vessels operating in SECAs are required to use fuels with maximum 0.1% sulphur content since 2015 (IMO, 2014c).

Despite using cleaner fuels, such as MGO, Norwegian fishing vessels consume large amounts of fuel and contribute largely to emissions. For example, from 2003 to 2012, Norwegian factory trawlers consumed on average 412 liters of fuel for catching one tonne of fish (Jafarzadeh et al., 2016). Demersal trawlers that target crustaceans consume even more fuel. In some regions, fishing vessels may be more energy intensive than the Norwegian vessels (Parker and Tyedmers, 2015). In addition, some large fishing vessels run on high sulphur HFO. Therefore, still there is room and motivation for reducing these emissions for environmental reasons.

There are three main ways for meeting sulphur requirements: (i) switching to fuels with the required sulphur content, (ii) cleaning the exhaust gases to reduce SO_x emissions, and (iii) consuming less fuel and, consequently, emitting less SO_x.

5.1.1 Alternative fuels

HFO can be further processed to reduce its sulphur. However, standard low sulphur bunker fuel cannot meet emission caps in SECAs. Therefore, it should be used in tandem with an abatement technology (e.g., scrubber). Alternatively, distillate fuels, such as MGO and marine diesel oil (MDO) can be utilized. Switching from HFO to MGO or MDO upon entrance to SECAs, although possible, may raise some challenges. For instance, the two fuels have different operating temperatures. The changeover can cause a rapid temperature fall and, consequently, a thermal shock if not handled properly. In addition, there are concerns about the capacity of the refining industry to supply the future demand for low sulphur fuel. Rising demand is also expected to increase the price uncertainty of low sulphur fuel (Cullinane and Cullinane, 2013; DNV, 2011; DNV GL, 2014).

Alternatively, other fuels with low sulphur content, which are not crude oil based, can be used. LNG is an option. LNG-fueled engines emit negligible amounts of SO_x and PM. However, for a similar energy content, LNG requires larger tanks in comparison to MDO. New-built LNG-fuelled ships require 20–25% more capital investment compared to oil-fuelled vessels. Converting an existing oil-fuelled vessel is even more expensive. Therefore, LNG seems more feasible for new builds. Although different views exist on future price of LNG, most studies are positive about its future price advantage (Wang and Notteboom, 2014). LNG may also offer lower maintenance costs. Possible fuel or emission taxes, such as the NO_x tax in Norway can increase economic interest in LNG. Solving current bunkering problems can also foster its adoption (DNV, 2011; Wang and Notteboom, 2014). Norway and other Scandinavian countries were the pioneers in developing the LNG bunkering infrastructure in ECAs (Aymelek et al., 2014). As of 2015, 9 LNG bunkering terminals existed on the Norwegian coastline. In addition, 12 industrial terminals were prepared for ship bunkering in Norway. Some of these terminals are suitable for bunkering specific ships and have limited functionality (EGN, 2015). With the exception of Norway, the adoption of LNG fuel in Europe is still in its infancy stage. Ship owners may postpone their investment and conversion plans due to missing LNG supply at their preferred ports of call. A lack of bunkering infrastructure along shipping routes causes economic challenges due to allocating cargo space to larger LNG tanks. In addition, the lack of consistency in bunkering procedures, forces ship owners to comply with different procedures and technical requirements in different ports of call (European Commission, 2013).

Other fuels, such as methanol and biofuels can also reduce SO_x emissions. For further information, see Cullinane and Cullinane (2013) and Brynolf et al. (2014).

5.1.2 Cleaning exhaust gases

Another measure to reduce sulphur emissions is using exhaust gas cleaning systems, commonly known as scrubbers. There are two main types of scrubbers: (i) wet scrubbers that use seawater or freshwater as the scrubbing medium and (ii) dry scrubbers that use a dry chemical.

There are three types of wet scrubbers: (i) open loop, (ii) closed loop, and (iii) hybrid. In open loop scrubbers, exhaust gas is directed into towers where seawater is pumped. Open loop scrubbers remove SO_x by utilizing the natural alkalinity of seawater and discharge the treated seawater into the sea. Closed loop scrubbers use fresh water with the addition of an alkaline chemical. The wash water from the closed loop scrubber passes through a process tank where it is cleaned before being recirculated. A tank collects the residual waste. Although closed loop scrubbers use less energy and are cheaper than the open loop alternatives, they are slightly more complex. A hybrid scrubber can operate in both open loop and closed loop modes. The hybrid alternative is even more complex as it requires tanks, caustic soda, and increased power (LR, 2012b; Petrospot, 2014).

Dry scrubbers bring the exhaust gas in contact with calcium hydroxide granules. Following the reaction, SO_x emissions are reduced. Unlike wet scrubbers, dry scrubbers do not require wash water treatment systems and their associated pipework and tankage. However, they need to store and handle consumables. Used granules must also be stored before disposal ashore (LR, 2012b).

5.1.3 Consuming less fuel

Another measure for reducing SO_x emissions is to reduce fuel consumption. While some energy-related studies focus on energy conservation, others address energy efficiency (Moezzi, 2000). In other words, while energy conservation aims at decreasing the consumed energy by reducing the demanded output, energy efficiency addresses using less energy to produce the same amount of useful output (Croucher, 2011). Energy conservation and energy efficiency should be considered simultaneously as improvement in energy efficiency may lead to increased ship speed instead of reduced fuel consumption (Faber et al., 2011). In other cases, increased energy efficiency may be followed by increased fuel consumption, which is referred to as the 'rebound effect'. This effect may outweigh the savings that could be gained (Sorrell, 2014; Sorrell and Dimitropoulos, 2008). Although fish quotas limit fishing efforts, potential disadvantages should be considered when developing future strategies to improve fuel efficiency.

5.2 NO_x abatement

The major component of NO_x emissions of ships is NO. As thermal formation is the principal mechanism by which NO is produced (Section 4.2), it is not possible to effectively reduce NO_x emissions by controlling the fuel consumed. Thermal formation is dependent on temperature, exposure time of the combustion gases to high temperature, and available oxygen. The rate of formation rises exponentially above 1500°C. There are two ways to reduce thermal NO_x emissions: (i) to reduce the formation of NO (i.e., primary control) and (ii) to treat exhaust gas (i.e., post-combustion abatement) (LR, 2012b).

Tier II limits under MARPOL Annex VI (Section 4.2) can be met using primary controls. These controls in general aim at reducing the combustion temperatures, the exposure time to high temperatures, and/or oxygen content in the combustion zone. Some measures focus on engine design and modify fuel injection, valve timing, etc. Some others include different 'wet' technologies: water-in-fuel, water sprays into the charge air (humid air motor), etc. (LR, 2012b).

With conventional fuel oils, Tier III limits (Section 4.2) are only achievable through (i) selective catalytic reduction (SCR) and (ii) exhaust gas recirculation (EGR). SCR is a post-combustion abatement technology. SCR systems inject urea into the hot exhaust gas to trigger its reaction with NO_x. Harmless nitrogen and water form as a result (LR, 2012b).

EGR systems recirculate a portion of the exhaust gas back to the cylinders with the charge air. This reduces oxygen content of the mixture and, consequently, peak combustion temperature. In this way, EGR systems control NO_x formation. As such, EGR better fits in primary controls rather than post-combustion abatement technologies (LR, 2012b).

To meet Tier III limits, other fuels, such as LNG can also be used. LNG emits up to 90% less NO_x compared to HFO due to reduced peak temperature in combustion process (Buhaug et al., 2009). However, this depends on the engine design. A pure gas Otto or Miller cycle engine can comply with Tier III caps; however, a gas engine based on Diesel cycle, which uses oil pilot ignition, cannot. Nevertheless, the latter still emits less NO_x compared to conventional oil-fueled engines (LR, 2015).

5.3 GHG abatement

Buhaug et al. (2009) suggest four options for reducing GHG emissions from shipping:

- Improving energy efficiency, which applies to both design and operation of ships,
- Using renewable energy sources, such as wind and sun,
- Switching to fuels with less emissions per unit of work done, such as biofuels and natural gas, and
- Using emission abatement technologies, such as chemical conversion.

Although the last measure is technically possible, it is not feasible. This is due to the large amount of GHG emissions and lack of space on ships. Therefore, such technologies are mainly of interest for other emissions, such as SO_x and NO_x (Buhaug et al., 2009).

5.3.1 Energy efficiency

Ship design can be modified to improve energy efficiency. Such modifications are mainly suitable for new builds. Speed, size, and draught, among other things, influence energy efficiency significantly. In addition, operational environment of a ship may change during its lifetime. Flexibility to allow efficient operation in different scenarios should be taken into account. The design point for optimization should be as relevant as possible to actual ship operation. The power generation system can also be modified to increase energy efficiency. For instance, in cases with variable operational profile, diesel-electric propulsion can be used. However, electric propulsion introduces transmission losses that must be recovered. As another example, exhaust gas recovery systems can enhance energy efficiency (Buhaug et al., 2009).

It is possible to save fuel through more conscious and optimal operation of ships. Fleet management (e.g., through traffic management), voyage optimization (e.g., through weather routing), and energy management (e.g., through monitoring fuel consumption) are possible solutions in this regard (Buhaug et al., 2009). In the case of fisheries, energy efficiency of a vessel, among other things, depends on the fishing method. For instance, purse seiners consume less energy compared to demersal trawlers for catching the same amount of fish (Schau et al., 2009).

5.3.2 Renewable energy sources

Different technologies, such as kites can exploit wind energy, which is more attractive in some regions than others. There is limited experience with such technologies on large vessels; nevertheless, wind has a potential for energy saving as a supplementary source of energy (Buhaug et al., 2009; Cullinane and Cullinane, 2013).

Considering the present technology, solar energy can only cover a small portion of total energy requirements. Therefore, solar energy is mainly interesting as a complementary source of energy (Buhaug et al., 2009).

5.3.3 Alternative fuels

To reduce GHG emissions, alternative fuels, such as biofuel, methanol, hydrogen, and LNG can be used. Among these alternatives, LNG is progressively getting more attention. Due to its higher hydrogen-to-carbon ratio than diesel, LNG emits approximately 25% less CO_2. However, methane, which has a stronger GWP than CO_2 (Section 4.3), may leak during production, transportation, and use of natural gas. This consequently can offset some of the benefits gained from switching to LNG in a life cycle perspective (Bengtsson et al., 2011; Brynolf et al., 2014; Buhaug et al., 2009; Chryssakis et al., 2015; DNV, 2011; LR, 2015; Wang and Notteboom, 2014). Most LNG-fueled engines operate on Otto cycle, which results in methane slip of 2–3%. However, a total methane leakage of 5.5% from the whole life cycle would make GHG emissions of LNG equivalent to the corresponding value for diesel fuel (Chryssakis et al., 2015).

5.4 PM abatement

All regulations on fuel quality are currently motivated by reducing SO_x and particulate sulphates. In other words, a reduction in SO_x emissions will decrease coarse particles, which are related to the sulphur and ashes in the fuel. However, finer particles are related to both fuel properties and combustion process. Few studies have investigated the impact of fuel quality on emissions of finer particles, such as BC. The possible effects of different components of the residual fuel on combustion conditions and, consequently, on BC formation are not well understood. According to Lack and Corbett (2012), the majority of studies suggest that distillate fuels decrease BC emissions: lower concentrations of sulphur, ash, or high molecular weight atomic hydrocarbons in distillate fuels increase combustion efficiency and, consequently, reduce BC. However, CIMAK (2013) criticizes this conclusion. Ristimaki et al. (2010) suggest that oxidative ability of heavy metals (e.g., vanadium and nickel) in residual fuel can decrease BC production.

Exhaust scrubbing can also reduce SO_x and coarse particles. However, their effectiveness in reducing smaller particles, such as BC is uncertain. For example, the effectiveness of wet scrubbers in removing BC emissions is uncertain, as BC particles may be hydrophobic or hydrophilic. Based on current studies, scrubbers can remove 25–70% of BC emissions from marine diesel engines, depending on sulphur content and scrubber design (Lack and Corbett, 2012). This removal rate is within the range Lack and Corbett (2012) present for switching from residual fuels to distillate fuels.

Apart from using distillate fuels or scrubbers, the following measures may decrease finer particles: (i) reducing fuel consumption through improved ship design or operation, (ii) improving engine performance and using cleaner alternative fuels, and (iii) cleaning exhaust gas (e.g., for ultrafine particle capture) (Di Natale and Carotenuto, 2015). For example, switching to LNG can reduce BC (Lack et al., 2012).

6 Research background

The topic of air emissions in shipping, including fishing, is rather broad. Several studies from various disciplines have contributed to the research body. Therefore, the intention of this section is to present an overview of relevant literature rather than an extensive literature review. The studies are organized based on their subjects, and within each subject, some of the most relevant studies to this thesis are included.

Section 6.1 explains different methods for modelling emissions from shipping. Although this thesis does not focus on emission modelling, the approaches taken for estimating energy consumption, and consequently emissions, are relevant. Section 6.2 sets forth the common practices for evaluating energy consumption and emissions of fisheries. Section 6.3 briefly presents the literature on the reasons for not adopting available energy-efficient measures that are cost-effective. As few studies have addressed this issue in shipping, this sub-section mainly relies on the available literature elsewhere. Section 6.4 briefly presents the literature on interactions among environmental regulations in shipping. Section 6.5 gives an overview of the systems perspective on energy. While Section 6.1 focuses on energy and emission estimation in the whole fleet or some segments of it, Section 6.5 focuses on energy analysis of one specific vessel. In other words, the studies in Section 6.1 aim at generalizing results and making broader conclusions for a fleet segment, while the studies in Section 6.5 aim at a better understanding of energy flow within a vessel by going into details. Section 6.6 presents literature on the use of LNG as a marine fuel since this technical measure is progressively getting more attention due to its environmental benefits.

6.1 Emission modelling

Several studies estimate emissions of air pollutants from shipping. These studies follow either one or a combination of two approaches. Both approaches estimate fuel consumption and multiply the result by emission factors. Their difference is in the way they estimate fuel consumption. The top-down or fuel-based approach uses bunker sales as a basis for estimating fuel consumption. The bottom-up or activity-based approach estimates fuel consumption based on ship activity.

The availability and accuracy of fuel data specify the approach to use; however, there are cases where intermediate approaches are favored. In any case, the accuracy of emission estimations also depends on the accuracy of emission factors. These factors show the ratios of emissions produced per unit fuel consumed, and they depend on fuel type (e.g., in the case of CO_2), sulphur content of fuel (for SO_x), and engine (for NO_x). Different sources, such as national authorities, estimate emission factors. In shipping, bottom-up estimates are higher than equivalent top-down estimates. These differences further complicate the overall uncertainty of estimating emissions (Kontovas and Psaraftis, 2016; Zis et al., 2015).

6.1.1 Top-down approach

The top-down method relies on fuel sales and assumes that the worldwide sales of bunker fuel represent total fuel consumption. Different sources, such as the International Energy Agency (IEA) provide data on fuel sales. Corbett et al. (1999) applied the top-down approach to estimate global NO_x and SO_x emissions from ships in 1993. In 2000, IMO published the first study on GHG emissions in shipping based on this approach (Skjølsvik et al., 2000).

If fuel data were reliable, emission estimates based on this method were the most accurate. However, this may not be the case (Kontovas and Psaraftis, 2016). For instance, although the IEA provides global energy data, since non-member countries are not obliged to follow the IEA's accounting methodologies, data for non-member countries may be less accurate (Buhaug et al., 2009). To be a member of the IEA, a country must also be a member of the Organization for Economic Cooperation and Development (OECD). However, the opposite does not hold. For example, at present some countries, such as Iceland and Mexico are not members of the IEA despite their memberships in the OECD. Currently, the IEA consists of 29 member countries, including Norway (IEA, 2015), while the OECD has 34 members (OECD, 2015b).

The accuracy of the IEA data for fishing vessels is uncertain. For instance, in 2005 the OECD countries reported 99% of global fuel consumption in fishing. This could be due to different reasons: the non-OECD countries may report fuel sales to fishing in other categories of ship fuel, or they may simply not report it. It is also possible that they report it in a non-shipping category, such as forest and agriculture, which was previously the case in the OECD countries (Buhaug et al., 2009). Besides, based on where domestic shipping and fishing buy fuel, the purchase may or may not be captured in the IEA marine bunkers. For instance, fishing vessels may purchase fuel at locations where also other sectors buy fuel. This may result in misallocation (Smith et al., 2014).

6.1.2 Bottom-up approach

When fuel data are either unavailable or unreliable, the bottom-up method may be used. In this approach, emission estimations are based on shipping activity and the contribution of individual vessels to the whole fleet. First, fuel consumption of each vessel is estimated for different operational profiles. Then, the results for individual vessels are added up to estimate the fleet's consumption. This method is data intensive and requires technical specifications (e.g., engine power) and operational profile (e.g., sailing speed) of each vessel. Therefore, emission estimations based on this approach contain many modeling assumptions and uncertainties.

In 2009 and 2014, IMO published updated GHG studies. Using the activity-based approach, the former study (i.e., the Second IMO GHG Study) estimated global emissions from all non-military shipping activities in 2007 (i.e., total shipping). To do so, first the total installed power (kW) within each ship category was derived by multiplying the average main engine power by the number of vessels in the corresponding category. Then, the category-specific operating hours of the main engine and the average engine load factor were used to calculate annual power outtake (kWh). Finally, using the specific fuel consumption (g/kWh), the total fuel consumption and emissions were estimated for the ship category. However, this estimation did not distinguish international shipping from domestic shipping and fishing[1]. Therefore, the activity-based fishing emissions were first calculated. Then, using the top-down approach and bunker statistics of the IEA, emissions from domestic shipping were estimated. By subtracting these two values, emissions from international shipping were derived. Therefore, this study used a combination of bottom-up and top-down approaches to estimate emissions from international shipping in 2007. Considering seaborne trade and changes in freight tonne-mile, the 2007 estimate was back casted to estimate emissions in the 1990–2007 period (Buhaug et al., 2009). The latter study (i.e., the Third IMO GHG Study) applied a similar approach to the previous study for estimating emissions from total shipping. However, while the former study used average values within a ship category, the latter calculated activity, fuel consumption, and emissions for individual vessels during 2007–2012 before aggregation. In addition, until 2009 only Automatic Identification System (AIS) data from shore-based stations were available. AIS, among other things, collects ship's identity, position, and speed at a given time. Since 2009, a greater geographical coverage achieved via satellite technology has improved the quality of data available for the activity-based approach. The Third IMO GHG used a different approach for estimating emissions from international shipping. This study assumed that some vessels, such as offshore supply vessels were more likely to engage in domestic navigation rather than international shipping. In this way, the study distinguished domestic and international shipping. This study also used a top-down approach for comparison of results (Smith et al., 2014).

The coverage of fishing vessels in databases used in this approach is uncertain. For instance, some studies, such as the Third IMO GHG Study derive the vessel activity data from the AIS database. However, the AIS covers larger vessels. For instance, in 2013 roughly 1000 Norwegian fishing vessels had AIS-transmitters. As a result, the database did not cover around 5000 Norwegian fishing vessels. Although the excluded vessels were relatively small, they contributed to approximately 20% of fuel consumption from the Norwegian fishing fleet (DNV GL, 2015). Moreover, the Third IMO GHG Study covers fuel consumption of vessels that appear in the IHS

[1] In the Second and Third IMO GHG Studies, international and domestic shipping exclude military and fishing vessels. Fishing is considered as a separate group. It includes "fuel used for inland, coastal, and deep-sea fishing. It covers fuel delivered to ships of all flags that have refueled in the country (including international fishing) as well as energy that is used in the fishing industry. Before 2007, fishing was included with agriculture/forestry and this may continue to be the case for some countries" (Buhaug et al., 2009; Smith et al., 2014).

Fairplay database and have an IMO number. While this should include all ships involved in international shipping, many domestic vessels (e.g., fishing vessels) may not be covered (Smith et al., 2014).

6.2 Energy and emissions analyses in fisheries

As mentioned earlier, the top-down and bottom-up approaches that are used in shipping (Section 6.1) mainly estimate global emissions. These estimations may give a good view on emissions of merchant ships; however, their coverage of fishing vessels is questionable. In addition, fishing in its nature is different from other segments of shipping: while most segments either transport goods (e.g., container ships) or deliver a service (e.g., offshore supply vessels), fishing vessels aim at catching and, in some cases, processing fish. There are also several categories of fishing vessels: while some rely on the movement of fish towards the fishing gear (e.g., longliners), others chase target species (e.g., trawlers). In addition, fishing practices, target species, and fishing management, among other things, differ from one region to another. These complications may be the reasons for existence of a research field for investigating energy consumption of fishing vessels.

Fuel consumption of fishing vessels is the greatest share of energy consumption and greatest cause of emissions in the value chain of seafood products, except for cases with airborne transportation (Avadí and Fréon, 2013; Parker et al., 2015a). In addition, since the most energy-intensive fisheries often have the highest seafloor effect and bycatch, energy use is suggested as an indicator of the overall environmental burdens associated with fisheries (Ziegler et al., 2013). Therefore, several studies have investigated the energy consumption of fishing vessels. However, the number of studies focusing on a life cycle perspective is increasing. In fisheries, mostly the focus has been on evaluating the energy consumption of vessels per amount of catch (i.e., fuel use intensity (FUI)). Most studies investigate FUI in specific regions, with the exception of few studies that present global assessments.

6.2.1 Global energy and emission analyses

Tyedmers et al. (2005) assembled fuel consumption, catch, and vessel/gear characteristic data from more than 250 fisheries based in 20 countries, including Norway. The majority of case studies provided fuel use data for a single year; however, some provided data for several years. When case studies included time series data, only values closest to 2000 were used. Based on these data, they derived average FUI for different species globally and where possible, regionally. Afterwards, the figures were integrated with species-specific, spatially resolved catch data for 2000. In this way, they derived global fuel consumption and average FUI in 2000. They also mapped the distribution of results. Finally, CO_2 emissions from fishing vessels were quantified. Regarding their findings, in 2000, global fisheries consumed almost 50 billion liters of fuel to land approximately 80 million tonnes of fish (i.e., on average 620 liters of fuel per tonne of fish). The estimated CO_2 emissions were approximately 134 million tonnes.

Parker and Tyedmers (2015) updated these results. This time, they analyzed fisheries operating in 1990 onwards, consisting of 1126 records. They distinguished results by species (e.g., finfish), fishing gear (e.g., bottom trawls), and region (e.g., Europe). The mean and median FUI for all fisheries were 706 L/t and 639 L/t, respectively.

Parker et al. (2015b) examined fuel consumption of the world's tuna fishing fleets in 2009. More specifically, they examined purse seiners primarily targeting skipjack and yellowfin tuna. Their data collection efforts yielded fuel consumption data from 93 tuna-fishing vessels employing purse seine, spanning the Atlantic, Indian, and Pacific oceans. Purse seine tuna landings reported represented 28% of total purse seine tuna landings in 2009 and 20% of total landings of the seven major tuna species regardless of gear. Regarding their findings, purse seiners fishing tuna had an average FUI of 368 L/t.

Cheilari et al. (2013) assembled data from 54 fleet segments of seven European countries (i.e., Belgium, Germany, Denmark, France, Italy, Netherlands, and Sweden), representing one fourth of the EU fishing fleet in terms of vessel numbers and one third in terms of the volume of landings. They studied the effect of fuel price increase on economic performance and energy efficiency of the EU fishing fleet from 2002 to 2008. They realized improvements in energy efficiency, especially after 2004, when the first recent fuel price increase was observed. They concluded that increases in fuel price and operational costs created an incentive for fishermen to rationalize fuel consumption. However, they did not investigate other possible influential factors (e.g., the state of fish stocks). The FUI for 2008 was on average 670 L/t, varying from 79 L/t for pelagic trawlers and seiners to more than 3500 L/t for large beam trawlers. They estimated that in 2008, the total EU-27 fishing fleet consumed approximately 3.7 billion liters of fuel, releasing 10 million tonnes of CO_2 into the atmosphere.

6.2.2 Regional energy and emission analyses

Several studies have investigated energy consumption and emissions in different fisheries, regions, and periods.

Ziegler and Hornborg (2014) studied fuel efficiency of Swedish demersal trawlers in the 2002–2010 period. Results showed an improvement in the overall fuel efficiency, which lead to FUI of approximately 200 L/t in 2010. They found a strong inverse correlation between the abundance of Baltic cod and fuel use.

Parker et al. (2015a) explored the association of fuel consumption and fuel costs in a wide range of Australian fisheries. Due to varying trends in fuel prices, the study focused on three periods: 1993–1999, 1999–2005, and 2005–2011. FUI in Australian fisheries ranged from just below 100 L/t to approximately 10000 L/t. Since 2005, the majority of fisheries experienced a decreasing trend in FUI while half of them experienced decreased fuel costs. Due to high seafood prices, Australian fisheries had a weaker incentive to improve fuel performance at times with high oil prices. Fish stock biomass and fishing capacity were considered more influential on fuel efficiency.

Schau et al. (2009) studied the energy efficiency of Norwegian fisheries from 1980 to 2005. They considered six fleet segments: (i) coastal gillnetting, jigging and Danish seining, (ii) coastal longliners, (iii) autoliners, (iv) wet fish trawlers, (v) factory trawlers, and (vi) purse seiners. FUI increased for all the segments in the period of interest. Trawling was the most energy-intensive fishing method. An inverse correlation between FUI and catch rate was observed for trawlers. A similar relationship with fuel price was also realized. They also used mass allocation and economic allocation to find the weighted average FUI for different species.

6.2.3 Life cycle assessment

Life cycle assessment (LCA) is an approach for a comprehensive evaluation of the environmental impacts of products, such as seafood products in their whole life cycle (i.e., from extraction of raw materials to final disposal). In practice, LCA studies are limited to some stages of the life cycle due to data restrictions or purpose of the study. Energy analyses are relevant to fisheries LCA due to the acknowledged environmental impacts of fishing stage. Avadí and Fréon (2013) reviewed LCA studies in fisheries. They realized that most studies considered only two stages: vessel use and maintenance phases of fishing operations. A few included construction or at least production of materials for construction, end of life phases, and pre-fishing activities, such as production of diesel and antifouling paints. Some of the LCA studies in fisheries are the LCA of Danish seafood products (Thrane, 2004), the study of Spanish tuna fisheries (Hospido and Tyedmers, 2005), life cycle screening of Norwegian cod fishing (Ellingsen and Aanondsen, 2006), and the study of carbon footprint of Norwegian seafood products (Ziegler et al., 2013). For a more thorough list of relevant studies, see Avadí and Fréon (2013).

6.3 Energy efficiency gap

While the studies presented in Sections 6.1 and 6.2 evaluate fuel consumption and emissions in shipping as a whole or in a particular shipping segment (i.e., fishing), some other studies investigate why ships are not more energy-efficient than what they currently are.

Even though cost-effective technologies that can improve energy efficiency are identified, they are not always implemented. This inconsistency between optimal and actual implementation is called the ‘energy efficiency gap’, which is often explained by the existence of some barriers (Backlund et al., 2012; Jaffe and Stavins, 1994). Barriers are rooted in different disciplines, such as economic, organizational, and behavioral sciences (Thollander and Palm, 2013). They can range from limited access to capital and weak energy management in an organization to putting little value on energy issues by individuals. A barrier is defined as "a postulated mechanism that inhibits investment in technologies that are both energy-efficient and (apparently) economically efficient" (Sorrell et al., 2000).

The energy efficiency gap has been a long-debated concept between technologists and economists. On the one hand, technologists point out the non-adoption of cost-effective energy saving measures. On the other hand, economists consider the non-adoption of these energy saving measures as evidence to their economic inefficiency. While not every energy-efficient measure is cost-effective, there are measures that are both energy-efficient and cost-effective (Jaffe et al., 1999; Johnson, 2013; Johnson et al., 2014; Weber, 1997). Hence, the latter group of measures is focused while addressing the energy efficiency gap: it is taken for granted that such measures (e.g., online monitor to balance speed, engine power capacity, and power utilization for propulsion (Krozer et al., 2003)) exist. Different studies have identified the existence of the energy efficiency gap in shipping (Buhaug et al., 2009; Eide et al., 2011; Johnson, 2013; Johnson and Andersson, 2011; Johnson et al., 2012, 2014).

Various studies have addressed barriers in different sectors (Blass et al., 2014; Blumstein et al., 1980; Brown, 2001; Cagno et al., 2013; Chai and Yeo, 2012; Fleiter et al., 2012a; Fleiter et al., 2011; Hirst and Brown, 1990; Howarth and Andersson, 1993; Jaffe and Stavins, 1994; Rohdin and Thollander, 2006; Thollander and Palm, 2013). While some studies focus on the prioritization of barriers (Apeaning and Thollander, 2013; Fleiter et al., 2012b; Rohdin et al., 2007; Thollander and Ottosson, 2008; Trianni et al., 2013a), others focus on categorizing them. The way an energy efficiency problem is defined determines the suitable categorization and the way to solve the problem (Thollander and Palm, 2013). So far, most studies on barriers have considered them isolated. Possible interactions have been disregarded while seeking solutions to overcome barriers. To avoid erroneous solutions, a holistic view on barriers and the interactions among them is required (Chai and Yeo, 2012). Some studies have addressed these interactions: Wang et al. (2008) identified direct and indirect interactions among barriers, and 'root' barriers that lead to other barriers were prioritized to deal with. Chai and Yeo (2012) and Hasanbeigi et al. (2010) presented the process of adopting energy-efficient measures and showed the dependency between barriers encountered at different stages of this process. Trianni et al. (2013a) and Trianni et al. (2013b) addressed correlations among barriers encountered in European foundry industry and in manufacturing small and medium enterprises, respectively. Cagno et al. (2013) and Trianni and Cagno (2012); Trianni et al. (2013a); Trianni et al. (2013b) investigated the interactions among barriers.

Most of the available studies address the energy efficiency gap in industrial sectors, for example, foundry (Trianni et al., 2013a) and paper and pulp (Thollander and Ottosson, 2008). Although shipping is quite energy intensive compared to many sectors, the focus on its energy efficiency has been limited. While energy cost may form about 20% of the costs of an energy intensive production plant, this share can rise to 50% for a shipping company (Johnson and Andersson, 2011). Few studies have addressed the energy efficiency gap in shipping. For instance, Johnson et al.

(2014) used an action research to investigate barriers that a short sea shipping company faced in implementing an energy management system. Johnson and Andersson (2016) explored barriers encountered in shipping by conducting 19 interviews within the Nordic shipping sector. In his licentiate thesis, Johnson (2013) further elaborates on these two articles.

At the time of writing this thesis, two other studies on barriers in shipping were published: Rehmatulla and Smith (2015a) used an online survey to assess the uptake of energy-efficient and cost-effective operational measures in shipping and to obtain views on barriers to their implementation. From the 170 respondents, 120 provided almost complete responses. Then, they focused on split incentives barrier[1]: they emailed 20 of the respondents to enquire their most commonly used charter parties.

Rehmatulla and Smith (2015b) used a bottom-up model to quantify EEDI of new builds from 2010 to 2025. Regarding their findings, under certain circumstances and scenarios, approximately 40% reduction in EEDI could be realized in 2015. However, under several scenarios, the EEDI of new builds would be close to the level defined in the EEDI regulations: progressing from 10% baseline reduction in 2015 to 30% baseline reduction in 2025. This showed the existence of energy efficiency gap. To investigate the barriers that might lead to the gap, they used the survey results from their previous study (Rehmatulla and Smith, 2015a).

6.4 Institutional interactions

Institutions can be defined as "persistent and connected sets of rules and practices that prescribe behavioural roles, constrain activity, and shape expectations" (Keohane et al., 1993). An institutional interaction[2] refers to a situation where two or more institutions affect each others' development and performance, such as environmental effectiveness (Oberthür and Gehring, 2001).

Institutions focus on a limited issue area (that can still be broad in itself). Institutions are established separately while disregarding possible side effects beyond the issue area. Institutional interactions may raise both conflicts and synergies for the development and success of international environmental policies (Oberthür and Gehring, 2001).

Fishing vessels operate in a web of environmental regulations. These regulations range from emission regulations presented in Section 4 to fish quota and restrictions

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[1] Split incentives addresses a situation where different stakeholders think about possible benefits to themselves by using energy-efficient measures. If stakeholders cannot foresee such benefits, they may not support the uptake of measures. Usually ship owners pay for technologies whereas charterers pay for fuel. Charterers may not be willing to share capital expenses as they may operate ships temporarily (See Article II in Part II).

[2] In the literature, other terms may refer to an institutional interaction, such as interplay, linkage, inter-linkage, overlap, and interconnection (Oberthür and Gehring, 2001).

on fishing gear to preserve fish stocks. Ship owners and operators may adopt different measures to meet various environmental regulations. However, they may overlook the interactions among these measures. A measure may be successful in meeting a regulation; however, it may indirectly affect the outcomes of other measures and regulations.

Despite the presence of numerous environmental institutions in shipping and fishing, to my knowledge, their interactions are not studied in a holistic way. The only exceptions are studies that address specific interactions. For instance, Larsen et al. (2015) investigated different configurations of diesel-based machinery systems to study the trade-off between NO_x emissions and fuel efficiency. Gilbert (2014) stresses the importance of taking a systems view and addressing SO_x and CO_2 emissions in tandem to avoid conflicts. Ziegler and Hornborg (2014) discuss the side effect of selective trawling on fuel efficiency.

6.5 Systems perspective on energy

A ship can be viewed as an energy system: it consists of sub-systems and components that influence energy balance of the whole system/ship. A ship consists of a large number of interacting components. Some of these interactions are nonlinear. In addition, a ship is more than the mere sum of its components; to fulfil the system's mission, the components should have a specific combination and relationship. Hence, marine energy systems can be considered complex (Baldi, 2013).

Traditional approaches attempt to improve energy efficiency of marine energy systems by optimizing individual system components. Such approaches may ensure the components' functionality; however, they do not ensure the functionality of the whole system as the interactions between the components may be overlooked. Therefore, to evaluate the energy consumption of the whole system under different operational conditions, it does not suffice to study separate components. The same applies when studying the effect of alternative technical or operational measures on energy efficiency. System-level modeling, simulation, and optimization methods are required to manage the increasing complexity of marine energy systems. In general, there are two system approaches to energy analysis: (i) a top-down approach and (ii) a bottom-up approach. The availability of data and the purpose of the study specify the suitable approach to use (Baldi, 2013; Dimopoulos et al., 2014).

6.5.1 Top-down system approach

Following the logic of the top-down approach in emission modelling (Section 6.1.1), this approach relies on available fuel data. The difference is that in emission modelling the aim was to derive global or regional fuel consumption data. However, in here the focus is on the fuel consumption of a specific vessel. Through energy audit and measurements onboard, it is possible to inspect and analyze energy flow within the vessel's energy system. This knowledge can be used for proposing measures to improve energy efficiency of the whole system.

Basurko et al. (2013) performed a comprehensive energy audit for three Basque fishing vessels during the 2010–2012 period. The relevant data were collected using different instruments, such as flow meters and torque meters. Through data analysis, they identified factors that can assist in determining the suitability of energy-efficient measures. These factors, among other things, included engine loads and the associated energy consumption for different fishing activities.

Sala et al. (2011) set up a fuel consumption monitoring system on two semi-pelagic pair trawlers in the Adriatic Sea. The system consisted of two mass flow meters, one multichannel recorder, and one data logger for global positioning system. The system logged working time duration, vessel speed, total fuel consumption, and instant fuel rate. The collected data were used to investigate energy performance of the vessels under different operational conditions (e.g., steaming).

6.5.2 Bottom-up system approach

Following the logic of the bottom-up approach in emission modelling (Section 6.1.2), this approach focuses on determining the fuel consumption of individual vessels based on vessel activity. The difference is that in emission modelling the available technical and operational data are usually combined in a simplifying way to estimate the fuel consumption of a ship category. However, in here the aim is to understand energy flow within the energy system of an individual vessel under different operational conditions. Therefore, using the engineering knowledge, this approach models the energy system of a vessel. By simulating the model, system behavior under different circumstances are evaluated.

The number of studies with a system view on energy modelling of ships is rather limited. However, with acknowledgment of the need for a holistic approach to energy analysis, the situation is changing. Shi et al. (2010) modeled a ship propulsion system, consisting of diesel engine, gearbox, shaft, and propeller. They investigated the impact of off-design operational conditions on overall energy efficiency. Shi (2013) modeled the energy system of a dredger to predict its energy consumption and emissions. Dimopoulos et al. (2008) modeled the integrated energy system of a cruise liner, consisting of electricity producing units (e.g., gas turbine generators), exhaust gas boilers, and electric propulsion motors. They assessed the ship's main operating modes for operation optimization. Pedersen and Pedersen (2012) developed a model library for facilitating the modelling of diesel electric power systems, while simultaneously increasing the understanding of the systems. Det Norske Veritas (DNV) Research & Innovation used Model-Based Systems Engineering (MBSE) for modelling, simulation, and optimization of integrated marine energy systems. This work resulted in a modelling framework and the associated computer implementation named DNV COSSMOS (COmplex Ship Systems MOdelling and Simulation) (Dimopoulos et al., 2014). Since energy processes include different energy domains (e.g., mechanical and electrical), Zou et al. (2013) used a multi-domain simulation method to model marine energy systems in the Matlab/Simscape environment. Lepistö et al. (2016) used a commercial simulator for dynamic analysis of energy system of a ferry, which included waste heat and LNG cold recovery systems. Baldi et al. (2015a); Baldi et al. (2015b) studied energy system of a cruise ship and a chemical tanker, respectively.

6.6 LNG-fueled propulsion

As mentioned in Section 5, ship owners and operators can adopt different measures to comply with emission regulations. Among these measures, the use of LNG fuel in shipping is progressively getting more attention, especially from an environmental perspective. Different studies have evaluated this measure from different perspectives, such as regulatory, environmental, economic, and safety.

Xu et al. (2015) examined the regulatory framework on the use of LNG as marine fuel. Wang and Notteboom (2014) reviewed 33 studies to represent pros and cons of using LNG onboard ships. Burel et al. (2013) analyzed the environmental and economic impacts of fueling merchant ships with LNG. Acciaro (2014) discussed the optimal time for investment in LNG retrofit. Brynolf et al. (2014) and Thomson et al. (2015) compared life cycle environmental performance of different marine fuels, including LNG. Vandebroek and Berghmans (2012) calculated the maximum distances from the point of release of LNG at which lethal effects may occur. Considering the limited operational experience with using LNG as marine fuel, Davies and Fort (2013) used data directory of the International Association of Oil & Gas Producers to estimate release likelihood from LNG fueling systems. Lee et al. (2015) compared the fire risk of two LNG fuel gas supply systems used in shipping.

7 Research questions

Fuel costs, environmental concerns, and environmental regulations challenge fishermen to reduce emissions of air pollutants from their vessels. This challenge has motivated the investigation of different ways for reducing these emissions in this PhD study.

Based on Section 5, there are two main approaches for reducing emissions:

- Indirectly through reduced fuel consumption, which consequently reduces emissions.
- Directly by cutting emissions, either by controlling emissions at source or by cleaning exhaust gases.

This PhD study initially focuses on the first approach. As mentioned earlier, there are two ways for reducing fuel consumption: (i) through improved energy efficiency and (ii) through energy conservation. This study focuses on energy efficiency. However, energy conservation should not be overlooked to avoid possible drawbacks of energy efficiency, such as the 'rebound effect' (Section 5.1.3). Research questions I–III are raised in the realm of energy efficiency.

This PhD study also focuses on direct reduction of emissions through controlling emissions at source. More specifically, it focuses on using LNG as an alternative fuel. Research questions IV and V are raised in this regard.

7.1 Energy efficiency: research questions I–III

Before any plan and decision-making for increasing energy efficiency, there is a need to set the baseline for efficiency. Thorough knowledge of the current level of energy efficiency is required to identify the status of different fleet segments in the Norwegian fisheries and to identify explanations for the current state of efficiency. Schau et al. (2009) found a reducing trend for energy efficiency of Norwegian fisheries from 1980 to 2005. However, as mentioned in Section 6.2, some fisheries elsewhere have experienced improvements in their efficiencies in recent years (Cheilari et al., 2013; Parker and Tyedmers, 2015; Ziegler and Hornborg, 2014). This raised research question I: *"Do Norwegian fisheries follow recent international trends in energy efficiency?"*

After setting the baseline and understanding how energy-efficient Norwegian fishing vessels are, it is important to know why they are not doing better. No doubt, it is important to invest in research and development (R&D) to find measures that improve efficiency in shipping. However, if these measures are not put into practice, they are of little interest. As mentioned in Section 6.3, few studies address the energy efficiency gap in shipping. This brought up research question II: *"Why do not ship owners and operators adopt the available energy-efficient measures that are cost-effective?"*

Research question III rose while investigating the answer to the former question (i.e., research question II). Several barriers were found that hinder the adoption of measures that are both energy-efficient and cost-effective. Some are information barriers that, among other things, relate to lack of information and improper form of information about energy efficiency. For example, ship owners and operators may not have enough and proper information about fuel consumption of their vessels. In addition, they may not know how different measures (e.g., slow steaming) affect the fuel consumption. As mentioned in Section 6.5, a systems view can give a better and more comprehensive understanding of energy flow within ships. This raised research question III: *"Can a systems approach to energy analysis reduce information barriers and consequently enhance the adoption of cost-effective and energy-efficient measures?"*

7.2 LNG fuel: research questions IV and V

Since 2000, different vessel types, such as ferries and offshore supply vessels have used LNG fuel. So far, no fishing vessel runs on LNG fuel. As mentioned in Section 6.6, the research body on the use of LNG fuel in shipping is growing. However, to my knowledge, none of these studies focuses on using LNG in fishing vessels. LNG fuel may potentially reduce emissions of fishing vessels, but there are several aspects that should be taken into account during design and operation phases. This raised research question IV: *"What are the benefits and challenges of using LNG on fishing vessels?"*

LNG as a marine fuel creates different types of hazards compared to traditional fuels, such as cryogenic temperature and increased fire intensity, creating explosion risk. To ensure safety, it is necessary to consider different and/or additional safeguards when using LNG (Davies and Fort, 2013). In addition, higher complexity, safety requirements, and space needed for LNG installations increase the capital costs of LNG-fuelled vessels compared to their oil-fuelled counterparts (Chryssakis et al., 2015; Tzannatos et al., 2015). To ensure profitability, lower operational expenses should compensate for the extra investment costs. In other words, environmental improvements should not come at the cost of safety and profitability; otherwise, ship owners may prefer other solutions to LNG. The available knowledge about safety and economic aspects of LNG fuel should be transferred from experienced sectors, such as offshore supply vessels to unexperienced sectors, such as fishing. Consequently, ship owners can use this knowledge in parallel with other decision-making processes to determine whether LNG fuel is a right choice for them or not. This leads to research question V: *"How can the available knowledge on safety and economic aspects of using LNG be transferred to fishing vessel owners?"*

8 Objectives

The main goal of this study is to contribute to the research body focused on mitigating emissions of air pollutants from fishing vessels. Better understanding the current body of knowledge and putting it into practice have been the focal points of this study. To achieve this goal, the following objectives are defined based on the research questions I–V (Section 7):

- Objective 1: to reduce emissions by enhancing energy efficiency
    - Objective 1.1: to investigate energy efficiency of Norwegian fishing fleet
    - Objective 1.2: to investigate the barriers that hinder adoption of cost-effective and energy-efficient measures
    - Objective 1.3: to enhance energy efficiency by reducing some of these barriers
- Objective 2: to reduce emissions by using cleaner alternative fuels
    - Objective 2.1: to investigate benefits and challenges of using LNG on fishing vessels
    - Objective 2.2: to propose an approach for transferring available knowledge on safety and economic aspects of using LNG to ship owners

A focus on energy efficiency has the benefit of reducing all or some types of emissions in parallel. For example, by burning less fuel, emissions of SO_x, GHG, larger particles, and BC can be reduced. Some fuel-efficient measures (e.g., exhaust gas power turbine) can also reduce NO_x emissions. However, not all measures that reduce fuel consumption can reduce NO_x emissions simultaneously. For example, adjusting engine parameters (e.g., the valve and injection timing) to reduce NO_x emissions increases specific fuel oil consumption and vice versa (Larsen et al., 2015). Moreover, fuel cost is one of the primary costs associated with fishing. Although the share of fuel costs varies among fisheries (Sumaila et al., 2008), it is economically beneficial to reduce fuel consumption.

There are several ways for controlling emission formation at source. Among the available solutions, this thesis focuses on the use of LNG fuel. Although the effect of using LNG on climate change depends on the amount of methane slip, it reduces other emissions. LNG can reduce NO_x emissions up to 90% depending on engine type. It also eliminates almost all the emissions of SO_x, coarse particles, and BC (Buhaug et al., 2009; Lack et al., 2012; LR, 2015). Moreover, in Norway the NO_x tax and fund system promotes switching to LNG. The NO_x fund has covered up to 80% of additional costs of LNG-fueled ships. Historically, the lower price of LNG compared to oil has recouped the remaining costs (EGN, 2015).

8.1 Overview of articles

Figure 1 illustrates the link between the objectives and focus of different articles. To address objective 1.1, Article I investigates energy efficiency of Norwegian fisheries in recent years to update and follow up the former study by Schau et al. (2009). To increase the accuracy of results, Article I follows a different approach from previous studies, which is explained in Section 10.1.

Articles II and III address objective 1.2 by contributing to the limited research body on energy efficiency gap in shipping. Following the approach explained in Section 10.2, Article II provides a framework for identifying and overcoming barriers encountered in shipping. Following the approach in Section 10.3, Article III further elaborates on a group of barriers identified in Article II (i.e., policy barriers).

To address objective 1.3, Articles IV focuses on reducing a group of barriers identified in Article II (i.e., information barriers). It suggests an approach to increase the knowledge of ship owners and operators about the energy consumption of their vessels and, consequently, narrow the energy efficiency gap. Section 10.4 elaborates on this approach.

To address objective 2.1, Article V reviews the relevant literature. Article VI uses a systems approach to fulfil objective 2.2. Sections 10.3 and 10.5 further explain Articles V and VI, respectively.

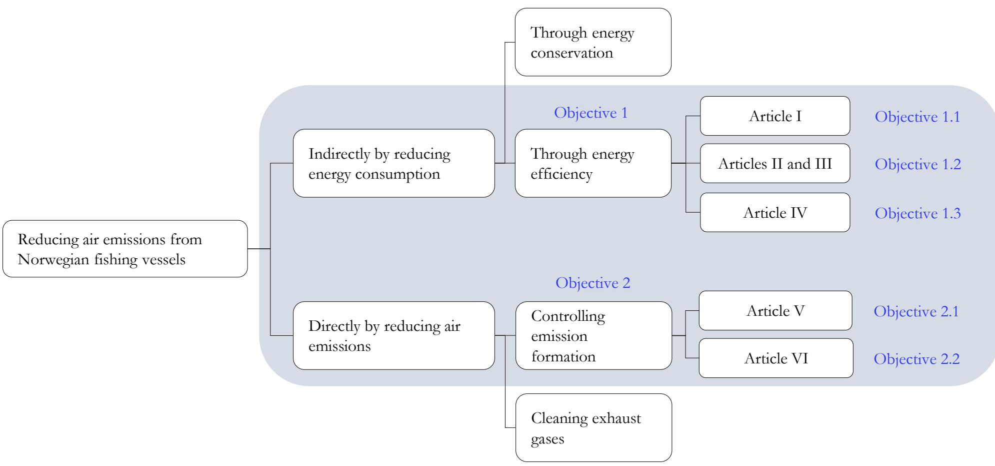

Figure 1. The link between the articles included in this thesis

8.2 Research scope

This PhD study only addresses energy efficiency and LNG fuel as possible solutions for reducing air emissions from ships. Other measures, such as energy conservation and cleaning exhaust gases are out of the scope.

This study focuses on energy consumption and emissions of fishing vessels. Other life cycle stages of seafood products (e.g., fish processing plants) are not covered. Other life cycle stages of fuel (e.g., fuel extraction) are also out of the scope. However, Article III touches upon the problem of reducing emissions of vessels by shifting emissions elsewhere in the life cycle.

This study focuses on Norwegian fishing vessels. However, the findings are of relevance to fishing vessels elsewhere as well as other ship types. While Article I is mainly relevant to fishing vessels, other articles can contribute to the knowledge body in shipping in general.

9 Research Methodology

This section includes some reflections on the methodology used in this PhD study. The term "methodology" is rather broader than the term "method". While "method" refers to use of specific techniques or procedures for collecting and analysing data, "Methodology" in addition includes the reflections behind the choice of these methods (Pruzan, 2016b).

Section 9.1 pinpoints the type of research performed in this study. Section 9.2 explains the interdisciplinary nature of this study. Section 9.3 elaborates on the systems view in this work. Section 9.4 presents research approaches used. Section 9.5 explains the approach for checking scientific value of this PhD thesis. Although research methods could be included in this section, they are explained separately in Section 10.

9.1 Research types

"Science includes any systematic or carefully done actions that are carried out to answer research questions or meet other needs of a developing research domain" (Johnson and Christensen, 2014). "R&D comprise creative and systematic work undertaken in order to increase the stock of knowledge […] and to advise new applications of available knowledge" (OECD, 2015a).

OECD (2015a) considers three types of R&D:

- Basic research, which is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view.
- Applied research, which is original investigation undertaken in order to acquire new knowledge. However, it is directed primarily towards a specific, practical aim or objective.
- Experimental development, which is systematic work, drawing on knowledge gained from research and practical experience and producing additional knowledge, which is directed to producing new products or processes or to improving existing products or processes.

Applied research either determines possible uses for the findings of basic research or determines new methods or ways of achieving specific and predetermined objectives. It considers the available knowledge and its extension in order to solve actual problems (OECD, 2015a). This PhD study can be classified as applied research since it aims at extending the available knowledge and using available methods for addressing specific objectives (Section 8).

To classify an activity as R&D, five core criteria have to be jointly satisfied (OECD, 2015a):

- Novelty: the work should aim at new findings.
- Creativity: the work should be based on original, not obvious, concepts and hypotheses.
- Uncertainty: the final outcome should be uncertain.
- Systematic: the work should be planned and budgeted.
- Transferability and/or reproducibility: the new knowledge should be transferred to allow other researchers to reproduce the results as part of their own R&D activities.

The research performed in this thesis has tried to follow the criteria mentioned above. Different articles are based on the research gaps identified through literature review (Sections 6 and 7) to ensure novelty. New concepts and ideas are applied during the research. For instance, in Article I the effect of multiple fishing gears on energy efficiency was studied, which to the knowledge of the authors was not performed previously. Before conducting the research, the results were uncertain. For instance, before performing research for Article I, it was not certain whether energy efficiency in Norwegian fisheries would follow recent international trends. The research was also systematic since it was conducted in a planned way, keeping records of both the followed process and the outcome. The work is transferable as the research outcomes are published in peer-reviewed journals and conferences. Finally, the work is reproducible as scientific approaches are followed, and the research methods are explained in the publications.

9.2 Interdisciplinary research

The topic of energy efficiency and emission reduction spans across several disciplines. Different factors, such as vessel characteristics (e.g., fuel type and engine power), regulations (e.g., allocated fish quota to vessels), and social aspects (e.g., fishermen's view on energy efficiency) affect fuel consumption and air emissions of fishing vessels. Since the topic is complex and cuts across different disciplines, this PhD study is interdisciplinary. Interdisciplinary research is not a type of research. Instead, it is a way of organizing research. Interdisciplinary research integrates the perspectives/methodologies/technologies of two or more disciplines (Pruzan, 2016a).

9.3 Systems thinking

A "system" is an assemblage of interrelated components functioning together towards some common objective(s) (Blanchard and Fabrycky, 2011). Classical practices usually decompose a system to its components to understand it. However, systems thinking prioritizes the study of a system as a whole. It recognizes system level behaviours, interactions, and structural characteristics that are missed by focusing on individual elements instead of "the big picture" (Driscoll, 2010). In other words, instead of detaching smaller and smaller components of the system, systems thinking expands its view to consider larger and larger number of interactions (Hürlimann, 2009).

Systems thinking investigates the systems from the top down rather than from the bottom up. Attention is first directed to the system as a black box that interacts with the environment. Next, attention is focused on how the smaller black boxes (i.e., subsystems) combine to achieve system objective(s). The lowest level of concern is components. This hierarchical focus on systems, subsystems, and components forces consideration of the relevant functional relationships. This is as opposed to classical practices that focus on system components. In systems thinking, a system is more than a mere some of components (Blanchard and Fabrycky, 2011).

Since this study is interdisciplinary and different factors may affect energy consumption and emissions of fishing vessels, a systems view is taken in different articles. For instance, Article I looks at the whole fishing fleet and different factors that affect energy efficiency. Article II investigates barriers from different disciplines that may prevent adoption of energy-efficient measures. Article III looks at the interactions among different environmental regulations. Article IV, models the power system of a vessel and looks at the interactions among the components to study energy flow within the system. Article V gives an overview of pros and cons of using LNG, with roots in various disciplines. Article VI looks at ship owners' decision-making problem from different angles and increases their knowledge about safety and economic aspects of LNG.

9.4 Research approach

Creswell (2014) divides research approaches into three groups: (i) quantitative, (ii) qualitative, and (iii) mixed methods. These approaches are not as discrete as it may appear. Quantitative and qualitative approaches represent the two ends of a continuum rather than two distinct categories. A study tends to be more quantitative or qualitative. Mixed research lies in the middle of this continuum since it includes elements of both approaches.

Quantitative research uses numbers and quantification to study the phenomenon of interest. It tests objective theories by examining the relationship among variables, which can be measured by, for instance, measurement instruments. In such an approach, based on a literature review and current knowledge, the researcher creates an image of the phenomenon to be examined and formulates the research question and research objective. Then, s/he tests the hypothesis by analyzing the numerical data (e.g., using statistical or computational techniques). The researcher should justify how and why s/he examined the question in the way s/he did, so that any other researcher can repeat the research (Creswell, 2014; Johnson and Christensen, 2014; Jonker and Pennink, 2010).

Qualitative research investigates phenomena in an interpretive manner. Qualitative researchers usually do not collect data in the form of numbers. Rather, they conduct observations and in-depth interviews, and the data are usually in the form of words. In social sciences, a qualitative researcher tries to understand specific organizational realities and occurring phenomena from the perspective of those involved. This approach is used when the theoretical knowledge about a specific phenomenon is incomplete, insufficient, or ineffective at the start of a research project. A qualitative researcher's attitude needs to be unprejudiced to achieve a full understanding of people's behavior in certain situations. S/he asks the questions, collects the data, makes interpretations, and records what is observed. For example, a qualitative researcher might conduct a focus group discussion while tape recording. Focus groups are group interviews that rely on the interaction within the group and the questions asked by the moderator to provide insight into specific topics. Later, the recording would be transcribed into words and analyzed (Creswell, 2014; Jackson et al., 2007; Johnson and Christensen, 2014; Jonker and Pennink, 2010)

Mixed research involves the mixing of quantitative and qualitative research methods. Advocates of mixed research argue that it is important to use both the confirmatory and exploratory methods in one's research. They view the use of only quantitative research or only qualitative research as limiting and incomplete for many research problems (Creswell, 2014; Johnson and Christensen, 2014; Jonker and Pennink, 2010).

Since this PhD study is interdisciplinary, a combination of quantitative and qualitative approaches enables the exploration of different disciplines. Articles I and IV are quantitative. Article I uses statistical analysis to assess the energy efficiency in Norwegian fisheries. Article IV uses mathematical modelling and simulation to evaluate the energy consumption of a fishing vessel under different operational conditions. Articles II and III are qualitative. Article II conducts focus groups to identify the barriers that lead to energy efficiency gap in shipping. Article III reviews the literature to identify interactions among environmental regulations in shipping and fishing. Article V has both qualitative and quantitative elements. First, it reviews literature to identify pros and cons of using LNG fuel on fishing vessels. Then, through a simple calculation, it shows the potential environmental benefits of switching to LNG. However, as the quantitative part is limited, it is classified as qualitative rather than mixed research. Articles VI combines qualitative and quantitative methods. Therefore, it can be considered mixed research. Articles VI investigates the relevant information that assist ship owners to use the environmental benefits of LNG without endangering safety and profitability. In addition, Articles VI calculates costs of building and operating a LNG-fueled fishing vessel (Table 3).

9.5 Quality assurance

To evaluate the scientific value of this PhD thesis, its quality should be assessed. For all publications, the quality of the research has been tested through the use of peer reviews in journals and conferences. In addition, by presenting different publications in international conferences, valuable feedback was obtained from experts. In addition to publication in peer-reviewed journals/conferences, Articles I, II, and IV used other approaches to validate findings:

Article I is based on a statistical analysis, and the steps defined by IEA (2014) are followed to validate the data. First, the input sample data was examined to ensure good coverage of the population. Second, internal consistency was evaluated to ensure that different elements in the datasets follow expected relationships with one another. An arithmetic check could for instance verify that total operational costs reported for a vessel equal the sum of sub-components (e.g., fuel cost). Third, external consistency was checked. Consistency checks with external sources ensure that the collected data are consistent with similar data produced by other sources. In this regard, fuel price data from the Directorate of Fisheries were compared with the corresponding value obtained from Statoil Fuel & Retail. Finally, plausibility was controlled. Plausibility checks ensure that values fall within expected ranges and that data and indicators make sense. In this regard, the results were compared with international publications. Some participants in the focus groups read the final version of Article II and provided feedback on its validity. The results obtained from mathematical modelling and simulation in Article IV were compared with measurements onboard as a sort of external validity check. In addition, different sources of error, both from simulation and onboard measurements, were explained in this article (Table 3).

Table 3. Research methodology

Articles	Research approach	Data collection	Data analysis	Quality assurance
Article I	Quantitative	- Assessing administrative sources - Obtaining fuel price data from Statoil Fuel & Retail	Statistics	- Following steps of IEA (2014): • Coverage • Internal consistency • Internal validity • External validity • Plausibility - Publication in a peer-reviewed journal
Article II	Qualitative	- Focus group - Literature review	Documentation, interpretation, and categorization	- Member checking - Publication in a peer-reviewed journal
Article III	Qualitative	Literature review	Literature review	Publication in a peer-reviewed conference
Article IV	Quantitative	- Measurements on board - Assessing data from engine manufacturer	Mathematical modelling and simulation	- Comparison with measurements on board - Publication in a peer-reviewed conference
Article V	Qualitative	Literature review	Literature review	Presenting in a conference and receiving feedback
Article VI	Mixed research	- Reviewing regulations - Literature review - Obtaining data from engine and equipment suppliers and a research institute	Systems engineering	- An earlier version was published in a peer-reviewed conference - Submission to a peer-reviewed journal

10 Research methods

Research methods compose of techniques or procedures for data collection and analysis. Different articles use different research methods, as shown in Table 3 in Section 9. This section states the research methods used for addressing the different objectives of this study (Section 8). Articles I–VI explain the methods more in detail.

10.1 Statistical analysis (Article I)

To address objective 1.1 (Section 8), data on fuel consumption and catch of different vessels in the Norwegian fishing fleet were required. The Directorate of Fisheries provided two datasets that covered sample fleet populations from 2001 to 2012 (For information on sampling, see Article I). One dataset included anonymous vessel names and the corresponding operational codes (i.e., "driftskoder" in Norwegian), characteristics (e.g., overall length and engine power), days at sea, fuel consumption, and operational costs (e.g., fuel price) and revenues. The other dataset included anonymous vessel names with their target species; it documented the round (live) weight and value of each species along with the fishing gear used (Directorate of Fisheries, 2014). While fishing gears merely show the type of gears employed (e.g., trawl) for catching different species, the operational codes more specifically categorise the vessels. For example, in 2003 operational code 8 represented vessels with cod trawling license. In the Norwegian fisheries, a vessel may use different gears to catch different species in different seasons in order to increase profitability. For example, a pelagic trawler may use conventional gears in addition to trawling. In recent years, the gear with the largest landing specified the vessel group and operational code (Persen, Personal communication in 2014).

First, these two datasets were merged for cross-analysis (Figure 2). The data analysis was performed with the R language, which is used for statistical computing and graphics (Ihaka and Gentkeman, 1993). The data analysis consisted of following steps (See Article I for detailed information.):

- The Directorate of Fisheries used different data collection and organization methods during the years of interest. To maintain consistency and enable data analysis, ten fleet segments were considered: four segments for conventional vessels (i.e., vessels using longline, gillnet, etc.) based on their quota length[1], two segments for coastal seiners based on their quota length, factory trawlers, pelagic trawlers, purse seiners, and wet fish trawlers.

[1] In Norway, traditionally, vessel length was the basis for quota allocation among coastal vessels. However, it is not desirable to extend a vessel or replace it with a larger one to claim a larger quota at

- A vessel may catch different species; however, the data resolution does not allow the division of fuel consumption among species. Therefore, vessels with shrimp catch were excluded as it is more fuel intensive to catch shrimp than other species (Parker and Tyedmers, 2015; Schau et al., 2009). In this way, the results may not be biased because of shrimp catch.
- As mentioned earlier, a Norwegian vessel may use different gears. However, the data resolution does not allow the allocation of fuel consumption among these gears. Therefore, first only vessels with one gear were studied. Their fuel efficiencies were compared, and the reasons behind their efficiencies were explored. Second, the effect of employing multiple gears on fuel efficiency was explored. In this regard, the vessels with single gear were compared with the vessels with multiple gears within the same fleet segments.

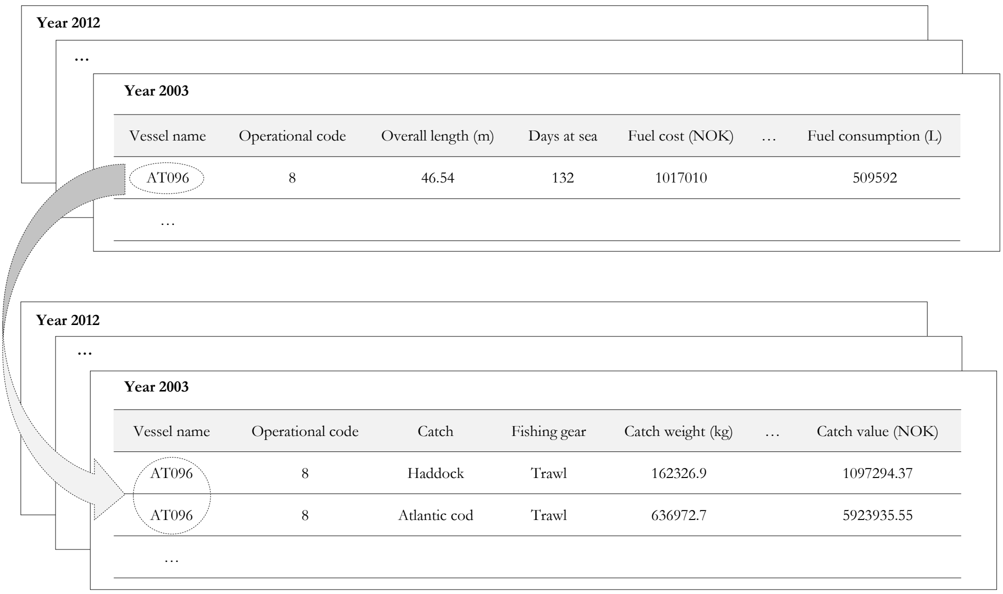

Figure 2. Merging the two datasets obtained from the Directorate of Fisheries

10.2 Focus groups (Article II)

To address objective 1.2 (Section 8), first a thorough literature review on barriers to energy efficiency was conducted. Given that there is a limited literature body on barriers to energy efficiency in shipping, this study aims at transferring accumulated

the expense of other vessels. Therefore, the vessel length on a specific date (i.e., "skjæringsdato" in Norwegian) is the basis for quota allocation, called the quota length (NFD, 2007). The vessel owners can still change to larger or smaller vessels; however, this will not affect the quota. Therefore, "quota length" might differ from actual vessel length (Standal and Hersoug, 2014).

knowledge and experience from other industrial sectors to shipping. The gathered data is tailored to reflect the barriers encountered in shipping. In shipping, there are operational measures in addition to technologies that can save fuel (Buhaug et al., 2009). As a result, in this study the definition of barriers is expanded to encompass mechanisms that hinder the adoption of operational measures that are energy saving and cost-effective as well.

Based on the gathered information, a preliminary framework was designed as a decision-making tool to help ship owners and (energy) managers to identify the barriers they face, to prioritize the barriers that are more critical or beneficial to deal with, to identify possible solutions to these barriers, to understand possible interactions among barriers, and consequently to reduce the energy efficiency gap.

To validate the framework, focus groups (i.e., workshops or group meetings) with the participants of the Energy Management in Practice II (EMIP II) project (Torvald Klaveness et al., 2013) were arranged in winter and spring 2013. The EMIP II project involved five ship owners in Norway (i.e., Torvald Klaveness, Wilh. Wilhelmsen, Solvang, BW Gas, and Grieg Star), two equipment suppliers (i.e., Kongsberg Maritime and Marorka), a research institute (i.e., MARINTEK), and a university (i.e., NTNU), which collaborated from September 2011 to September 2013 to increase energy efficiency in shipping. The ship owners operate different fleets including containers, roll-on/roll-off (ro-ro) ships, LNG carriers, product tankers, bulk carriers, large gas carriers, etc. Besides, they offer services, such as logistics and ship management. The equipment suppliers are providers of energy management solutions and marine automation systems. The research institute develops technical and operational solutions for the maritime sector. Twelve participants provided feedback on the framework. They had different job positions, such as technical vice president/director, technical sales manager, shipping and environment manager, environmental performance manager, fuel efficiency manager, naval architect, research manager, senior project manager, corporate social responsibility manager, and product manager.

The participants discussed their viewpoints and provided feedback on the relevance or irrelevance of the identified barriers with supporting examples from their experience with working on energy efficiency in shipping. They also suggested some additional barriers and practices or possible solutions to overcome the barriers. Additionally, they mentioned their viewpoints about the whole framework and its practicality and usefulness. The workshops were followed up with individual discussions with the participants. After including the feedback from the participants, the framework was modified. For more information, see Article II.

10.3 Literature analysis and synthesis (Articles III and V)

To address objective 1.2 (Section 8), Article III analyses the literature to identify examples of policy barriers in shipping and fishing. More specifically, Article III identifies some of the interactions between environmental institutions that may lead to energy efficiency gap. This article goes beyond the energy efficiency gap and covers other interactions and side effects. For example, it mentions the issue of problem shifting: reducing emissions of vessels at the expense of increasing emissions elsewhere in the life cycle. Article III mainly focuses on interactions that indirectly contradict each other. However, it also touches upon some interactions that indirectly support each other. Then, it synthesizes these examples into categories that represent similar types of interaction, for instance, interactions between environmental regulations on air pollution and fish stocks.

To address objective 2.1 (Section 8), the available information was reviewed to identify benefits and drawbacks of LNG-fueled propulsion. For more information, see Article V.

10.4 Power system modelling using bond graph (Article IV)

Ship owners and operators may not have enough knowledge about the current energy consumption of their ships and their status in the sector compared to that of their competitors. They may also not be familiar with the effectiveness of available energy saving measures; thus, they may hesitate in adopting such measures despite their cost-effectiveness. These are some examples of information barriers identified in Article II. To reduce these barriers and address objective 1.3 (Section 8), the power system of a fishing vessel was modeled using the bond graph method. The aim was to make a decision-making support that may increase knowledge of ship owners and operators on energy consumption of their vessels and energy-efficient measures.

This power system included the *main engine* and the power consumers dependent on it, namely the *cooling system of main engine*, *propulsion system*, *winch system* and *icemakers, fridge, and deck pumps*. The drag on the fishing gear while trawling[1] was considered in the *propulsion system*. Moreover, the speed controllers for the engine, vessel, and winch were considered within the model. The 20-sim software (Controllab Products, accessed 2015) was used for modelling and analyzing the machinery system. The fuel consumption of the fishing vessel during steaming[2], trawling, and hauling[3] of the fishing gear were found by simulating the bond graph model. Besides, the effect of slow steaming on energy consumption was studied. Finally, the findings were compared with the data from the measurements onboard the vessel conducted by CNR-ISMAR in Ancona, Italy (Fisheries Section, Institute of Marine Sciences, National Research Council of Italy). In other words, the results from two system approaches to energy analysis (Section 6.5) were compared: (i) the results from power system modelling and simulation (i.e., the bottom-up system approach) and (ii) the

[1] Trawling refers to the operation in which the fishing gear is set in water and the vessel is fishing.
[2] Steaming refers to the operation in which the vessel sails between the harbor and fishing grounds and searches for fish schools.
[3] Hauling refers to the operation in which the fishing gear and the fish trapped in it are pulled onboard the vessel.

results from measurements on board (i.e., the top-down system approach). For more information, refer to Article IV.

Classical engineering practices usually decompose a system to its components to understand it. Then, separate groups are assigned to work on different components or tasks in isolation. In a fishing vessel, for instance, separate groups design the engine, refrigerator, and fishing gear. These groups should interact to ensure the functionality of the system in addition to that of its components. Otherwise, individual groups may make oversimplified assumptions about the system operation, which may negatively affect the system design (Karnopp et al., 2012b).

It is common to use graphical representation and modelling for analyzing systems. Models are simplified constructs that predict system behavior. This thesis focuses on mathematical modelling rather than physical modelling. By following formal rules, not only do mathematical models prevent misunderstandings, but also they allow for an automatic transformation into an executable program by software packages (Borutzky, 2010).

Among the available modelling approaches, bond graph method is well suited for modelling physical systems that involve multidisciplinary engineering subsystems. Such systems consist of elements from different energy domains, such as hydraulic and mechanical domains. Bond graph uses a universal language and a small set of elements to construct models of such multidisciplinary systems. Then, standard techniques translate these models into differential equations and enable computer simulations (Karnopp et al., 2012b).

Bond graph views systems as assemblies of components that interact by exchanging energy. Therefore, to study systems, bond graph looks at the energy flow between the components. Energy flows in from one or more sources (e.g., voltage supplies). Some system components may temporarily store the energy (e.g., springs) or partially dissipate it (e.g., dampers). Some other components transform the type of energy (e.g., hydraulic rams that transform hydraulic energy to mechanical energy). Finally, energy arrives to "loads" where it produces the desired effect (Calvo et al., 2014; Karnopp et al., 2012b).

In bond graph method, energy flows between the 'ports' of subsystems through the 'power bonds' linking them. Each bond carries two 'power variables' at time *t*: effort *e(t)* and flow *f(t)*. The multiplication of these variables is power *P(t)* (Karnopp et al., 2012c):

$$P(t) = e(t).f(t) \quad (1)$$

In translational mechanics, for instance, force and velocity represent *e(t)* and *f(t)*, respectively. A power bond is illustrated by a half arrow with *e(t)* placed above or to the left of it, while *f(t)* is represented below or to the right of it. The direction of the half arrow shows the direction of positive power. As each bond connecting two subsystems carries two power variables, one of these variables is determined by one subsystem, while the other variable is determined by the other subsystem. In bond graphs, a short, perpendicular line at one end of the bond specifies the inputs and outputs: a 'causal stroke'. The end with the causal stroke indicates the subsystem that receives the effort as input and computes the conjugate flow (Karnopp et al., 2012c). Figure 3 illustrates a power bond.

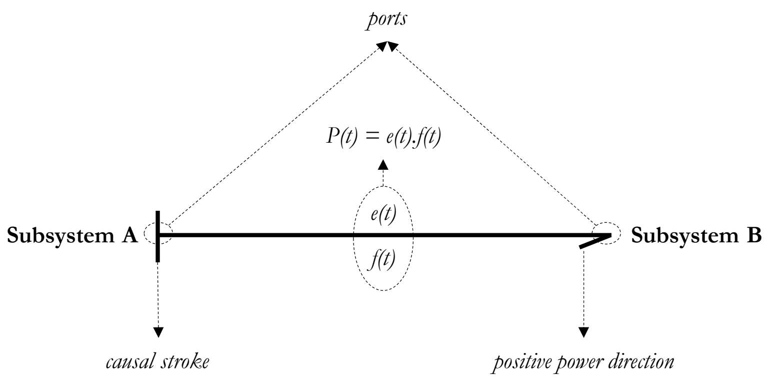

Figure 3. A power bond. *P(t)*, *e(t)*, and *f(t)* are power, effort, and flow at time *t*, respectively (adapted from Khemliche et al. (2006)).

Two other variables, called 'energy variables', are important in studying systems: momentum *p(t)* and displacement *q(t)*, which are time integrals of *e(t)* and *f(t)*, respectively (Karnopp et al., 2012c):

$$p(t) = \int^{t} e(t)dt = p_0 + \int_{t_0}^{t} e(t)dt \qquad (2)$$

$$q(t) = \int^{t} f(t)dt = q_0 + \int_{t_0}^{t} f(t)dt \qquad (3)$$

p_0 and q_0 indicate momentum and displacement at time t_0, respectively. The differential forms of equations (2) and (3) are as follows (Karnopp et al., 2012c):

$$dp = edt \qquad (4)$$

$$dq = fdt \qquad (5)$$

Energy *E(t)* carried by a power bond is the time integral of power *P(t)* (Karnopp et al., 2012c):

$$E(t) = \int^{t} P(t)dt = \int^{t} e(t).f(t)dt \tag{6}$$

The reason *p(t)* and *q(t)* are called energy variables is that using equations (4) and (5) one can express equation (6) as follows (Karnopp et al., 2012c):

$$E(t) = \int^{t} f(t)dp(t) = \int^{t} e(t)dq(t) \tag{7}$$

If sensors and instruments are included in bond graphs and the sensing of signals is of primary concern, the power conveyed through the bond connecting the sensor and the rest of the system can be neglected. This means that one of the two conjugate power variables associated with this bond can be dropped, turning the bond into a so-called 'active bond' or 'signal'. Full arrows represent signals as shown in Figure 4. For instance, an ideal voltmeter receives the voltage (i.e., *e(t)*) of the component it is measuring as an input without influencing the current (i.e., *f(t)*) passing through that component (Borutzky, 2009; Karnopp et al., 2012c).

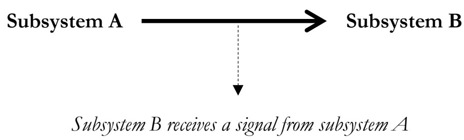

Figure 4. An active bond or signal

10.4.1 Bond graph elements

There are nine basic bond graph elements as shown in Table 4. Each physical component can be modeled by one or more elements (Borutzky, 2009):

Energy sources: Two bond graph elements represent energy supply: (i) effort source S_e, which imposes effort onto the system and (ii) flow source S_f, which imposes flow. The input effort or flow may be constant or a function of time. For example, a hydraulic pump providing a constant volume flow rate can be modelled as a flow source. Sources may also have a signal port for feedback control, such as controlled hydraulic pumps. In this case, they are modulated sources (i.e., MS_e or MS_f).

Energy dissipation: Resistors *R*, such as dampers dissipate energy. In other words, power flows into them without coming out.

Energy storage: Two bond graph elements store and give up energy without any loss: (i) capacitor or compliance *C* and (ii) inertia *I*. In bond graph terminology, an element that relates *e(t)* to *q(t)* is a capacitor. For instance, a spring relates the force inserted on it (i.e., *e(t)*) to its relative displacement (i.e., *q(t)*), and therefore it is a capacitor. Inertia relates *f(t)* to *p(t)*. For instance, the inertia element is used to model mass in mechanical systems, which relates linear velocity (i.e., *f(t)*) to momentum (i.e., *p(t)*).

Junctions: Two bond graph elements distribute power, without dissipating or storing it: (i) *0-junction* and (ii) *1-junction*. The efforts on all bonds of a *0-junction* are identical, and the algebraic sum of the flows vanishes. For a *1-junction*, the role of effort and flow is interchanged.

Energy transformation: Two bond graph elements transform energy while conserving power: (i) transformer *TF* and (ii) gyrator *GY*. A *TF* element, such as a mechanical gear relates the efforts at the ports (i.e., moments) and separately relates the flows (i.e., rotational speeds). A *GY* element, such as a gyroscope relates the effort of one port (i.e., force) to the flow of the other port (i.e., velocity) and vice versa. These elements may be modulated and have a signal port in addition to the power ports (i.e., *MTF* and *MGY*). Transformers may also change energy domain, such as hydraulic rams that transform hydraulic energy to mechanical energy.

After modeling all components using these nine elements, they can be linked by power or active bonds to form the whole system. There are well-defined procedures to follow to model physical systems. For more information on these procedures, see Karnopp et al. (2012e).

Table 4. Bond graph elements (adapted from Karnopp et al. (2012c); Khemliche et al. (2006))

Name	Symbol	Defining relationship*
Effort source	Se ⇀	$e = e(t)$
Flow source	Sf ⇀	$f = f(t)$
Resistor	⇀ R	$e = \emptyset_R(f)$
Capacitance	⇀ C	$\int f(t)dt = \emptyset_C\,(e)$
Inertia	⇀ I	$\int e(t)dt = \emptyset_I\,(f)$
0-junction	↽ 0 ⇀, ↿	1. common effort on all bonds 2. algebraic sum of flows = 0
1-junction	↽ 1 ⇀, ↿	1. common flow on all bonds 2. algebraic sum of efforts = 0
Transformer	⇀ TF ⇀ (m)	$e_{input} = me_{output}$ $mf_{input} = f_{output}$
Gyrator	⇀ GY ⇀ (r)	$e_{input} = rf_{output}$ $rf_{input} = e_{output}$

*$\emptyset_R$, $\emptyset_C$, and $\emptyset_I$ are single valued functions of resistance, capacitance, and inertia, respectively. m and r are the transformer modulus and gyrator modulus, respectively.

10.4.2 Causality

In the next step, causality should be assigned to the model. Some bond graph elements are constrained with respect to possible causalities, some are indifferent to causality, and some exhibit their constitutive laws in different forms for different causalities.

As mentioned earlier, S_e and S_f sources impose an effort and a flow on the system, respectively. Figure 5 shows the only possible causalities for these sources, where the causal stroke indicates the direction of effort signal. In contrast to the sources, resistors are indifferent to causality. For causality of other elements, see Karnopp et al. (2012a). There are well-defined procedures to follow to assign causality to the whole model. These sequential procedures are explained in Karnopp et al. (2012d).

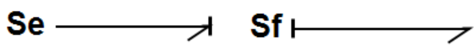

Figure 5. Causality of energy sources. S_e and S_f represent an effort source and a flow source, respectively.

System equations

Once the bond graph model is made and causality is assigned to it, state-space equations of the system can be derived in an orderly fashion, as explained in Karnopp et al. (2012d). One of the main benefits of bond graph method is its straightforward procedure for deriving system equations. Considering that bond graph method uses the same elements to model any system component irrespective of the energy domain, only one formulation and solution procedure is required.

By using a computer program, such as 20-sim, it is possible to directly simulate the bond graph model without deriving equations of motion manually. The 20-sim software has a library of bond graph elements. By using these elements and connecting them, the model is made. By formulating the equations underlying each element, the causality is defined. 20-sim automatically indicates non-preferred causalities that may lead to algebraic loops. It also derives the state-space equations automatically. Such programs are particularly useful when the model involves nonlinear constitutive laws since analytical results are seldom possible (Karnopp et al., 2012d).

10.5 Systems engineering (Article VI)

To address objective 2.2 (Section 8) systems engineering (SE) is used to assist ship owners, naval architects, and crew in harnessing environmental benefits of LNG without endangering safety and profitability (Article VI).

There is no commonly accepted definition of SE. For example, while INCOSE (2015)[1] defines SE as "an interdisciplinary approach and means to enable the realization of successful systems", IEEE P1220 (1994)[2] defines it as "an interdisciplinary collaborative approach to derive, evolve, and verify life-cycle balanced system solution which satisfies customer expectations and meets public acceptability". Despite the differences in the definitions, there are some common threads and areas of emphasis, such as (Blanchard and Fabrycky, 2011):

- A top-down approach: although classical engineering practices are required for designing components (using a bottom-up approach), the interrelations of the components and the way they perform together is usually overlooked.
- A life-cycle orientation: SE can focus on different phases, such as system design, development, operation, maintenance, phase-out, and disposal. In the past, the focus was on system design, with little consideration given to its impact on operations and maintenance for example. To identify the risks associated with decision-making, the decisions should be based on life-cycle considerations.
- A front-end definition of system requirements: the lack of an early definition of system requirements leads to individual design efforts downstream. SE emphasizes this early requirement definition and relates the requirements to design criteria to enhance decision-making. It also enables the traceability of these requirements from system level downwards.
- An interdisciplinary approach: such an approach enables a team approach to system design and development. It requires the understanding of different disciplines and their interrelations. This can facilitate addressing all system objectives.

The SE process is composed of a SE technical process and a SE management process. The technical process is the engineering work that supports and specifies the product in the life cycle. The management process supports the technical process with planning, review, and coordination. In other words, it makes the technical process work (Jacobs, 2011; Oliver et al., 1997). This thesis focuses on the SE technical process, which hereinafter is referred to as the SE process.

After tailoring the SE technical process, it comprises of six sequential steps and one iteration loop. In Article VI, Steps 1–5 are followed to shed light on safety and economic aspects of using LNG in fishing vessels and to increase ship owners, crew, and naval architects' knowledge. If these stakeholders find it feasible and promising to switch to LNG, they can further proceed to Steps 6 to plan for its implementation.

[1] International Council on Systems Engineering

[2] Institute of Electrical and Electronics Engineers (IEEE) Standard for Application and Management of the Systems Engineering Process

11 Contributions

This section contains a summary of the main results of different articles. More specific results and details are presented in Part II.

11.1 Contribution I

The analysis of energy efficiency in Norwegian fishing fleet

This contribution is in line with objective 1.1, which aims at defining the baseline for fuel efficiency of the Norwegian fisheries. This contribution resulted in Article I.

Article I identified the regulatory changes that affect the available data for analysis of fuel efficiency in the Norwegian fisheries. Based on these changes, this article conditioned the data to enable data analysis in the 2003–2012 period. The fuel efficiency of ten fleet segments were compared through the years of interest. Regarding the findings, the energy efficiency of all segments improved from 2003 to 2012, which is in line with recent studies elsewhere. Energy efficiency varied among the segments. Factory trawlers and coastal seiners were the least and most energy-efficient segments, respectively.

To investigate the reasons for the current levels of energy efficiency, factory trawlers were studied in detail since they were the least efficient segment. The article explored catch per unit of fishing effort (CPUE) (i.e., catch amount per days at sea), total stock biomass, fish quotas, and fuel prices as possible influential factors. Significant correlations between energy efficiency and CPUE, total stock biomass, and fish quotas were obtained, as opposed to a weak correlation with fuel price. Fish abundance and availability were the main reasons for the improvements in energy efficiency.

This article also examined the effect of combining fishing gears on efficiency, which to the knowledge of the authors is the first study to address this issue. Only five fleet segments were studied in this step due to lack of data on other segments: two groups of coastal seiners, two groups of conventional vessels, and purse seiners. Coastal seiners with multiple gears employ other gears, such as trawl in addition to seine. Such gears were more fuel intensive than seine. Therefore, coastal seiners with multiple gears were less efficient than the seiners with single gear. In the case of conventional vessels, the use of more efficient gears, such as seine in combination with conventional gears increased their efficiency. From 2003 to 2007, purse seiners with multiple gears were more efficient than purse seiners with one gear. However, the situation reversed after 2008. The changes in blue whiting quota and landings may explain this situation: trawls of purse seiners landed less blue whiting since 2008 and consequently their fuel efficiency reduced.

11.2 Contribution II

Providing a framework for overcoming the barriers to energy efficiency in shipping

This contribution is in line with objective 1.2, which aims at understanding the reasons for the hesitance of ship owners and operators in adopting cost-effective measures that can improve energy efficiency since the relevant literature in shipping is limited. This contribution resulted in Article II.

Based on the literature review and input from the participants in the EMIP II project, Article II provides a framework for overcoming the barriers to energy efficiency that are encountered in shipping. This framework consists of five iterative steps: (i) Identifying barriers and categorizing them, (ii) Analyzing the barriers and determining their criticality, (iii) Assigning possible measures for overcoming the most critical barriers, (iv) Assessing the influence of overcoming some barriers on the status of the others, and (v) Documenting results and follow-up.

In Step 1, Article II identified several barriers and categorized them in seven groups: (i) Information barriers, (ii) Economic barriers, (iii) Intra-organizational barriers, (iv) Inter-organizational barriers, (v) Technological barriers, (vi) Policy barriers, and (vii) Geographical barriers. Not all the barriers encountered in other sectors, such as manufacturing were found relevant to shipping (e.g., the low priority of energy efficiency). In addition, some barriers that are encountered in shipping, but may not be of relevance elsewhere (e.g., conflicting regulations) were added to the literature body. Ship owners and policy makers can use the findings in this step as a library of barriers faced in shipping. Then, they can assess whether individual barriers are relevant for them.

Although Article II does not prioritize the identified barriers in Step 2, it presents the viewpoints of the participants on the most and least important barriers to deal with. The results of this article show that different stakeholders have different viewpoints on barriers and their importance, which makes prioritization process complex. Ship owners and policy makers can use a structured approach, such as analytic hierarchy process[13] to prioritize the barriers to deal with as limited resources and time may not allow addressing all.

In Step 3, the participants suggested several measures for overcoming the barriers. Ship owners and policy makers can apply these measures to alleviate the barriers they

[13] See Triantaphyllou et al. (1999) for more information on this approach.

face. Step 4 touches upon the importance of a systems approach to solving barriers: the effect of solving or reducing some barriers on the others should be explored. Finally, Step 5 mentions the importance of documenting the knowledge gained in the previous steps for future reference. This knowledge can also be transferred to other organizations as a basis for solving their energy-related problems.

11.3 Contribution III

Investigating interactions between environmental regulations in shipping and fishing

This contribution is in line with objective 1.2, which aims at understanding the barriers leading to energy efficiency gap. It mainly focuses on understanding a group of barriers previously identified in Article II: policy barriers. This contribution resulted in Article III.

Article III identifies examples of interactions among environmental regulations in shipping and fishing. In this way, it aims at highlighting policy barriers and their effect on energy efficiency gap. In addition to interactions that act as policy barriers to energy efficiency, Article III reviews examples of institutional interactions that affect energy consumption and emissions in a broader context. For instance, Article III talks about adopting measures to reduce sea pollution (e.g., systems for ballast water treatment) that may indirectly increase fuel consumption. As another example, Article III refers to the problem of reducing emissions of vessels at the expense of increasing emissions in other life cycle stages (e.g., by using low sulphur HFO).

11.4 Contribution IV

Making a decision-making support that advises on fuel consumption of vessels and effectiveness of energy-efficient measures

This contribution is in line with objective 1.3, which aims at narrowing energy efficiency gap and, consequently, facilitating the adoption of energy-efficient and cost-effective measures. This contribution resulted in Article IV.

Article IV contributes to Step 3 of the framework provided in Article II: assigning possible measures for overcoming the most critical barriers. Information barriers are among the barriers identified in Article II. If a ship owner or operator faces such barriers, s/he may use the bond graph approach proposed in Article IV as a decision-making support for alleviating them.

Article IV uses the bond graph method to model the power system of a fishing vessel. The fuel consumption of the vessel during steaming, trawling, and hauling were found by simulating the bond graph model. The results were compared with measurements taken onboard the vessel by Sala et al. (2011). The bond graph model closely resembles the real operational measurements. In addition, the main energy consumers during different operations were specified. To illustrate the effect of using possible energy saving measures, the effect of reducing vessel speed while steaming was studied. The bond graph shows fuel savings by slowing steaming speed. However, the amount of fuel saved due to slower steaming is different from the amount obtained by the regression analysis conducted by Sala et al. (2011). The margin of error can be assigned to different reasons, which are explained in Article IV.

Although this model was made for a specific fishing vessel, it can be tailored to represent the power system of another fishing vessel or another vessel type. As mentioned in Section 10.4, the bond graph model includes several sub-models, such as propulsion system and winch system. The model was made systematically, and each sub-model can be modified or removed to resemble another machinery system. One can also model and add other sub-models (e.g., auxiliary engines) without the need to change the rest of the system. In addition, by changing the parameters in the control systems (See Section 10.4 and Article IV), one can simulate other operational conditions.

11.5 Contribution V

Clarifying the technical aspects of LNG-fuelled systems, their potential implementation costs, and the expertise and training needed for operating them in a safe manner

This contribution is in line with objective 2.2, which aims at transferring available knowledge on safety and economic aspects of using LNG to ship owners. This contribution resulted in Article VI. It should be noted that Article V, which is in line with objective 2.1, was performed as a preliminary study and starting point for Article VI. Article V reviewed some of the benefits and challenges of using LNG fuel for fishing vessels.

The progressively tightening environmental regulations complicate the investment decisions. Article VI uses the SE approach to assist in decision-making. The steps of the SE approach are explained through their application to design of a LNG-fuelled shrimp trawler: After stating the problem of knowledge transfer, Article VI reviews relevant information (e.g., safety regulations and environmental taxes and fund) for building and operating LNG-fuelled vessels. Then, based on regulations and requirements of stakeholders, some criteria[14] (i.e., compliance with safety requirements and life cycle cost) are defined to judge alternative LNG-fuelled solutions. In the next step, the available information is structured in three models to

[14] In SE terminology, these criteria are called measures of effectiveness. See Sproles (2001, 2002) and Article VI for more information.

better understand requirements, behaviour, and structure of the LNG-fuelled system. For illustration, the models are based on technical and operational requirements. These models clarify the logic in safety regulations and the functions and components required to meet them. By linking these models to the bowtie[15] analysis, Article VI shows how different requirements may mitigate the undesirable events and prevent accidents. Finally, the criteria are used to evaluate alternative designs. As an illustration, the life cycle cost of an alternative design is evaluated. In this alternative, the vessel only consumes LNG. In addition, to accommodate the gas unit, the vessel is elongated.

[15] A bowtie diagram is a graphical illustration of an accident scenario, starting from accident causes and ending with its consequences (Khakzad et al., 2012). See Article VI for more information.

12 Discussion

Supplementing the discussion of the individual articles in Part II, this section provides a discussion of the scientific and practical contribution of the work presented in the thesis as a whole. Section 12.1 reflects on theoretical and practical implications of this study. Section 12.2 evaluates the extent to which the research objectives are met. Section 12.3 notes the limitations of this study. Section 12.4 explains the data gaps encountered during the research.

12.1 Theoretical and practical implications

This thesis primarily focuses on reducing emissions via improving energy efficiency. In this regard, it first defines the baseline for the current energy consumption in the Norwegian fishing fleet. Second, it investigates the reasons behind the gap between the current efficiency and the higher potential efficiency. Third, it uses modelling and simulation to narrow the gap. Then, the thesis looks into the use of LNG as an alternative fuel for reducing emissions. In this regard, it gives an overview of pros and cons of LNG-fueled propulsion of fishing vessels. Then, it uses a systems approach to enhance the adoption of LNG fuel without endangering safety and profitability.

Article I serves as the first step towards increasing energy efficiency in Norwegian fisheries. Such a long-term energy analysis can serve as an input to the life cycle inventory of seafood products and enable a more accurate LCA. To the knowledge of authors, this is the first study to filter vessels based on their target species to avoid biased results due to the relative high fuel consumption for catching shrimp compared to other species. This contribution also puts different fleet segments into perspective. In this way, it pinpoints the least efficient segment and some of the factors that affect its efficiency. To my knowledge, this is also the first study to investigate the effect of employing a combination of fishing gears on energy efficiency. In this way, it shows the trade-offs between different regulatory decisions (e.g., quota distribution and gear combination on vessels) and fuel efficiency. Ship owners and policy makers can use the results to plan for enhancing energy efficiency of fishing vessels. Regulatory bodies can also plan for a more thorough data collection method based on the data gaps identified in Article I. In this way, more detailed data may be available for an improved data analysis. Although this article mainly focuses on Norwegian fisheries, its research approach and findings are of relevance to fisheries elsewhere.

Ship owners and policy makers can use the framework presented in Article II to overcome/alleviate the barriers they face and adopt available energy-efficient measures that are cost-effective. In this way, they may increase the energy efficiency in shipping. Even though the article focused on merchant shipping, it is expected to be relevant for fishing vessels, as well.

Although several studies focus on addressing individual regulations, few acknowledge interactions between these regulations. Institutional interactions have largely been overlooked in policy setting. In addition, ship owners may take a shortsighted approach to address current environmental regulations without considering the effect of their decisions in the presence of other possible regulations in the future. The unintended consequences of environmental decisions suggest that decisions should not be made in isolation. By focusing on institutional interactions, Article III highlights the importance of taking a holistic view on environmental regulations and tackling them in tandem.

The bond graph approach presented in Article IV can aid ship owners and operators in attaining a greater insight of the fuel consumption of their vessels and the major energy consumers onboard. Further, this approach can be utilized to study the effects of modifications either pre or post installation of any new energy saving technology (e.g., an alternative machinery system with diesel electric engine), retrofits, or changes in operational methodologies (e.g., slow steaming). Despite the uncertainties, the bond graph approach verifies the potential benefits of slower steaming speeds. Ship operators can therefore identify the value of this consideration and weigh its advantages (e.g., less fuel consumption) and disadvantages (e.g., delayed delivery of fish and increases in manning costs). Bond graph method can assist in decision-making regarding the determination of an optimum speed during various operations. It can also be used to check and modify the accuracy of measurement equipment early after their installation onboard the vessel.

Article V investigates the pros and cons of fueling fishing vessels with LNG. To my knowledge, Article VI is the first study to offer an approach for transferring knowledge on LNG-fueled propulsion from experienced sectors (e.g., offshore oil and gas supply vessels) to potential adopters of LNG (e.g., fishing vessels). This study shows how the SE approach may increase knowledge of ship owners, naval architects, and crew about the financial, technical, and operational aspects of using LNG fuel. Better insight of economic and safety aspects may support ship owners when evaluating the LNG option. Ship owners may also use this approach to plan for harnessing the environmental benefits of LNG without exposing crew and fishing vessels to higher risk. Moreover, naval architects may benefit from better management of available information and crew may improve their understanding of safety rationale. In fact, combining SE and bowtie analysis allows visualizing the potential effects when missing safety requirements. The suggested approach may be broadened and applied to other ship types. Additional requirements of stakeholders may be added to the SE models.

12.2 Research objectives revisited

In Section 8, two main objectives and five sub-objectives are defined. In addition, Figure 1 illustrates the link between the objectives and the focus of different articles. Section 11 further clarifies the contribution of articles to different objectives.

Objective 1.1 aims at investigating energy efficiency in Norwegian fishing fleet. Article I fulfills this objective. However, to increase accuracy of results, this study eliminates vessels with shrimp catch. Therefore, although this study increases the knowledge on energy efficiency of some vessel groups, it does not cover all the Norwegian fleet.

Objective 1.2 aims at investigating the barriers that hinder adoption of cost-effective and energy-efficient measures. Articles II and III fulfil this objective through literature reviews and discussions with some stakeholders in shipping. However, the identified barriers are not exhaustive. The participants in Article II were based in Norway and Iceland. Although they provide services globally, they may not be representative of all stakeholders in shipping, such as those in developing countries. In addition, they were working for a research institute, ship owning companies, or equipment suppliers. Most of them had a management position. Crew, policy makers, and classification societies, among others, may have other views on barriers.

Objective 1.3 is to enhance energy efficiency by reducing some of these barriers. Article IV addresses this objective. However, this article only focuses on a group of barriers (i.e., information barriers). Although the participants in Article II stressed these barriers, a ship owner may find other barriers more critical to deal with.

Objective 2.1 aims at investigating benefits and challenges of using LNG on fishing vessels. Although Article V supports this objective, it does not fulfill it totally. This article suggests the possibility of using LNG in fishing vessels and briefly touches upon the pros and cons of LNG propulsion. The main reason is that the scope of this study is rather limited, and it mainly is a preliminary study and starting point for Article VI.

Objective 2.2 is to propose an approach for transferring available knowledge on safety and economic aspects of using LNG to ship owners. Article VI fulfills this objective. Although there may be other approaches to fulfill this objective, the SE approach seems to be well suited to this objective since it provides an overall view of different aspects of LNG.

12.3 Limitations

Some limitations are due to the conscious definition of research boundaries and scope. Some other are related to resource constraints.

Although interdisciplinary, this study only looked into energy efficiency and LNG fuel as possible measures for reducing emissions from fishing. Other possible measures, such as cleaning exhaust gases were out of the research scope. In addition, some may argue that we can simply fish less to save both target species and fuel (i.e., energy conservation). This was also excluded from this study since it requires a broad knowledge on topics, such as food demand and the capacity of agriculture in fulfilling it.

This study also focuses on the emissions from fuel consumption of vessels. Other stages of the life cycle, such as vessel construction and onshore processing of seafood are out of the scope. This study also does not cover emissions from refrigeration onboard.

In Article I, it was not possible to distinguish fuel consumption for ship operation from the corresponding value for fish processing and cooling. In addition, this study did not correct for fuel used to catch bait.

Article II used a qualitative approach and more specifically, workshops for studying barriers to the energy efficiency gap. Although this approach illuminated the similarities and contradictions between the viewpoints of the participants, it is time consuming as the researcher should record the discussions among participants and later analyse them. In addition, focus groups are limited in size and availability; they include few people so that they can all participate in discussions. As a result, they provide depth rather than breadth. Surveys, on the other hand, can gather information from a larger sample in a relatively shorter time: they can provide breadth rather than depth.

Article III reviews some examples of interactions between environmental institutions in shipping and fishing. The examples, however, are not exhaustive.

Due to lack of data, some assumptions were made while modelling the energy system of a fishing vessel in Article IV. For instance, fuel consumption of icemakers, fridge, and deck pumps was estimated. In addition, measurements onboard add to inaccuracies. For instance, measurements of engine shaft moment may be imprecise.

Article V gave an overview on pros and cons of using LNG in fishing vessels; however, it did not go into details. It was meant to be an introductory study for Article VI. Despite its benefits, the SE approach used in Article VI has some limitations. Defining criteria (i.e., measures of effectiveness) may be challenging. Different stakeholders should agree on these measures well in advance to avoid costly future problems. Although models enable the investigation of systems from different perspectives, constructing accurate models is time and resource consuming. Professionals from different disciplines, such as naval architects, safety engineers, and equipment suppliers should collaborate to collect and analyse data. In addition, some stakeholders may be used to compiling and analysing data in text and document format. It may be difficult to define the relationship between requirements, barrier functions, and barrier elements as different pieces of information are spread across different documents. Finally, cost estimation for relatively new technologies, such as LNG propulsion, may be challenging.

12.4 Data gaps

During the course of this research, I experienced different obstacles while searching for relevant information. The obstacles were mainly encountered while working on Articles I, IV, and VI.

The Directorate of Fisheries, which provided the necessary data for Article I, changed its data collection and organisation methods over the years. Although these alterations were in accordance with regulatory changes, comparing data between years was difficult, and in some cases, impossible. The Directorate of Fisheries surveyed vessels primarily to analyse profitability rather than fuel efficiency. Therefore, fuel consumption for some participant vessels was not available. Moreover, even fewer vessels reported days at sea. Some vessels reported fuel consumption intermittently rather than continually. Although data were sufficient for data analyses, if more data were available, the uncertainties would have been reduced.

While working on Article IV and seeking information on the machinery system of a fishing vessel, I realized that the level of confidentiality for such data is high. I spent a great deal of my effort contacting different research institutes, shipping companies, and engine suppliers to access the relevant data for a fishing vessel. Most of the time, my request was refused due to confidentiality. In some other cases, I got general information that are of limited use when working with a data intensive bottom-up approach.

Gathering financial data for Article VI was rather challenging. There are handful of gas engine and equipment suppliers, which makes cost data confidential and less accessible. LNG price is highly uncertain and varies from one region to another. There is also room for negotiation on fuel price, both for MGO and LNG, for major fuel consumers.

13 Conclusions

This PhD thesis aims at contributing to the research body on environmental profile of fisheries. More specifically, this study focuses on reducing emissions of air pollutants from fishing vessels. The topic of emission reduction is rather broad and spans across several disciplines. As a result, this PhD study is interdisciplinary. Since the focus is on several disciplines, systems thinking has dominated this study. In this way, the focus is on "the big picture" and various factors and interactions that affect energy consumption and emissions rather than on one specific factor.

First, this study focuses on reducing the air emissions indirectly by increasing energy efficiency of fishing vessels. Second, this study explores the possibility of fuelling fishing vessels by an alternative fuel (i.e., LNG) and reducing emissions directly. The main contributions of this thesis are as follows:

- The analysis of energy efficiency in Norwegian fishing fleet,
- Providing a framework for overcoming the barriers to energy efficiency in shipping,
- Investigating interactions between environmental regulations in shipping and fishing,
- Making a decision-making support that advises on fuel consumption of vessels and effectiveness of energy-efficient measures, and
- Clarifying the technical aspects of LNG-fuelled systems, their potential implementation costs, and the expertise and training needed for operating them in a safe manner.

The results of this study show the benefit of taking a holistic view on the topic of energy efficiency and emission abatement in fisheries. By adopting systems thinking, "the big picture" is not lost due to focusing on a single aspect. By taking a systems view, several factors that affect energy efficiency were identified. In the same way, several barriers that lead to the energy efficiency gap were identified. A holistic view on environmental regulations enabled the identification of their interactions and possible effects on the environmental performance. An overall view on the power system of a vessel enabled the analysis of energy consumption for different operations. A systems view on different aspects of LNG was used to transfer existing knowledge on LNG to its possible future adopters.

The main goal of this research is fulfilled, and this study has contributed to the knowledge on energy efficiency of fishing vessels and the LNG alternative. Nevertheless, there is a need for future work and research to further improve environmental profile of fisheries.

14 Future work

Each of the objectives addressed in this thesis has the potential to be further elaborated in future work:

Objective 1.1: *to investigate energy efficiency in Norwegian fishing fleet*

Due to regulatory changes, the Directorate of Fisheries uses fragmented methods for collecting and organizing data in different years. Gathering data for the purpose of energy efficiency analysis might solve some of these problems. For example, higher-resolution data on vessel speed during fishing/steaming, on fishing grounds, and on hours spent fishing/steaming could increase the accuracy of the results. Additionally, the availability of fish quotas for individual vessels could be used to better explain the relationship between fish quotas and fuel efficiency.

In addition, this thesis focused on energy efficiency of vessels. Future work can address energy efficiency of other stages of the value chain, such as fish processing.

Objective 1.2: *to investigate the barriers that hinder the adoption of cost-effective and energy-efficient measures*

Future work should be conducted, for example, to study the viewpoints of more stakeholders, such as authorities, classification societies, agents, captains, crew, and charterer parties, who are not included here. Different stakeholders may encounter dissimilar barriers, and the benefit to all of them should be considered. They may also define different criteria with different weights for prioritizing barriers.

In addition, although focus groups give a detailed view on barriers, they are limited in size. Using surveys in combination with focus groups may further strengthen the findings and enable generalization.

To my knowledge, this study was the first to give an overview of institutional interactions in shipping. A future study may further expand this study and elaborates on it.

Objective 1.3: *to enhance energy efficiency by reducing some of these barriers*

This thesis focused on reducing information barriers. Future work can seek solutions to other types of barriers, such as inter-organizational barriers.

In addition, by accessing more accurate input data (e.g., from measurements onboard), the bond graph model can be improved.

Objective 2.1: t*o investigate benefits and challenges of using LNG on fishing vessels*

This thesis gave an overview of pros and cons of using LNG fuel by reviewing literature, which covers sectors other than fishing. Future work can include stakeholders from fishing industry to corroborate the relevance of the findings to fishing.

Objective 2.2: *to propose an approach for transferring available knowledge on safety and economic aspects of using LNG to ship owners*

In this study, SE models were made based on safety requirements. Additional requirements of stakeholders (e.g., requirements on fishing operation) may be considered. The SE models can be expanded accordingly.

In this study, the economic feasibility of one alternative design was considered. The economic feasibility of alternative LNG-fueled designs, such as the use of dual fuels (i.e., MGO and LNG) can be studied. The use of smaller fish holds for accommodating LNG tanks may be another interesting alternative.

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Part II

Articles

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Energy efficiency of Norwegian fisheries from 2003 to 2012

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ABSTRACT

Operation of the Norwegian fishing fleet in harsh waters is energy demanding. The large amount of fuel consumption combined with the associated fuel costs, emission taxes, environmental concerns, and emission regulations call for improved energy efficiency within fisheries. This study examined the energy efficiency of the Norwegian fishing fleet from 2003 to 2012. The goal of this study was to determine the important statistical characteristics and to facilitate the development of future strategies to improve fuel efficiency. Data analysis was performed with R programme, an open source software for statistical computing. First, vessels with single gear were explored. Ten fleet segments within the demersal and pelagic fisheries were compared. Energy efficiency varied among the segments. Factory trawlers, with a mean fuel use coefficient of 0.354 kg fuel/kg fish, and coastal seiners, with a mean fuel use coefficient of 0.054–0.058 kg fuel/kg fish, were the least and most energy-efficient segments, respectively. Nevertheless, the energy efficiencies of all of the segments have improved over recent years. The effects of catch per unit of fishing effort, total stock biomass, fish quota, and fuel price on energy efficiency were explored for factory trawlers. Correlations between energy efficiency and these factors were found. Fluctuations in energy efficiency were primarily due to changes in fish abundance and availability. Energy efficiency and fuel price showed the weakest long-term correlation. Little evidence of technological improvements, which affect energy efficiency, was found either. Second, the effect of employing multiple gears was explored. Coastal seiners, conventional vessels, and purse seiners with single gear were compared with corresponding vessels with multiple gears. Employing other gears in addition to seine on coastal seiners rendered them less efficient, as the additional gear (e.g., trawl) was more energy demanding. The opposite was observed for conventional vessels: using more efficient gears (e.g., seine) in combination with the main gear made conventional vessels more energy-efficient. Purse seiners with multiple gears used trawl to catch blue whiting (*Micromesistius poutassou*); therefore, the efficiency of the trawl was affected by the fluctuations in blue whiting catch and abundance during the years. The energy efficiency of fisheries may be improved by inclusion of energy efficiency in political goals, improvement in fish stocks, better allocation of quotas, and imposition of fuel and emission taxes. Energy efficiency can be further improved by the introduction of energy-saving technologies and alternative fuel systems.

1. Introduction

The fishing industry has evolved along with technological, operational, and institutional developments. The goals of these advancements are to maximise and preserve catch and to implement safe practices (Eigaard et al., 2014). Powerful engines, mechanical hauling systems, and onboard freezers increase the mobility of fishing vessels, thus increasing their harvesting abilities (Standal and Utne, 2011). As a consequence, fisheries are strongly dependent on fossil fuels for shipbuilding, propulsion, fish harvest, and refrigeration (Parker and Tyedmers, 2014; Tyedmers, 2004).

Fuel is one of the primary costs associated with fishing, and its proportion varies among fisheries (Sumaila et al., 2008) (Table 1). Different factors, such as target species, the status of fish stocks, fish quotas, harvesting methods, the distance to fishing grounds, fleet age/condition, and fuel subsidies/taxes affect fuel consumption and fuel cost. Larger vessels in general are more dependent on fuel prices because fuel is a larger proportion of the operational costs of large vessels than for smaller vessels. For small vessels, labour is more than half of the operational costs (STECF, 2013). However, there are some exceptions. For example, purse seiners and pelagic

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Table 1
Share of fuel cost for different fisheries.

Fishery, year	Fuel cost/operational costs (%)	Source
Italian fishing fleet, 2011	38	(STECF, 2013)
54 fishing fleet segments in Europe (aggregated), 2008	29	(Cheilari et al., 2013)
European demersal/beam trawlers, 2008	50	(Cheilari et al., 2013)
European artisanal fleet, 2008	5	(Cheilari et al., 2013)
Commercial fisheries in Hong Kong, 2007	60	(Sumaila et al., 2007)
Australian abalone harvested by divers, 2012	3	(Parker et al., 2015)
Australian Torres Strait prawn harvested by bottom trawlers, 1993–2008	51	(Parker et al., 2015)
Norwegian shrimp trawlers, 1980–2005	35[a]	(Schau et al., 2009)

[a] Fuel cost/operational revenues (%).

trawlers are energy-efficient (Parker and Tyedmers, 2014; Schau et al., 2009) and more flexible in response to fuel prices, despite their large size. Fig. 1 shows the breakdown of operational costs for an average Norwegian demersal/pelagic vessel in 2013. In demersal and pelagic fisheries, labour wages and fuel costs were the primary expenses. Labour wages and shares to the crew accounted for approximately 39% and 34% of the operational costs in demersal and pelagic fisheries, respectively, and fuel and lubrication oil accounted for 14% and 13% of the operational costs (Directorate of Fisheries, 2015).

Fishing vessels accounted for approximately 1.2% of the worldwide oil consumption and 134 million tonnes of carbon dioxide (CO_2) emissions in 2000 (Tyedmers et al., 2005). The International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI was revised in 2011 to increase the energy efficiency of ships and to reduce greenhouse gas (GHG) emissions by introducing the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) (IMO, accessed 2013a). Although the EEDI does not currently apply to fishing vessels, corresponding regulations may be enforced in the future (Bazari and Longva, 2011). In 2012, the Doha Amendment to the Kyoto Protocol was adopted to reduce GHG emissions of involved parties, including Norway, during the new commitment period of 2013–2020 (UNFCCC, accessed 2014).

Additionally, fishing vessels emit sulphur oxides (SO_X), nitrogen oxides (NO_X) (Ellingsen et al., 2009), and particulate matter (PM). Fishing vessels of 400 GT and higher comply with the MARPOL Annex VI, which regulates SO_X, NO_X, and PM (DNV GL, 2014; IMO, accessed 2013b). In 2012, the Gothenburg Protocol was revised to set, among other factors, NO_X ceilings for 2020. Norway ratified this protocol (UNECE, accessed 2014). To comply with the Gothenburg Protocol, Norway introduced a NO_X tax in 2007. The NO_X tax applies to different sectors, including domestic shipping and fishing. In 2008, the Norwegian state and 14 business organisations reached a NO_X agreement for the 2008–2010 period. Later, the same members and an additional business organisation signed a NO_X agreement for 2011–2017. As part of the agreement, the involved parties cofounded a NO_X fund, and they pay a smaller amount to the NO_X fund instead of the tax when emission-reducing measures are implemented. The fund supports NO_X-reducing measures in addition to covering administrative costs. The Norwegian Fishermen's Association, the Norwegian Fishing Vessel Owners' Association, and the Norwegian Seafood Federation are among the cooperating organisations (EFTA, 2011; Høibye, 2012; NHO, 2013; Åsen, 2013).

Seafood consumers and other relevant stakeholders are becoming aware of the environmental consequences of fishing, and they may request environmental information to select green seafood products. Therefore, the environmental impacts of seafood products may influence the market shares (Magerholm Fet et al., 2010). Conventional fishery research has addressed the direct environmental effects of fishing, such as decreasing the size of

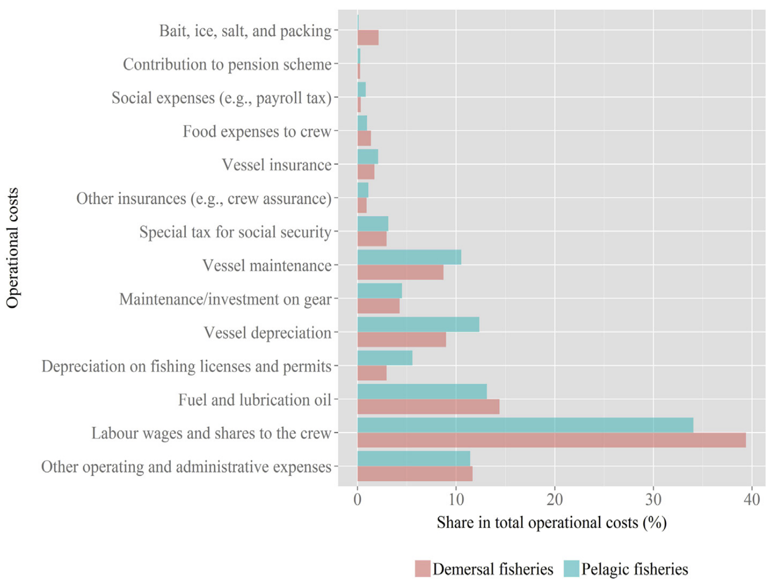

Fig. 1. Operational costs for an average Norwegian demersal/pelagic vessel in 2013 (based on Directorate of Fisheries, 2015).

target fish stocks, the effects on bycatch stocks, ghost fishing, and the effects of bottom trawlers on the seabed. Until recently, the indirect environmental effects of fishing have been underestimated, and they are related to the use of fossil fuels, antifouling substances, and refrigerants on fishing vessels, among other things (Schau, 2012; Winther et al., 2009).

Several studies have investigated the relative environmental impacts of various steps in the value chain of fish products. The fuel consumption of fishing vessels is the greatest share of energy consumption and greatest cause of emissions in the value chain of seafood products, except for cases with airborne transportation (Avadí and Fréon, 2013; Ellingsen and Aanondsen, 2006; Parker et al., 2015; Parker and Tyedmers, 2014; Schau et al., 2009; Svanes et al., 2011; Tyedmers, 2004; Ziegler et al., 2013). Besides, the most energy-intensive fisheries often have the highest seafloor effect and bycatch. Therefore, energy use is suggested as an indicator of the overall environmental burdens associated with fisheries (Ziegler et al., 2013). Ramos et al. (2011) performed life cycle assessment (LCA) of Basque coastal purse seiners over an eight-year period. Energy use in the fishery dominated most of the impact categories. However, environmental burdens varied substantially over the years due to variations in stock size. Their study highlighted the importance of extending life cycle inventories (LCI) over long periods to increase the accuracy of the results.

These restrictive, primarily economic, factors act as incentives to improve the energy efficiency of fishing fleets and to ensure economically and environmentally sound fisheries. Thorough knowledge of the current level of energy efficiency is required to identify the status of a fishery in the market and to identify the explanations for the current state of efficiency. Additionally, energy analyses over long periods are relevant to fisheries' LCA due to the acknowledged importance of fuel consumption to the associated environmental impacts (Avadí and Fréon, 2013; Ramos et al., 2011). Long-term energy analyses can serve as an input to the LCI of seafood products and enable a more accurate LCA. Such information can serve as a baseline and a foundation for decision-making and improvements. Improvements in energy efficiency may be followed by increased vessel speed instead of reduced fuel consumption (Faber et al., 2011). In other cases, increased energy efficiency may be followed by increased fuel consumption, known as the 'rebound effect'. This effect may outweigh the savings that could be gained (Sorrell, 2014; Sorrell and Dimitropoulos, 2008). Although fish quotas limit fishing efforts, potential disadvantages should be considered when developing future strategies to improve fuel efficiency.

This study identified the level of energy efficiency in Norwegian fisheries from 2003 to 2012 and compared different fishing gears in terms of energy efficiency. This study concentrated on the fuel consumption of fishing vessels, and it excluded energy consumption for shipbuilding and onshore processing, among others. Energy efficiency is defined as the fuel input to a fishing vessel per amount of output or captured fish. A fuel use coefficient (kg fuel/kg fish) was used as an indicator of energy efficiency. High fuel use coefficients indicate low energy efficiency and vice versa.

This article is a follow-up to a study on the fuel consumption of Norwegian fisheries covering the 1980–2005 period (Schau et al., 2009). Ten fleet segments were studied, which reflected the latest grouping of Norwegian fisheries by the authorities. To investigate the reasons for the current levels of energy efficiency, factory trawlers were studied in detail because they were the least efficient segment. This article explored the catch per unit of fishing effort (CPUE: catch amount per days at sea), total stock biomass, fish quotas, and fuel prices as possible influential factors. The article also examined the effect of combining gears on efficiency. In this regard, the efficiency of vessels with single gear was compared with the efficiency of vessels with multiple gears.

The remainder of this article is organised as follows. Section 2 briefly states the structural and economic aspects of Norwegian fisheries. Section 3 explains the materials and methods. Section 4 presents the results, followed by a discussion in Section 5 and conclusions in Section 6.

2. Norwegian fisheries

Norway is surrounded by the Skagerrak to the south, the North and Norwegian Seas to the west, and the Barents Sea to the north and northeast. Norway has established two zones of 200 nautical miles in addition to the Norwegian exclusive economic zone (EEZ), consisting of the two fishery protection zones around Svalbard and Jan Mayen. Norway holds several fishing agreements with Russia, the European Union, Iceland, the Faroe Islands, and Greenland. These agreements specify the total allowable catch (TAC) and quota distribution among the involved parties (FAO, accessed 2014; NFD, 2011; OECD, 2013).

The Norwegian fishing fleet consists of different fishing gears, such as handline, longline, Danish seine, trawl, and purse seine (FHL and NSC, 2012). The Norwegian fisheries are divided into pelagic and demersal fisheries. The pelagic fisheries target Atlantic herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*), northeast Atlantic mackerel (*Scomber scombrus*), and capelin (*Mallotus villosus*), among others. The demersal fisheries catch Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*), Atlantic redfish (*Sebastes mentella*), and northern prawn (*Pandalus borealis*), among others (Directorate of Fisheries, 2013b, 2014b).

In 2013, Norway was the second largest exporter of seafood products worldwide, providing seafood to customers in more than 140 countries. In the same year, the value of Norwegian seafood exports exceeded NOK 60 billion (one Norwegian krone (NOK) ≈ 0.13 EUR ≈ 0.17 USD in 2013). Aquaculture and capture fisheries accounted for 69% and 31% of the export value, respectively (Norges Bank, accessed 2014a; NSC, accessed 2014b).

In 2013, the Norwegian fishing fleet included 6128 vessels with an average age of 27 years. The Register of Fishermen listed 11601 fishermen in 2013 (Directorate of Fisheries, 2014c). The Directorate of Fisheries published the preliminary figures for the Norwegian catch weight and value in 2013. The Norwegian catch exceeded 2 million tonnes live weight, with Atlantic herring and cod accounting for 22.62% and 21.07% of the total catch, respectively. Moreover, the first-hand value[1] of the Norwegian catch was more than NOK 12 billion. Atlantic cod and herring were the most economically dominant species, accounting for 31.90% and 19.15% of total first-hand values, respectively (Directorate of Fisheries, 2014b). Table 2 presents the share of different species in Norwegian catch weight and value.

3. Materials and methods

3.1. Data sources

Some of the responsibilities of the Directorate of Fisheries are to collect data on a sample population of Norwegian fisheries as input for policy making (Directorate of Fisheries, 2010) and to conduct

[1] "The value of catch is the amount paid to the fishermen for the catch (first-hand value). This includes freight and price subsidies and special taxes (paid to social security, tax to finance control activities and contribution to pension scheme), but not tax to the sales union. Value added tax is not included" (Directorate of Fisheries, 2014b).

Table 2
Preliminary figures for Norwegian catch weight and first-hand value in 2013 (based on Directorate of Fisheries, 2014b).

Fish species	Share in total catch weight (%)	Share in total catch value (%)
Pelagic	49.62	37.92
Demersal excluding crustaceans	36.24	56.20
Crustaceans	7.24	5.65
Seaweed	6.88	0.24

annual surveys to evaluate the profitability of Norwegian fisheries. These surveys represent fishing vessels with a specific minimum income. For example, the profitability survey of 2012 represented 1565 vessels corresponding to 89% of total first-hand value in Norwegian fisheries, which was composed of 6211 vessels. However, only a subset of these vessels (e.g., 335 vessels in 2012) were surveyed (Directorate of Fisheries, 2013b) (Appendix A). Sampling of vessels for the profitability surveys consists of three steps: first, vessels are grouped based on their operation and length. Then, the number of sample vessels from each group are determined: the income of each group relative to the total income determines the number of vessels to be drawn from each group; therefore, more samples are drawn from the groups with higher income. Finally, the samples are drawn using simple random sampling without replacement.

Appendix B divides the Norwegian fishing fleet and vessels represented/studied in the profitability surveys based on their overall lengths in 2012. The vessels represented by the Directorate of Fisheries accounted for approximately 14%, 60%, and 95% of all of the vessels less than 11 m in overall length, 11–27.9 m in overall length, and greater than 28 m in overall length, respectively. Therefore, most of the largest vessels, such as factory trawlers, were covered.

The Directorate of Fisheries provided two datasets that covered sample fleet populations from 2001 to 2012. One dataset included anonymous vessel names and the corresponding operational codes (i.e., "driftskoder" in Norwegian), characteristics (e.g., overall length and engine power), days at sea, fuel consumption, and operational costs (e.g., fuel price) and revenues. The other dataset included anonymous vessel names with their target species; it documented the round (live) weight and value of each species along with the fishing gear used (Directorate of Fisheries, 2014a).

Statoil Fuel & Retail is a leading Scandinavian fuel retailer (Statoil Fuel and Retail, accessed 2014). Statoil Fuel & Retail provided the average market prices for fuel incurred by Norwegian factory trawlers from 2003 to 2013 (Husebø, Personal communication in 2014). These prices were compared with the corresponding values obtained from the Directorate of Fisheries to validate the fuel cost claims by fisheries.

Norway has separate management plans for northeast Arctic and North Sea cod, saithe, and haddock (NFD, 2013a,b,c). Most of the Norwegian catches of cod, saithe, and haddock are northeast Arctic species (Directorate of Fisheries, 2014b). For example, more than 90% of the cod catch was from the northeast Arctic cod stock (NSC, accessed 2014a). Therefore, this study focused on the total stock biomass of northeast Arctic cod, saithe, and haddock. The total stock biomass data of these species were derived from the Statistics Norway database (Statistics Norway, 2014a). Statistics Norway is an agency that collects official statistics in Norway (Statistics Norway, 2014b). The stock figures are based on estimates from the International Council for the Exploration of the Sea (ICES) and the Institute of Marine Research (Statistics Norway, 2014a). ICES evaluates fish stocks based on information gained from landings at ports, fisheries, and research vessel surveys. After data collection, scientists use mathematical models to combine the available data. In ICES working groups, which focus on fish stocks in different regions, mathematical models are discussed. In addition, independent scientists review stock estimates from working groups (ICES, 2014).

The Directorate of Fisheries publishes annual national quotas and their distribution among fleet segments. The open source database of the Directorate of Fisheries provided input on Norwegian fish quotas (Directorate of Fisheries, 2013a). Additionally, the Organisation for Economic Cooperation and Development (OECD) publishes reviews of fisheries in OECD countries, including Norway. These reviews provide information on aggregated national quotas for important species in Norwegian fisheries (OECD, 1997–2013).

3.2. Fleet segments

The Directorate of Fisheries used different data collection and organisation methods during the years of interest. Some of the changes were as follows:

- Prior to 2003, one could distinguish among gillnet, handline, Danish seine, longline, and miscellaneous gears, whereas currently, all of these are grouped as conventional gears. These vessels (i.e., conventional vessels) were further subdivided. Since 2003, quota length (i.e., "hjemmelslengde" in Norwegian) replaced overall length as the benchmark for the subdivision. Thus, groups of different lengths and operational codes represented these vessels during the years of the study. In Norway, traditionally, vessel length was the basis for quota allocation among coastal vessels. However, it is not desirable to extend a vessel or replace it with a larger one to claim a larger quota at the expense of other vessels. Therefore, the vessel length on a specific date (i.e., "skjæringsdato" in Norwegian) is the basis for quota allocation, called the quota length (NFD, 2007). The vessel owners can still change to larger or smaller vessels; however, this will not affect the quota. Therefore, quota length might differ from actual vessel length, which was the case for approximately 600 vessels (Standal and Hersoug, 2014).
- Conventional vessels were divided into five, six, and five groups based on their quota length from 2003 to 2006, 2007 to 2008, and 2009 to 2012, respectively.
- In 2001–2002, wet fish trawlers, factory trawlers and other/small trawlers (i.e., trawlers without quotas or with limited quotas) were identified. In 2003–2008, wet fish trawlers and factory trawlers were further divided based on shrimp quotas. After 2009, these trawlers were grouped together.
- In 2001–2002, coastal seiners were divided into six groups based on their overall length. After 2003, they were grouped based on quota lengths. However, the number of groups changed over time, and in 2003–2006, 2007–2008, and 2009–2012, coastal seiners were subdivided into six, seven, and three groups, respectively.
- In 2001–2002, the cargo capacity and holding a blue whiting license were the criteria for grouping purse seiners. In 2003–2008, purse seiners were grouped based on whether they held a purse seine license only or a pelagic trawl/blue whiting license as well. After 2009, they were unified as purse seiners.

To maintain consistency, this study covered the 2003–2012 period. Data analysis contained some of the latest fleet segments as of 2012. However, some groups were merged for data comparison during the years of the study because the quota lengths of individual vessels were not available. Appendix C presents data conditioning for the conventional vessels as an example. A similar approach was used for the coastal seiners and purse seiners. The wet fish trawlers and factory trawlers were traced back to 2008 or even earlier for identification as they were not separated after 2009. No data conditioning was required for pelagic trawlers because their data collection and organisation did not change over the years. The following fleet segments were covered:

- Coastal seiners less than the 21.36 m quota length (coastal seiners less than 11 m were combined with 11–21.35 m quota length seiners.),
- Coastal seiners larger than or equal to the 21.36 m quota length,
- Conventional vessels less than the 15 m quota length (conventional vessels less than 11 m were combined with 11–14.9 m quota length vessels.),
- Conventional vessels with a quota length of 15–20.9 m,
- Conventional vessels with a quota length of 21–27.9 m,
- Conventional vessels with a quota length larger than or equal to 28 m (i.e., autoliners and miscellaneous vessels),
- Factory trawlers,
- Pelagic trawlers,
- Purse seiners, and
- Wet fish trawlers.

3.3. Catch type

The resolution of the data did not allow the fuel consumption to be treated separately for catching various species. For consistency, vessels within the fleet segments previously described (Section 3.2) with shrimp catch were excluded from this study because of a higher fuel use coefficient for catching shrimp than for catching other species (Parker and Tyedmers, 2014; Schau et al., 2009). Shrimp trawlers were also excluded because they catch other species in addition to shrimp.

3.4. Number of gears employed on vessels

In the Norwegian fisheries, a vessel may use different gears to catch different species in different seasons in order to increase profitability. For example, a pelagic trawler may use conventional gears in addition to trawling. In recent years, the gear with the largest landing specified the vessel group (Persen, Personal communication in 2014). However, with the resolution of the available data, determining the fuel consumption of the different gears was not possible. Therefore, data analysis was conducted in two steps:

In the first step, the goal was to compare different gears regarding fuel efficiency. Therefore, vessels with multiple gears were excluded from the analysis. Some vessels employed only one gear to catch fish despite having multiple gears. Such vessels were treated as single gear vessels. All the fleet segments previously described (Section 3.2) were explored in this step. The factory trawlers were further studied to investigate the factors that may affect efficiency. Among the factory trawlers only one employed multiple gears and was excluded.

In the second step, the goal was to explore the effect of employing multiple gears on fuel efficiency. Therefore, the vessels with single gear were compared with the vessels with multiple gears within the same fleet segments. Only five fleet segments were studied in this step due to lack of data on other segments: (i) coastal seiners less than the 21.36 m quota length, (ii) coastal seiners larger than or equal to the 21.36 m quota length, (iii) conventional vessels less than the 15 m quota length, (iv) conventional vessels with a quota length of 21–27.9 m, and (v) purse seiners.

In the datasets, some vessels did not include information on fuel consumption and/or days at sea. In this study, only vessels with fuel consumption information were included. In the examination of the relationship between energy efficiency and CPUE, only vessels with information on both fuel consumption and days at sea were included. Table 3 shows the populations of samples covered in this study. Appendix B divides the samples covered in this study in 2012 based on their overall lengths. The vessels studied in this article covered approximately 84%, 76%, and 70% of the vessels less than 11 m in overall length, 11–27.9 m in overall length, and greater than 28 m in overall length, which were studied in the profitability surveys, respectively.

3.5. Statistical analyses

First, the two datasets provided by the Directorate of Fisheries were merged for cross-analysis. The data analysis was performed with the R programme, an open source software for statistical computing and graphics (Ihaka and Gentkeman, 1993).

The Directorate of Fisheries provided the fuel dataset in litres, and the main fuel consumed by fishing vessels was marine gas oil. A density of 0.86 kg/L was used to convert fuel data to kilograms (NP, 2013). The fish landing values were in round weight. The operational costs and revenues provided to this study were nominal values in NOK. The year 2012 was considered the basis for converting nominal values to real, or inflation-adjusted, values. The price calculator of Norges Bank, which is Norway's executive and advisory body for monetary policy, served this purpose (Norges Bank, 2007; accessed 2014b).

As mentioned previously, the fuel use coefficient was used to indicate energy efficiency of Norwegian fisheries. The fuel use coefficients of fleet segments were calculated and compared. In contrast to individual vessels, the focus in this study was on fleet segments as a unit. Thus, to calculate the fuel use coefficient, the total fuel consumption of a fleet segment was divided by its total catch. This calculation might affect the results differently from an approach that focused on individual vessels, for which the fuel use coefficient was calculated for individual vessels, and the mean value was determined.

Tukey's boxplot was constructed to display the data distribution (i.e., fuel use coefficients of factory trawlers), with the boxes representing the lower quartile (Q_1), median, and upper quartile (Q_3) of values. The whiskers represented the lowest data within a 1.5 interquartile range (i.e., 1.5 (Q_3 − Q1)) of Q_1 and the highest data within a 1.5 interquartile range of Q_3 (Wikipedia contributors, 2014).

Some figures include shaded areas, which show the 95% confidence areas of the regression lines. The confidence area combines the confidence intervals of the slope and intercept. The regression line is the best-fit line determined from a particular sample of the entire population. Therefore, it is unlikely to be the best-fit line for the entire population. Thus, there is 95% certainty that the overall best-fit regression lies somewhere within the confidence area. The confidence areas are curved but do not allow for the possibility of a nonlinear relationship between the variables. The curvature is only a method of encompassing the possible straight lines (Motulsky, 2014).

3.6. System boundary

This study focused on the fuel consumption of fishing vessels. Factory trawlers process fish on board, whereas other vessels, such as wet fish trawlers, land fresh fish. Therefore, the fuel consumption

Table 3
Population of the studied samples.

Year	Vessels with single gear and fuel consumption information in this study[a]	Vessels with single gear and fuel consumption and days at sea information in this study[a]	Vessels with multiple gears and fuel consumption information in this study[b]
2003	323	149	92
2004	298	109	123
2005	295	218	153
2006	275	175	116
2007	296	196	101
2008	274	198	97
2009	139	100	84
2010	129	99	85
2011	161	105	66
2012	161	125	91

[a] Excluding (i) other/small trawlers, (ii) vessels with shrimp catch, and (iii) one trawler in 2011 and two trawlers in 2012 that could not be traced back to 2008 or earlier to identify whether they were wet fish trawlers, factory trawlers, or other/small trawlers.
[b] Including (i) coastal seiners less than the 21.36 m quota length, (ii) coastal seiners larger than or equal to the 21.36 m quota length, (iii) conventional vessels less than the 15 m quota length, (iv) conventional vessels with a quota length of 21–27.9 m, and (v) purse seiners with no shrimp catch.

of factory trawlers included energy for fish processing. Schau et al. (2009) allocated 5–7% of fuel consumption of factory trawlers to fish processing.

Larger vessels used fuel onboard to cool the fish, whereas smaller vessels used ice produced onshore. Therefore, for the larger vessels, energy for cooling the fish was included in this study. However, the corresponding energy consumption is assumed negligible (Schau et al., 2009).

Some fishing vessels, such as longliners, used bait when fishing. This study did not correct for fuel consumption used to catch bait. Schau et al. (2009) allocated 12–13% of fuel consumption to bait.

4. Results

4.1. Energy efficiency of Norwegian fisheries

Fig. 2 illustrates the fuel use coefficients of Norwegian fishing fleet segments from 2003 to 2012. The fuel use coefficients of all of the fleet segments exhibited decreasing trends. The most energy-efficient gears were the coastal seiners and purse seiners. Coastal seiners below and above the 21.36 m quota length had mean fuel use coefficients of 0.054 and 0.058 kg fuel/kg fish, respectively. Purse seiners had an average fuel use coefficient of 0.085 kg fuel/kg fish. Factory trawlers and wet fish trawlers were the least energy-efficient segments, with mean fuel use coefficients of 0.354 and 0.322 kg fuel/kg fish, respectively.

4.2. Factory trawlers

Factory trawlers were further studied to investigate possible factors that influenced the variation in fuel use coefficients, and this study focused on factory trawlers because of their low energy efficiency compared with other fleet segments (Fig. 2). Fig. 3 illustrates the distribution of the fuel use coefficients of factory trawlers from 2003 to 2012. There is considerable difference in the fuel efficiencies of vessels using the same fishing technique, even within a specific year. For example, the fuel use coefficients of factory trawlers ranged from approximately 0.31 to 0.55 kg fuel/kg fish in 2007. In 2003, the fuel use coefficients of factory trawlers ranged from 0.30 to 0.47 kg fuel/kg fish, except for one outlier vessel with a

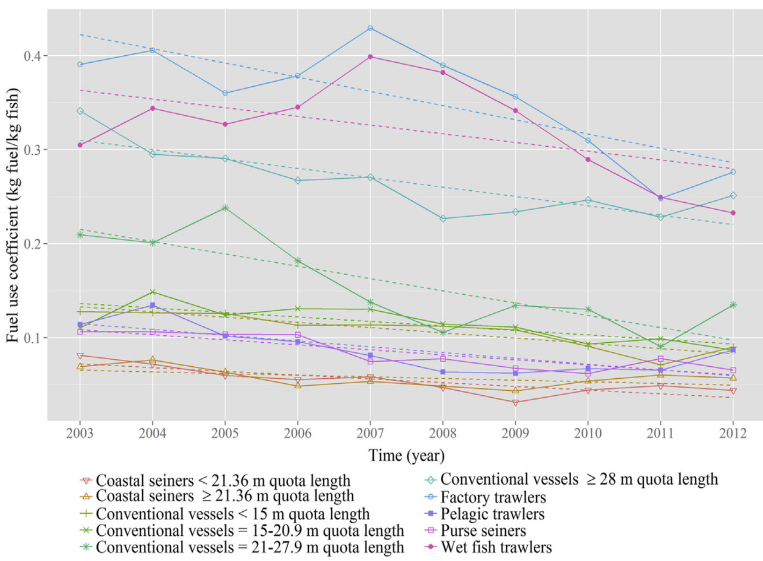

Fig. 2. Fuel use coefficients of segments of Norwegian fisheries from 2003 to 2012. Dashed lines represent trends.

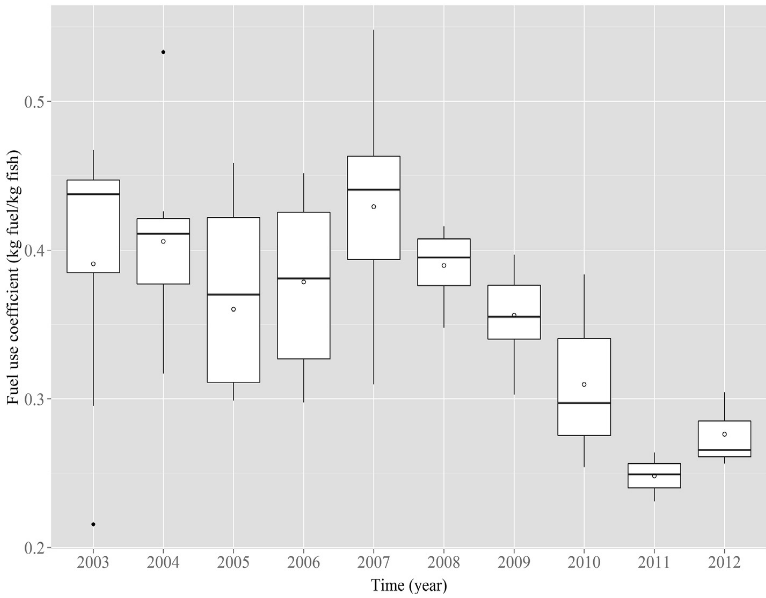

Fig. 3. Distribution of the fuel use coefficients of Norwegian factory trawlers from 2003 to 2012. The boxes represent the 1st and 3rd quartiles, with the median. The whiskers follow Tukey's method. The black dots are outliers, and the white dots are the fuel use coefficients of the fleet segment, as shown in Fig. 2.

fuel use coefficient of 0.22 kg fuel/kg fish. There was also an outlier vessel in 2004.

Fig. 4 compares the shares of the five primary fish species landed by Norwegian factory trawlers from 2003 to 2012. In 2003 and 2004, saithe, Atlantic cod, and Atlantic redfish were the three largest catches, accounting for more than 80% of the landings, with haddock in the fourth place. From 2005 to 2012, the haddock catch exceeded Atlantic redfish. Since 2005, saithe, Atlantic cod, and haddock comprised more than 90% of the catch on average.

4.3. Influential factors

Fig. 5(a)–(c) show the fuel use coefficient, CPUE (1000 kg fish/days at sea), and fuel use per unit of fishing effort (FPUE: 1000 kg fuel/days at sea) of factory trawlers during 2003–2012, respectively. As illustrated in Fig. 5(a), the fuel use coefficient of factory trawlers decreased from 2003 to 2012. During this period, the CPUE markedly increased (Fig. 5(b)), whereas the FPUE remained more stable (Fig. 5(c)).

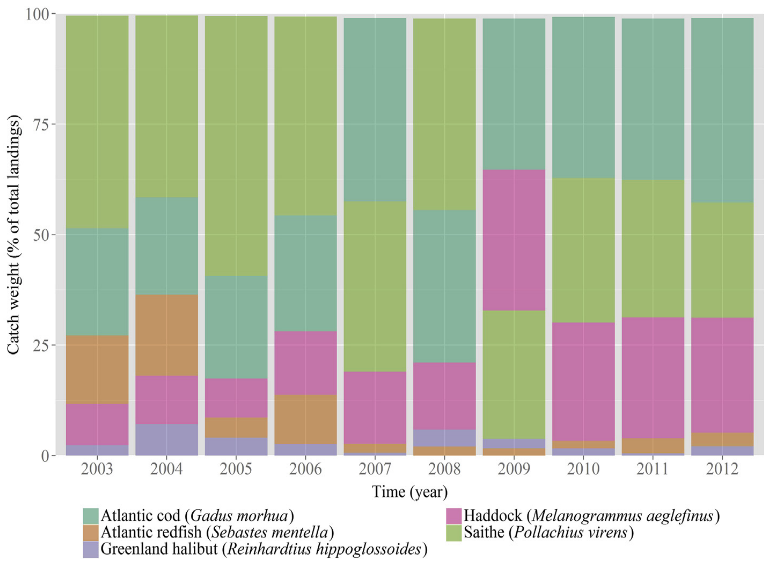

Fig. 4. Main catches of Norwegian factory trawlers from 2003 to 2012.

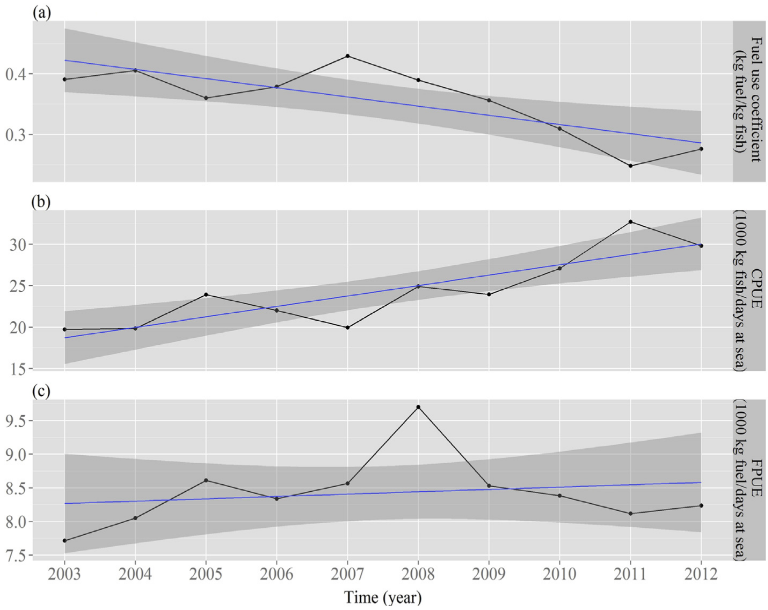

Fig. 5. (a) Fuel use coefficient, **(b)** catch per unit of fishing effort (CPUE), and **(c)** fuel use per unit of fishing effort (FPUE) of Norwegian factory trawlers from 2003 to 2012. The blue lines and shaded areas show linear trend lines and 95% confidence limits, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This article investigated the effects of fish abundance and availability on fuel efficiency: changes in the CPUE, total stock biomass, and fish quotas were further studied. The effect of fuel price on fuel efficiency was also examined.

4.3.1. CPUE

Possible correlations between CPUEs and fuel use coefficients of factory trawlers were investigated (Fig. 6). The fit suggested an inverse correlation between fuel use coefficients and CPUEs.

4.3.2. Total stock biomass

As previously shown in Fig. 4, from 2003 to 2012, saithe and Atlantic cod were the two largest catches of factory trawlers. Before and after 2005, haddock was the fourth and third main catch, respectively. The only exception was in 2009 when the haddock catch was slightly more than the saithe catch. To study the possible effect of total stock biomass on fuel efficiency while maintaining consistency, the total stock biomass of Atlantic cod, saithe, and haddock from 2003 to 2012 was considered.

The fuel use coefficients of factory trawlers from 2003 to 2012 are plotted against the corresponding total stock biomass derived from the Statistics Norway database (Statistics Norway, 2014a). As illustrated, energy efficiency increased by increasing the total stock biomass (Fig. 7).

4.3.3. Fish quotas

As possible influential factors, Atlantic cod, saithe, and haddock quotas allocated to Norwegian trawlers were considered. The data on these fish quotas were extracted from the open source database of the Directorate of Fisheries (Directorate of Fisheries, 2013a). The fish quotas of trawlers are aggregated in Fig. 8. Atlantic cod, saithe, and haddock quotas for trawlers north of 62 °N and the saithe quota for trawlers in the North Sea were covered (Directorate of Fisheries, 2013a). Because these were annual quotas for the entire fishery as opposed to individual vessel quotas (IVQ), the fuel use coefficients of the fleet segment were plotted against quotas (Fig. 8). An inverse

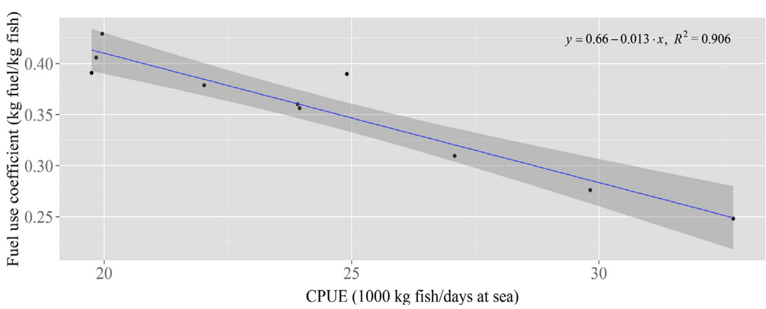

Fig. 6. Fuel use coefficient versus catch per unit of fishing effort (CPUE) of Norwegian factory trawlers from 2003 to 2012. The blue line and shaded area show the linear trend line and 95% confidence limit, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

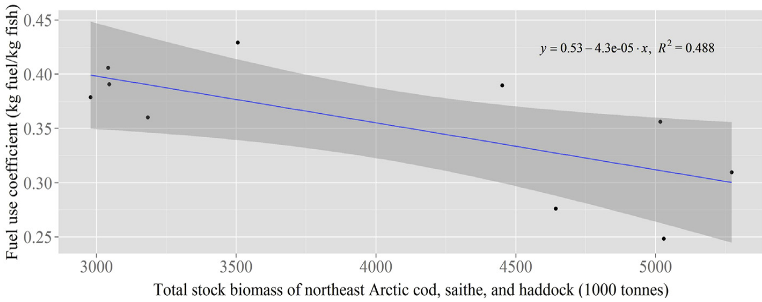

Fig. 7. Fuel use coefficients of Norwegian factory trawlers versus total stock biomass of the main target species from 2003 to 2012. The blue line and shaded area show linear trend line and 95% confidence limit, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

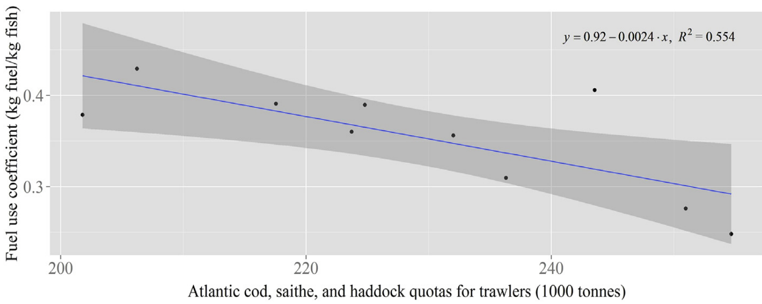

Fig. 8. Fuel use coefficients of Norwegian factory trawlers versus quotas of the main target species from 2003 to 2012. The blue line and shaded area show linear trend line and 95% confidence limit, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

correlation between the fuel use coefficients and fish quotas was identified.

4.3.4. Fuel price

Fig. 9 shows the fuel prices incurred by Norwegian fisheries from 2003 to 2012. The two data sources compared in Fig. 9 are (i) the dataset from the Directorate of Fisheries, which included fuel prices for individual vessels in different fleet segments (Directorate of Fisheries, 2014a), with an illustration of the average fuel prices, and (ii) an estimation of the average fuel prices paid by Norwegian factory trawlers according to Statoil Fuel & Retail (Husebø, Personal communication in 2014). The fuel prices

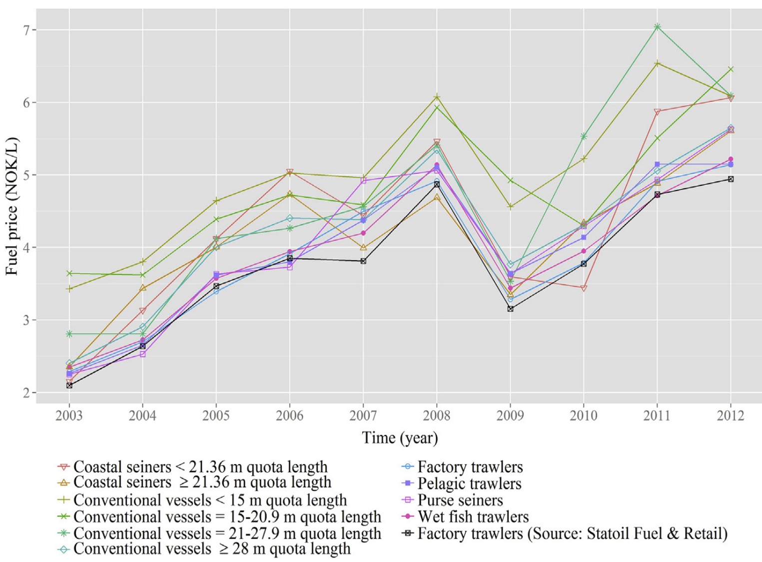

Fig. 9. Fuel prices incurred by different Norwegian fishing fleet segments from 2003 to 2012. Prices are inflation-adjusted in 2012 NOK.

incurred by the factory trawlers from the data sources are similar. This corroborates the fuel cost claims by fisheries in the dataset from the Directorate of Fisheries. Major fuel consumers (e.g., factory trawlers) negotiate and pay lower fuel prices compared with other fleet segments, which was noted in the earlier study on Norwegian fisheries (Schau et al., 2009).

Fig. 10 shows the possible relationships between fuel use coefficients and fuel prices paid by Norwegian factory trawlers according to the dataset from the Directorate of Fisheries. A weak long-term inverse correlation was evident from the R squared and confidence area.

4.4. Vessels with single gear versus vessels with multiple gears

To examine the effect of employing multiple gears on fuel efficiency, vessels with single gear were compared with those with multiple gears within the same fleet segments. Five fleet segments composed of coastal seiners, conventional vessels, and purse seiners were explored. The vessels with multiple gears exhibited improved efficiency from 2003 to 2012; however, their efficiency varied from the efficiency of similar vessels with single gear (Fig. 11):

Coastal seiners and purse seiners with multiple gears employ, for instance, trawl or conventional gears in addition to seine. Coastal seiners below and above the 21.36 m quota length with multiple gears had mean fuel use coefficients of 0.063 and 0.070 kg fuel/kg fish, respectively, which were higher than the corresponding values for the single gear seiners (Section 4.1). Regarding Fig. 11, from 2003 to 2007 purse seiners with multiple gears were more efficient than purse seiners with one gear. However, the situation reversed after 2008. Mean fuel use coefficient of purse seiners with multiple gears during the 2003–2012 period was 0.084 kg fuel/kg fish, which was similar to the corresponding value for purse seiners with single gear (Section 4.1).

Conventional vessels may use gears, such as trawl or seine, in combination with their main conventional gears. Regarding Fig. 11, conventional vessels that used multiple gears were more efficient than the vessels with single gear. Conventional vessels less than the 15 m quota length with single gear and multiple gears had mean fuel use coefficients of 0.108 and 0.083 kg fuel/kg fish, respectively. Conventional vessels with a quota length of 21–27.9 m with single gear and multiple gears had mean fuel use coefficients of 0.156 and 0.108 kg fuel/kg fish, respectively.

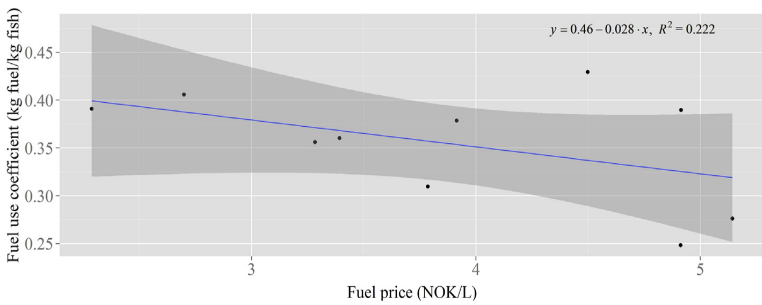

Fig. 10. Fuel use coefficients of Norwegian factory trawlers versus fuel prices from 2003 to 2012. Prices are inflation-adjusted in 2012 NOK. The blue line and shaded area show linear trend line and 95% confidence limit, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

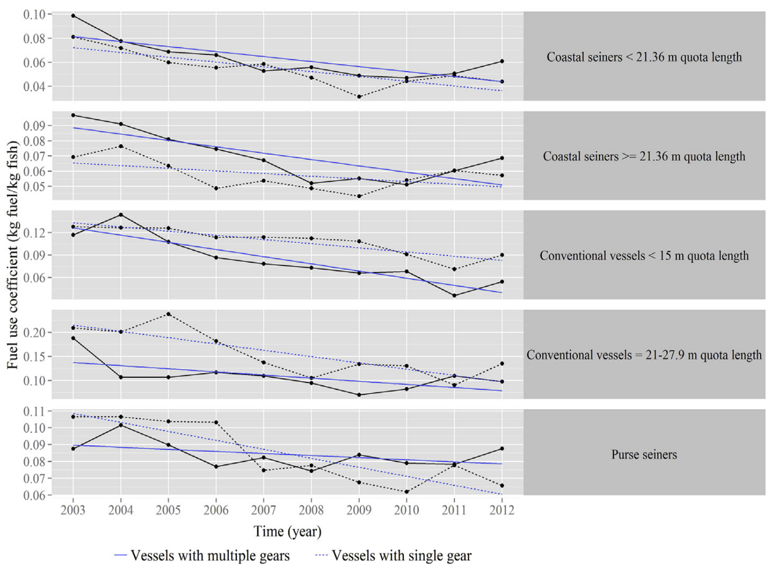

Fig. 11. Fuel efficiency of vessels with single gear versus vessels with multiple gears. Blue lines represent trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Discussion

5.1. Norwegian fisheries in an international context

This study revealed that Norwegian fisheries showed reduced fuel use coefficients from 2003 to 2012 (Fig. 2). Previously, an increasing trend for fuel use coefficients of Norwegian fisheries was observed from 1980 to 2005 (Schau et al., 2009). Thus, the energy efficiency of Norwegian fisheries has improved in recent years. Energy efficiency varied among the segments. Factory trawlers, with a mean fuel use coefficient of 0.354 kg fuel/kg fish, and coastal seiners, with a mean fuel use coefficient of 0.054–0.058 kg fuel/kg fish, were the least and most energy-efficient segments, respectively. Additionally, the fuel use coefficients of factory trawlers/wet fish trawlers (i.e., bottom trawlers) and longliners were distinctly different; Norwegian bottom trawlers were more fuel intensive than longliners (Fig. 2). Table 4 shows the mean fuel use coefficients of the studied fleet segments.

Similar progress was observed in Swedish demersal trawlers from 2002 to 2010 (Ziegler and Hornborg, 2014). A study of the European fishing fleet from 2002 to 2008 indicated similar improvements, particularly after 2004 (Cheilari et al., 2013). The Australian prawn and tuna fisheries also experienced similar improvements in efficiency (Parker and Tyedmers, 2014).

Parker and Tyedmers (2014) analysed the fuel consumption of global fisheries based on a state-of-the-art approach. Fisheries operating since 1990 were included, yielding 1126 records (Parker and Tyedmers, 2014). Some of the findings in the present article were compared with those previously reported by Parker and Tyedmers (2014) and with the earlier study of Norwegian fisheries by Schau et al. (2009) (Table 4).

In a comparison of the relative energy efficiency of different fishing gears, all of the studies agree on the poor efficiency of bottom trawlers (Table 4 and Fig. 2). However, the fuel use coefficients of Norwegian factory trawlers and wet fish trawlers were lower than the corresponding values reported for bottom trawlers elsewhere. Whether the bottom trawlers were factory/wet fish trawlers or whether shrimp catching vessels were excluded in the previous report remained unclear (Parker and Tyedmers, 2014).

In all of the studies, the most efficient fleet segment was the seiners. However, the efficiency varied among the regions (Table 4). For surrounding nets in Latin America, the fuel use coefficient was only approximately one tenth of the corresponding values in other regions, including Norway (i.e., fuel use coefficient of Norwegian purse seiners). This result might be due to different distances to fishing grounds, weather conditions or the abundance of fish stocks/catch, such as large catches of pelagic species in Peru (Durand and Seminario, 2009; FAO, 2014). Moreover, Parker and Tyedmers (2014) did not distinguish purse seines and other surrounding nets (e.g., coastal seiners).

In Norwegian fisheries, the fuel use coefficients of bottom trawlers were distinctly higher than the corresponding values for longliners (Fig. 2). However, in other regions, the distinction is not observed. For example, hooks and lines and bottom trawls had similar fuel use coefficients in Oceania, with values of 0.472 and 0.463 kg fuel/kg fish,

Table 4
Mean fuel use coefficients of Norwegian fisheries compared with fisheries elsewhere. Conv., N. America, and L. America are Conventional vessels, North America, and Latin America, respectively. Specified lengths represent quota lengths.

Gear type[a], location	Species	Mean fuel use coefficient (kg fuel/kg fish)[b]	Source[c]
Gillnet, N. America	Finfish	0.380	(Parker and Tyedmers, 2014)
Gillnet, Norway	Ground fish	0.19	(Schau et al., 2009)
Conv. < 15 m, Norway	Atlantic cod, saithe, etc.	0.108	This study
Conv. = 15–20.9 m, Norway	Atlantic cod, saithe, etc.	0.115	This study
Conv. = 21–27.9 m, Norway	Atlantic cod, saithe, etc.	0.156	This study
Hooks and lines, Europe	Finfish	0.797	(Parker and Tyedmers, 2014)
Hooks and lines, N. America	Finfish	0.353	(Parker and Tyedmers, 2014)
Hooks and lines, Oceania	Finfish	0.472	(Parker and Tyedmers, 2014)
Long line, Norway	Ground fish	0.31	(Schau et al., 2009)
Conv. > 28 m, Norway	Atlantic cod, saithe, etc.	0.265	This study
Pelagic trawl, Europe	Small pelagic	0.144	(Parker and Tyedmers, 2014)
Pelagic trawl, N. America	Small pelagic	0.087	(Parker and Tyedmers, 2014)
Pelagic trawl, Oceania	Small pelagic	0.201	(Parker and Tyedmers, 2014)
Trawl, Norway	Pelagic fish	0.09	(Schau et al., 2009)
Pelagic trawl, Norway	Blue whiting, Atlantic herring, etc.	0.087	This study
Surrounding net, Asia	Small pelagic	0.131	(Parker and Tyedmers, 2014)
Surrounding net, L. America	Small pelagic	0.009	(Parker and Tyedmers, 2014)
Surrounding net, Oceania	Small pelagic	0.077	(Parker and Tyedmers, 2014)
Purse seine, Norway	Atlantic herring, capelin, etc.	0.09	(Schau et al., 2009)
Coastal seiners	Atlantic herring, mackerel, etc.	0.054–0.058	This study
Purse seine, Norway	Atlantic herring, capelin, etc.	0.085	This study
Bottom trawl, Asia	Finfish	0.656	(Parker and Tyedmers, 2014)
Bottom trawl, Europe	Finfish	0.650	(Parker and Tyedmers, 2014)
Bottom trawl, N. America	Finfish	0.587	(Parker and Tyedmers, 2014)
Bottom trawl, Oceania	Finfish	0.463	(Parker and Tyedmers, 2014)
Trawl, Norway	Ground fish and blue whiting	0.28	(Schau et al., 2009)
Wet fish trawl, Norway	Atlantic cod, saithe, etc.	0.45	(Schau et al., 2009)
Wet fish trawl, Norway	Atlantic cod, saithe, etc.	0.322	This study
Factory trawlers, Norway	Atlantic cod, saithe, etc.	0.354	This study

[a] Gears from this study refer to single gear vessels.
[b] Density of 0.86 kg/L converts fuel consumption from liter to kilogram (NP, 2013). It is assumed that results in Parker and Tyedmers (2014) reflect round weight of fish, as this is the case in this study and Schau et al. (2009).
[c] Schau et al. (2009) investigated fuel efficiency in 1980–2005. Parker and Tyedmers (2014) examined this from 1990 onward. This study covered 2003–2012.

respectively. European hooks and lines had a higher fuel use coefficient than European bottom trawls, with values of 0.797 and 0.650 kg fuel/kg fish, respectively (Table 4). This difference between Norwegian and international fisheries was also observed in another study (Schau et al., 2009). The large stock of northeast Arctic cod in the Barents Sea and Lofoten fishery may be one of the reasons for high efficiency of Norwegian large vessels (e.g., autoliners) and traditional fishing gears (e.g., coastal longliners), respectively (Grønnestad, 2013). Moreover, because of a lack of information, this study did not correct for fuel consumption for catching bait.

Another explanation for the dissimilarity of results and lower fuel use coefficients in this study could be the difference in the time intervals studied. Schau et al. (2009) investigated fuel efficiency from 1980 to 2005, and Parker and Tyedmers (2014) examined the fuel efficiency from 1990 onward. However, this study considered a more recent period, 2003–2012. As noted above, the fuel efficiency of different fisheries has improved in recent years.

5.2. Factors affecting energy efficiency

5.2.1. CPUE, total stock biomass, fish quotas, and fuel price

Different factors influenced the energy efficiency of Norwegian fisheries. In this study, the relationships between the fuel use coefficient and CPUE, total stock biomass, fish quotas, and fuel price were analysed for factory trawlers (Section 4.3). The findings for the factory trawlers were assumed to hold for the other fleet segments. Inverse correlations between the fuel use coefficients and these factors were found. The effect of each factor could not be quantified because they acted simultaneously. However, significant inverse correlations with CPUE, total stock biomass, and fish quotas were obtained, as opposed to a weak inverse correlation with fuel price (Figs. 6–8 and 10). Fish abundance and availability were the main reasons for the improvements in energy efficiency.

An improved fish stock was the primary driver of improvements in the energy efficiency of Swedish demersal fisheries. The fuel price and technological improvements had limited effects (Ziegler and Hornborg, 2014). High fuel prices led to increased fuel efficiency for European fisheries. However, the study did not investigate other possible drivers (Cheilari et al., 2013). In a study of Australian fisheries, biomass and fishing capacity influenced fuel performance more than technological or operational measures. Additionally, the high value of Australian seafood products compensated for high fuel costs (Parker et al., 2015). The effects of CPUE, fish stocks, and fish quotas might have overshadowed the effect of fuel price in Norway. Furthermore, Norwegian fisheries were exempt from different taxes related to fuel consumption. Norwegian fishing vessels operating in the EEZ were reimbursed for fuel and CO_2 taxes, and Norwegian fisheries operating in high seas were exempt from these taxes. The NO_x tax does not apply to high-seas fishing (Borrello et al., 2013). Exemption from taxes as a subsidy might justify a lower fuel efficiency (Ziegler and Hornborg, 2014).

5.2.2. Single gear versus multiple gears

Coastal seiners with multiple gears employ other gears in addition to seine (e.g., trawl, conventional gears, etc.). Such gears were more fuel intensive than seine as previously shown in Fig. 2. Therefore, coastal seiners with multiple gears were less efficient than the seiners with single gear (Fig. 11).

From 2003 to 2012, Atlantic herring was the largest catch of conventional vessels less than the 15 m quota length and with a quota length of 21–27.9 m, which employ multiple gears. The only exceptions were for the former in 2004 and 2012, when Atlantic cod was their main catch. On average, Atlantic herring formed 39% and 49% of their annual catch during 2003–2012, respectively. Atlantic herring was mainly caught by seine. However, a small proportion was fished by trawl and conventional gears in conventional vessels less than the 15 m quota length. Therefore, the use of more efficient gears, such as seine in combination with conventional gears may explain the higher efficiency (Fig. 11).

Purse seiners may use gears, such as trawl and conventional gears in addition to seine. Purse seiners have IVQs for catching some species, such as Atlantic herring with seine gear. Some purse seiners have the license to use pelagic trawl to fish blue whiting in addition. There were no IVQs for blue whiting until 2006, and vessels were allowed to catch until the total quota was fished. In 2005, the coastal states of the European Union, the Faroe Islands, Iceland, and Norway signed an agreement to manage the blue whiting stock. Regarding this agreement, from 2006 the involved parties reduced annual landings of blue whiting (Bjørndal and Ekerhovd, 2014; Ekerhovd, 2007). In the period 2003–2007, blue whiting was the largest catch of purse seiners with multiple gears, forming on average 58% of their total annual catch. Since 2008, the corresponding value dropped to 19%. From 2003 to 2007, purse seiners with multiple gears were more efficient than purse seiners with one gear. However, the situation reversed after 2008 (Fig. 11). The changes in blue whiting quota and landings may explain this: trawls of purse seiners landed less blue whiting since 2008 and consequently their fuel efficiency reduced.

5.2.3. Other factors

Installed power may affect the fuel consumption of fishing vessels. The total engine power of Norwegian fisheries showed a decreasing trend from 2003 to 2012, but the number of active vessels also decreased in such a degree that the average engine power of individual vessels increased for all fleet segments with the exception of coastal seiners less than the 21.36 m quota length (Table 5). We could however not find any direct impact from a generally increased installed engine power level in the singular vessels and the specific energy consumption.

Energy efficiency varied considerably between vessels (Fig. 3). These variations could be due to factors previously mentioned, or due to other factors, such as vessel capacity, technical and operational aspects, or logistics. For example, vessels might have different engine powers, or some vessels might have additional capacity. Moreover, skippers might have different operational preferences, such as postponing fishing in bad weather conditions to increase safety and fuel efficiency. Some ship owners have realised the advantages of using energy management systems on fishing vessels (Basurko et al., 2013). However, such soft choices and motivation campaigns must be followed by changes that are more permanent, such as using new technologies or changes in formal strategies. Some technologies, such as fish finding equipment, may increase catch, and indirectly improve energy efficiency, whereas others, such as heat recovery systems, can more directly reduce fuel consumption.

As previously discussed in Section 4.3, FPUE of the factory trawlers did not change considerably from 2003 to 2012. In addition, the average ages of the studied factory trawlers in 2003 and 2012 were 16 and 20, respectively. Therefore, the factory trawlers in 2012 were relatively old and most likely, were not more advanced than the vessels in 2003. Thus, it can be concluded that fluctuations in the fuel use coefficient were primarily due to changes in fish abundance and availability rather than technological improvements. A similar relationship was found for the Swedish demersal trawl fisheries (Ziegler and Hornborg, 2014). This indicates a need for the introduction of new technologies, new ship designs, and

Table 5
Average engine power of Norwegian fisheries from 2003 to 2012 (based on the datasets provided by the Directorate of Fisheries).

Fleet segment	Average power in 2003 (hp)	Average power in 2012 (hp)	Average power in 2003–2012 (hp)
Coastal seiners < 21.36 m quota length	567.88	461.69	476.08
Coastal seiners ≥ 21.36 m quota length	713.25	1360.38	1086.95
Conventional vessels < 15 m quota length	164.25	278.96	197.21
Conventional vessels = 15–20.9 m quota length	361.52	441.48	404.88
Conventional vessels = 21–27.9 m quota length	557.20	594.00	576.55
Conventional vessels ≥ 28 m	1006.18	1637.39	1173.07
Factory trawlers	3449.11	3857.50	3939.53
Pelagic trawlers	1781.82	2924.75	2460.69
Purse seiners	3044.46	3248.69	3293.91
Wet fish trawlers	1989.33	2699.00	2501.99

alternative fuel systems in the fleet to improve energy efficiency further.

Norwegian fisheries management favours a varied fleet composed of small and oceangoing vessels (Standal, 2008). The management focus is on the following objectives: (i) sustainability of fish stocks, (ii) profitability of fisheries, (iii) protection of fishing communities, and (iv) safety of work environments. These goals may conflict with each other (Heen et al., 2014). For example, Norwegian factory trawlers operate in a web of regulations. They should ensure a yearlong fish supply to land-based industries, but onboard processing is limited, and they cannot operate in coastal areas. During the 1990s, the quota base of factory trawlers was halved. These regulations were introduced to protect coastal vessels, land-based industries, and employment (Standal, 2008); however, all of the regulations had implications for the energy efficiency of factory trawlers. For instance, as factory trawlers cannot operate in coastal waters, they consume more energy for steaming to fishing grounds.

Energy efficiency is at the heart of economic and environmental concerns. However, it may not be a part of national and international policies. Institutional interactions can favour other issues at the expense of energy efficiency. For example, selective trawling protects fish stocks, vessels may use different abatement options to comply with environmental regulations that reduce SO_X, and ballast water treatment protects the sea environment. However, these solutions may solve some environmental issues at the expense of increased fuel consumption (Blanco-Davis and Zhou, 2014; Ma et al., 2012; Ziegler and Hornborg, 2014). Furthermore, to land fish as soon as possible to preserve fish quality, vessels may increase speed and fuel consumption, and fuel savings may not justify the lost premium due to lower fish quality. Energy efficiency may be improved by its inclusion in political goals, as well as the investigation of institutional interactions.

5.3. Data gaps

As stated in Section 3.2, the Directorate of Fisheries changed its data collection and organisation methods over the years. Although these alterations were in accordance with regulatory changes, comparing data between years was difficult, and in some cases, impossible.

The Directorate of Fisheries surveyed vessels primarily to analyse profitability rather than fuel efficiency. Therefore, fuel consumption for some participant vessels was not available. Moreover, even fewer vessels reported days at sea. Some vessels reported fuel consumption intermittently rather than continually. Thus, the available data were limited; however, the data were sufficient for data analysis.

Gathering data for the purpose of energy efficiency analysis might solve some of these problems. For example, higher-resolution data on vessel speed during fishing/steaming, on fishing grounds, and on hours spent fishing/steaming could increase the accuracy of the results. Additionally, the availability of fish quotas for individual vessels could be used to better explain the relationship between fish quotas and fuel efficiency.

6. Conclusions

This study revealed that Norwegian fisheries exhibited improved energy efficiency from 2003 to 2012, in line with recent international studies (Cheilari et al., 2013; Parker and Tyedmers, 2014; Ziegler and Hornborg, 2014). The Norwegian factory trawlers and wet fish trawlers were the most energy-intensive segments, with mean fuel use coefficients of 0.354 and 0.322 kg fuel/kg fish, respectively. Coastal seiners and purse seiners were the most efficient. Coastal seiners below and above the 21.36 m quota length had mean fuel use coefficients of 0.054 and 0.058 kg fuel/kg fish, respectively. Purse seiners had an average fuel use coefficient of 0.085 kg fuel/kg fish.

Conventional vessels improved their efficiency by employing efficient gears, such as seine in combination with their main gear. Coastal seiners that employed trawl or conventional gears in addition to seine, had lower efficiency compared to those seiners that merely used seine. The efficiency of purse seiners with trawling licence varied with the availability of blue whiting; in times with high catches of blue whiting, combining trawl with seine improved the efficiency of purse seiners.

Several simultaneous factors were responsible for the increase in energy efficiency of the factory trawlers. These factors included increasing catches per days at sea, improved fish stocks, changes in fish quotas, and high fuel prices. Although it was not possible to determine the separate effect of each factor, the former three factors appeared more effective than the fuel price. Little evidence of technological improvements, which affect energy efficiency, was found. Fuel efficiency may however be enhanced by the introduction of energy-saving technologies, ship designs, and fuel systems. The conclusions for the factory trawlers were assumed relevant and valid for the other fleet segments.

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Appendix A

Table A
Population of the Norwegian fishing fleet and profitability surveys (based on Directorate of Fisheries, 2013b).

Year	Norwegian vessels	Vessels represented by profitability surveys	Vessels studied in profitability surveys
2003	9915	2056	606
2004	8189	1913	662
2005	7722	1678	648
2006	7300	1652	632
2007	7038	1709	624
2008	6785	1716	607
2009	6506	1776	332
2010	6310	1731	333
2011	6250	1525	328
2012	6211	1565	335

Appendix B

Table B
Population of different vessel groups in the Norwegian fishing fleet, profitability surveys, and this study in 2012.

Vessel groups	Norwegian vessels[a]	Vessels represented by profitability surveys[a]	Vessels studied in profitability surveys[a]	Vessels covered in this study with single gear/multiple gears
Vessels less than 11 m in overall length	4901	691	67	52/4
Vessels 11–27.9 m in overall length	1054	631	127	67/30
Vessels greater than 28 m in overall length	256	243	141	42/57
Total	6211	1565	335	161/91

[a] Source: (Directorate of Fisheries, 2013b)

Appendix C

Table C
Data conditioning for the conventional vessels. Ranges of quota length represent different vessel groups in different periods.

The studied fleet segments with conventional gears	Quota length in 2003–2006 (m)	Quota length in 2007–2008 (m)	Quota length in 2009–2012 (m)
Conventional vessels less than the 15 m quota length	8–9.9	8–9.9	<11
	10–14.9	10–10.9	
		11–14.9	11–14.9
Conventional vessels with a quota length of 15–20.9 m	15–20.9	15–20.9	15–20.9
Conventional vessels with a quota length of 21–27.9 m	21–27.9	21–27.9	21–27.9
Conventional vessels with a quota length larger than or equal to 28 m	28≤	28≤	28≤

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Article II

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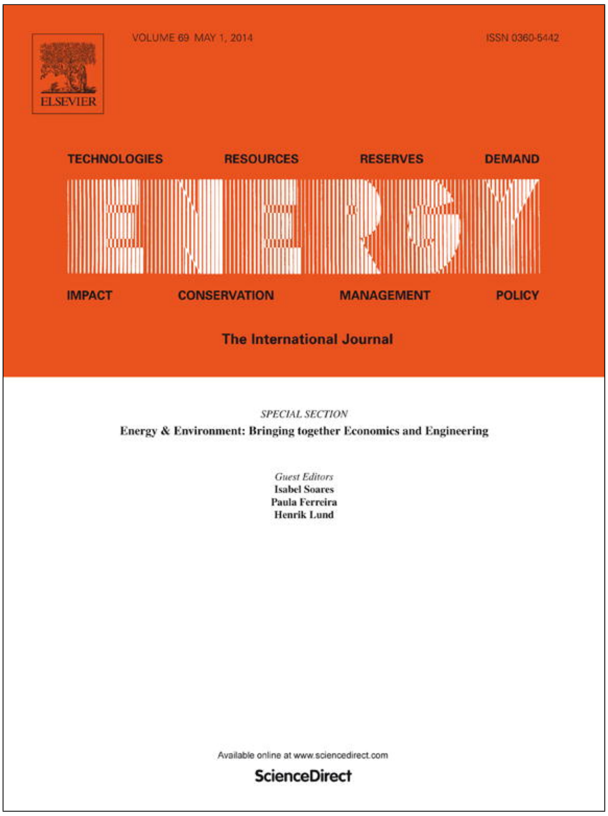
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A framework to bridge the energy efficiency gap in shipping

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ABSTRACT

Environmental concerns, emission regulations, fuel prices, and emission taxes increase the demand to improve energy efficiency in shipping. However, several barriers prevent the adoption of cost-effective energy saving measures. In this article a framework is offered to overcome the barriers encountered in shipping. 12 participants from five ship owners in Norway, two equipment suppliers, and a research institute have provided input to this study. The framework makes the barriers evident to ship owners and (energy) managers. It helps them to prioritize and overcome the critical barriers to improve energy efficiency in a consistent manner. Researchers and policy makers can also utilize the framework as it makes challenges to energy efficiency apparent. Finally, due to its generic structure it can be applied to industries other than shipping.

1. Introduction

Shipping is the most energy-efficient way of transporting bulk freights [1]. Still, it accounted for 3.3% of global CO_2 emissions in 2007 [2]. Shipping also emits sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM), etc. [3,4]. The International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI was revised in 2008 to reduce SO_x, NO_x, and PM [5]. More amendments were made in 2011 to decrease greenhouse gas (GHG) emissions [6]. Besides, the increasing and fluctuating fuel prices form another incentive to reduce fuel consumption and emissions as fuel cost can form a great share of operational costs [7,8].

In Norway a NO_x tax was introduced in 2007 which among various sectors applies to domestic shipping, including fishing [9]. In 2011, a NO_x agreement was made between several organizations including Norwegian Ship owners' Association (NSA) and Norwegian Fishermen's Association (NFL) to reduce NO_x emissions and pay a lesser amount to the NO_x fund instead of the tax [9–11]. The positive outcomes of using the fund in Norway have inspired the European Commission to consider using a similar fund [12]. Besides, the establishment of a CO_2 tax in the future seems likely [3].

The growing environmental concerns in shipping, the need for complying with stricter emission regulations, and the financial burdens due to fuel price and emission taxes have brought up several studies and debates in favor of improving the current situation. Significant further progress may be achieved by implementing operational or technological measures [2]. While some energy-related studies focus on energy conservation, others address energy efficiency [13]. In other words, while energy conservation aims at decreasing the consumed energy by reducing the demanded output, energy efficiency addresses using less energy to produce the same amount of useful output [14]. Energy conservation and energy efficiency should be considered simultaneously as improvement in energy efficiency may lead to increased ship speed instead of reduced fuel consumption [15]. In other cases, increased energy efficiency may be followed by increased fuel consumption which is referred to as the 'rebound effect' in various sectors. This cancels out the savings that could be gained [16]. For convenience energy conservation and energy efficiency terms are used interchangeably in this article.

Even though cost-effective technologies that can improve energy efficiency are identified, they are not always implemented [17]. In addition to technological measures, operational measures in shipping can save fuel [2]. This inconsistency between optimal and actual implementation is called the 'energy efficiency gap' [17] which is often explained by the existence of some barriers [17,18]. Barriers are rooted in different disciplines, such as economic, organizational, and behavioral sciences [19]. They can range from limited access to capital and weak energy management in an organization to putting little value on energy issues by individuals [20]. Several studies have identified the existence of the 'energy efficiency gap' in shipping [2,21–25].

The 'energy efficiency gap' has been a long-debated concept between technologists and economists. On the one hand,

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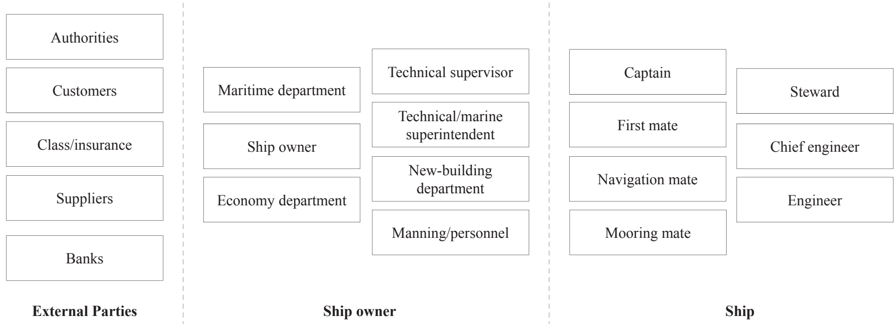

Fig. 1. The stakeholders to the energy consumption of shipping, adapted from Ref. [53].

technologists point out the non-adoption of cost-effective energy saving measures. On the other hand, economists consider the non-adoption of these energy saving measures as evidence to their economic inefficiency. While not every energy-efficient measure is cost-effective, there are measures which are both energy-efficient and cost-effective [24-27]. In this article, the latter group of measures is focused while addressing the 'energy efficiency gap': it is taken for granted that such measures (e.g., on-line monitor to balance speed, engine power capacity, and power utilization for propulsion [28]) exist. A barrier is defined as "a postulated mechanism that inhibits investment in technologies that are both energy-efficient and (apparently) economically efficient" [20]. In shipping there are operational measures in addition to technologies that can save fuel [2]. As a result, in this article the definition of barriers is expanded to encompass mechanisms that hinder the adoption of operational measures that are energy saving and cost-effective as well.

Various studies have addressed barriers in different sectors [17,19,29–38]. While some studies focus on the prioritization of barriers [39–43], others focus on categorizing them. The way an energy efficiency problem is defined determines the suitable categorization and the way to solve the problem [19]. So far most studies on barriers have considered them isolated. Possible interactions have been disregarded while seeking solutions to overcome barriers. To avoid erroneous solutions, a holistic view on barriers and the interactions among them is required [34]. The importance of these interactions is emphasized in Refs. [34,35]. Studies conducted by Refs. [34,35,39,44–47] have addressed these interactions. Ref. [46] identifies direct and indirect interactions among barriers, and consequently 'root' barriers that lead to other barriers are prioritized to deal with. The process of adopting energy-efficient measures is presented in Refs. [34,47], and it is shown that barriers encountered at the different stages of this process are dependent. Correlations among barriers encountered in European foundry industry and in manufacturing small and medium enterprises (SMEs) are addressed in Refs. [39] and [45], respectively. Refs. [35,44] investigate the interactions among barriers.

Most of the studies referred to so far and several other studies address the 'energy efficiency gap' in industrial sectors, for example, foundry [39] and paper and pulp [40]. Even though shipping is quite energy intensive compared to many sectors, the focus on energy efficiency has been limited. While the energy cost may form about 20% of the costs of an energy intensive production plant, this share can rise to 50% for a shipping company [22]. [2,8,15,21–23,48–51] touch upon a few barriers in shipping, and [22–25] only enlarge on a handful of barriers.

Shipping is a multi-addressee environment. Stakeholders range from an operator who directly interacts with, for example, an engine to a manager who indirectly interacts with the whole energy system [52]. A ship owner may own ships but not necessarily operate them. Fig. 1 illustrates some of the stakeholders that influence the energy consumption in shipping.

Stakeholders within a shipping company are not the only ones affecting the adoption/rejection of energy saving measures. There are external institutional factors which influence the operations of shipping companies: regulations, international trade pressures and competitiveness, and shippers' requests. Balancing economic and environmental performance within this context is essential to the continued operation of shipping companies [54].

The main objective of this article is to provide a framework for overcoming barriers encountered in shipping. The interactions among various barriers are also explored. The framework is a result of work performed in the Energy Management in Practice (EMIP) II project [55] involving five ship owners in Norway, two equipment suppliers, a research institute, and a university. The outcomes of this article should be of interest to ship owners and (energy) managers that need to reduce the energy consumption of their ships. The framework aims at making the barriers more transparent to these stakeholders and helps them identifying and prioritizing the barriers to address. Consequently, they can plan for overcoming these barriers and reducing energy consumption. The framework can also make challenges to energy efficiency in shipping more transparent to researchers and policy makers. Finally, the overall framework is generic and can be applied to other industries.

The remainder of this article is organized in the following manner: After explaining the method used in this article in Section 2, results and discussions are presented in Section 3. Finally, conclusions are drawn in Section 4.

2. Methodology

2.1. Research method

In the present study, first a thorough literature review on barriers to energy efficiency was conducted. Given that there is a limited literature body on barriers to energy efficiency in shipping, this study aims at transferring accumulated knowledge and experience from other industrial sectors to shipping. The gathered data is tailored to reflect the barriers encountered in shipping.

Second, a preliminary framework was designed as a decision making tool to help ship owners and (energy) managers to identify the barriers they face, to prioritize the barriers that are more critical or beneficial to deal with, to identify possible solutions to these barriers, to understand possible interactions among barriers, and consequently to reduce the 'energy efficiency gap'.

Third, to validate the framework, workshops or group meetings with the participants of the EMIP II project were arranged in winter and spring 2013. The EMIP II project involves five ship owners in Norway, two equipment suppliers, a research institute, and a university, which collaborated from September 2011 to September 2013 to increase energy efficiency in shipping. The ship owners operate different fleets including containers, roll-on/roll-off (ro–ro) ships, liquefied natural gas (LNG) carriers, product tankers, bulk carriers, large gas carriers, etc. Besides, they offer services, such as logistics and ship management. The equipment suppliers are providers of energy management solutions and marine automation systems. The research institute develops technical and operational solutions for the maritime sector. 12 participants provided feedback on the framework. They had different job positions, such as technical vice president/director, technical sales manager, shipping and environment manager, environmental performance manager, fuel efficiency manager, naval architect, research manager, senior project manager, corporate social responsibility (CSR) manager, and product manager.

The participants in the present study discussed their viewpoints and provided feedback on the relevance or irrelevance of the identified barriers with supporting examples from their experience with working on energy efficiency in shipping. They also suggested some additional barriers and practices or possible solutions to overcome the barriers. Additionally, they mentioned their viewpoints about the whole framework and its practicality and usefulness. The workshops were followed up with individual discussions with the participants.

Finally, after including the feedback from the participants the framework was modified. The earlier versions of this article including the final framework were proofread by some of the participants.

2.2. A framework for overcoming barriers to energy efficiency

The framework, as illustrated in Fig. 2, consists of five iterative steps, namely (i) Identifying barriers and categorizing them, (ii) Analyzing the barriers and determining their criticality, (iii) Assigning possible measures for overcoming the most critical barriers, (iv) Assessing the influence of overcoming some barriers on the status of the others, and (v) Documenting results and follow-up.

2.2.1. Step 1: identifying barriers and categorizing them

Having an organized set of barriers makes it easier to identify existing barriers in a company and analyze them more in detail. The proposed taxonomy is developed with a practical perspective in mind to avoid making it too complex and resource demanding.

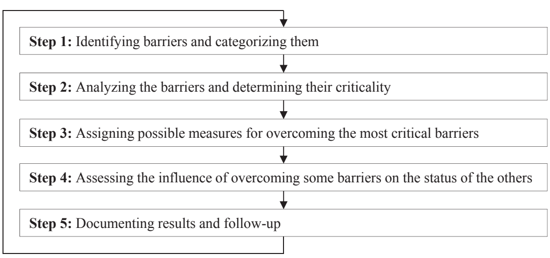

Fig. 2. The framework for overcoming barriers to energy efficiency.

Initially the taxonomy in Ref. [20] was considered; later it was expanded to include some of the barriers mentioned in Refs. [15,17,19,29,33–35,39,48,51,56-64]. However, the taxonomy is adapted and expanded further to include information provided by the participants in the EMIP II project. Some barriers faced in other industries were not deemed relevant or as important in shipping. The participants also suggested some additional barriers that they have encountered with. As a result several new barriers are identified in this study.

2.2.2. Step 2: analyzing the barriers and determining their criticality

Since several barriers may hinder the uptake of a cost-effective energy-efficient measure and various stakeholders may have conflicting objectives, it may be challenging to prioritize and identify barriers which are more critical or beneficial to deal with. If a structured option is needed, multi-criteria decision making (MCDM) can be used [65]. Various MCDM methods exist: among them the weighted sum method (WSM), the weighted product method (WPM), and the analytic hierarchy process (AHP) [66]. Any of these methods can be utilized to rank the barriers. Further explanation of WSM, WPM, and AHP can be found in Ref. [66].

2.2.3. Step 3: assigning possible measures for overcoming the most critical barriers

After the identification of the critical or the most beneficial barriers to overcome, some measures should be selected as the most feasible for overcoming these barriers. For instance, [21] and [23] have suggested the enforcement of regulations and using an energy management system like ISO 50001 [67] as solutions, respectively.

2.2.4. Step 4: assessing the influence of overcoming some barriers on the status of the others

So far little attention has been paid to interactions among barriers when introducing measures to overcome them; (groups of) barriers usually have been treated in isolation when coming up with solutions to deal with them, which may result in ineffective solutions [34]. Solving/reducing one barrier may result in solving/reducing another, which is beneficial. However, the opposite may also occur, which should be avoided.

Interactions may exist between the barriers of different natures (e.g., between an economic barrier and an organizational barrier) and between barriers of the same group (e.g., between two economic barriers). In Ref. [35] three forms of interactions between barriers i and j are identified, namely (i) causal relationship (i.e., barrier i generates/modifies barrier j), (ii) composite effect (i.e., barriers i and j are effective only when they act simultaneously), and (iii) hidden effect (i.e., barrier i leads to barrier j; however, only barrier j is apparent). There may also be loops of interactions: barrier i may affect barrier j, which subsequently affects barrier i [68,69].

2.2.5. Step 5: documenting results and follow-up

As a result of previous steps some barriers may be reduced. Through the steps some more barriers that have not been realized initially may show up. In the next round, the new set of barriers, excluding the resolved barriers and including the possible new ones, is considered in Step 1. Steps 2 to 5 are followed again. Thus, an iterative loop will be formed that leads to the continuous improvement of energy efficiency.

3. Results and discussions

3.1. Step 1: identifying barriers and categorizing them

The taxonomy developed in the present study is shown in Fig. 3. The barriers are categorized into seven groups: (i) Information barriers, (ii) Economic barriers, (iii) Intra-organizational barriers, (iv) Inter-organizational barriers, (v) Technological barriers, (vi) Policy barriers, and (vii) Geographical barriers. The participants in the study found *the low priority of energy efficiency*, which is a barrier found in some industries like manufacturing [60], irrelevant in shipping. Energy cost forms a great share of operational costs in shipping. Therefore, those involved in shipping are concerned about energy consumption. However, their concern may not be reflected on practice due to various barriers that are further explained in the following subsections.

3.1.1. Information barriers

Due to *the lack of information* about the available energy-efficient measures, stakeholders may not be able to choose the best options to implement [63]. For example, agents may not have enough information about vessels. Thus, they prefer that vessels rush to ports and lay there due to possible congestions instead of slow steaming and saving fuel. In addition to *the lack of information*, *the overload of information* can be problematic. It can be difficult to assess all information. This overload of information may even come from the abundance of gathered data by measurement instruments.

While most new-build ships have at least the minimum measurement equipment to gather data, some older ships have none, and the only available data is total fuel consumption per day. *New-building contracts not including information technologies* form another barrier. As a consequence, cheap measurement equipment may be installed, and some equipment, such as torque meters may not be installed at all.

In some cases stakeholders are *not using information* due to a misconception that simply by installing measurement equipment energy can be saved. *Not maintaining information* is also a barrier. When measurement equipment is installed onboard a vessel, continuous measurement is required to gain benefits.

The inaccuracy of information is another barrier. Impartial and correct data about energy-efficient measures is needed for choosing the best option [20]. Moreover, while using several energy-efficient measures on a ship, it is impossible to separate the share of each in fuel saving. It is also difficult to distinguish fuel savings due to technologies from savings due to slow steaming (e.g., due to recession in the market).

The improper form of information is another barrier [20]. All stakeholders may not be able to understand the way all technologies function. While some stakeholders demand high frequency data with high quality, others only require basic information, and they may get confused by small details presented to them. However, they need to see the benefits of using energy-efficient measures, such as economic gains in order to invest.

Cultural differences regarding the required information can prevent investments. Stakeholders with different cultural backgrounds and nationalities may demand different amounts/types of information prior to decision making. While some stakeholders ask about the possible energy saving by measurement equipment and are not easily convinced to invest in such technologies, others have realized the importance of knowing the current level of energy consumption prior to starting improvement.

While binding contracts on energy-efficient measures one party may have relevant information, but may not convey it to the other party, for example, due to not having published technical reports. Thus, the information available for the two parties is

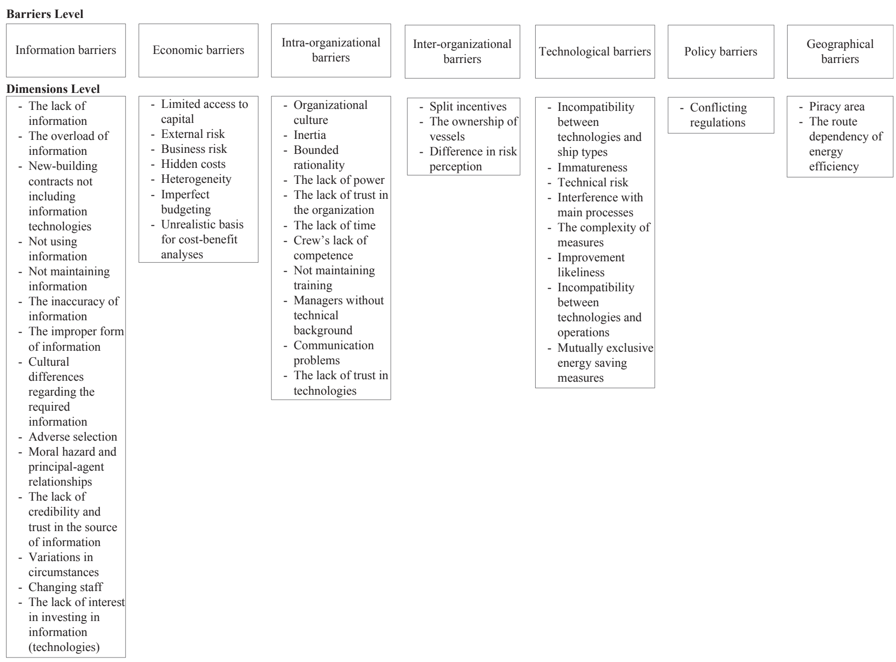

Fig. 3. The barriers encountered in shipping, adapted from Refs. [15,17,19,20,29,33–35,39,48,51,56–64] and the present study.

asymmetric [19,20], which can lead to *adverse selection* or sub-optimal decisions [34,35]. Therefore, stakeholders may select technologies based on visible aspects, such as price only [39]. *Moral hazard and principal-agent relationships* are encountered after binding contracts when one party has incentives to act in a way that does not match with other party's preference. For example, vendors may provide ship owners with less efficient components to increase their profit [20].

The lack of credibility and trust in the source of information can also prevent investments. Credibility depends on different factors, such as past experiences with the source [20]. Different sectors have established their own inferred knowledge concerning energy-efficient measures; the influence of social relationships should not be overlooked [63].

Variations in circumstances are problematic. External conditions are not fixed while operating a vessel: the vessel may have a new trading pattern, or there may be bad weather conditions occasionally. Energy consumption is dependent on these changes. Thus, it may be difficult to show savings to decision makers and persuade them to continue investments.

Changing staff can act as a barrier. If energy managers or crew who work with energy systems and available information are changed, gained knowledge may get lost.

The lack of interest in investing in information (technologies) is another barrier. Decision makers may be more interested in energy-efficient measures that directly save fuel (e.g., ducted propeller) rather than obtaining data on available energy-efficient measures and investing in information technologies (e.g., measurement equipment) that indirectly affect energy consumption by justifying other investments. This can make it difficult to get funding for information related investments.

3.1.2. Economic barriers

Energy-efficient technologies may be expensive, and *limited access to capital* may be challenging [19], especially during market recession [15]. Even if capital needed to invest in a technology per vessel may not be high, the investment for the whole fleet can be considerable. *External risk* (e.g., expected reductions in fuel prices) and *business risk* (e.g., uncertainty about sectorial economic trends) can hinder investments [20].

Hidden costs, in spite of not being quantified, may hinder investments [33]. Due to the cost of gathering information on energy-efficient measures, consumers may not access full information [19,20]. This is specially the case for smaller ship owning companies that cannot use the gathered information on a large fleet [48]. The possible interference of energy-efficient measures with normal operations, required modifications in systems to fit in measures [35], personnel training, staff recruitment [33,35], binding contracts [19], and the opportunity cost of investing in energy-efficient measures instead of elsewhere [48] may form other hidden costs.

An energy-efficient measure may be cost-effective on average, but not in all cases [19]. For example, if a vessel does not operate in Emission Control Areas (ECAs), there may be fewer financial motives to save fuel and reduce emissions as emission taxes do not apply. If crew is incompetent, installing technologies, such as main engine performance systems that alert about mistakes made can save lots of fuel. However, if crew is competent, installing such technologies will save only a bit. Such examples refer to *heterogeneity* barrier [19].

Available capital may not be allocated to various purposes properly due to *imperfect budgeting*. Thus, there may not be funding to adopt energy-efficient measures. This can be problematic even in companies that have everything in-house (i.e., ship owner, ship manager, etc.) as their different departments may have different budgets to meet.

Unrealistic basis for cost-benefit analyses conducted to justify the adoption of energy-efficient measures can hinder investments. For instance, while analyzing the cost-benefit of using waste heat recovery systems mistakes may be made: the idea is to recover the exhaust gas heat of boilers to produce steam and electricity. The steam production requires certain engine power; however, this power may be more than the power enforced by charterers. Not fulfilling the charterers' requirements may be costly, and it may not be worth the money saved due to the saved fuel.

3.1.3. Intra-organizational barriers

This group refers to the barriers faced within organizations:

Organizational culture can explain underinvestment in energy-efficient measures [20]. Concerns about environment and moral commitment are the examples of values persuading investments in energy-efficient measures. The lack of such values may hinder investments [19]. Investors may put more value on initial cost while choosing a measure to invest in [34].

Inertia refers to routines that affect decision making. Individuals and organizations try to reduce uncertainty and change, and altering this habit may be difficult [19]. For instance, ship yards may be reluctant to accept ship designs other than the standard ones [51]. *Bounded rationality* means that individuals tend to make satisfactory decisions instead of optimum decisions. Stakeholders may use the rule of thumb instead of optimization analyses due to the lack of ability to process information [20].

The lack of power is another barrier. If organizations lack strong energy management, energy-efficient measures may not be adopted [19]. Nobody may be responsible for fuel consumption [58]. Different stakeholders' performance regarding energy may not be evaluated. For instance, the main task of ship managers is to ensure safety; energy efficiency is just an add-on. *The lack of trust in the organization* and between different stakeholders can lead to disagreement about investing in energy-efficient measures [20]. *The lack of time* can be a barrier. Small organizations usually have few staff who have to deal with several issues; they may not get time to focus on energy matters [60].

There are technologies onboard ships, such as measurement equipment which may not be utilized properly due to *crew's lack of competence*. Sometimes crew is trained for safety and maintenance and not for energy-efficiency. In some other cases there is the lack of learning despite training. In the same way that *not maintaining information* is problematic, *not maintaining training* is also a barrier. As available information changes, crew's training should be updated to put new information into practice.

Managers without technical background may have difficulty realizing savings and continuing investments. For example, when occasionally there is a bad weather condition and savings are not apparent, managers with technical background may realize that without the energy-efficient measures in place the situation might have been worse. However, managers without technical background may find it difficult to realize energy savings as financial savings are not obvious.

Communication problems can prevent investments. When technical people hold a discussion with economic people about energy related investments, they may have difficulty understanding each other as they approach the problem from different perspectives.

The lack of trust in technologies is another obstacle. For instance, captains may not use weather routing equipment as they do not believe in them.

3.1.4. Inter-organizational barriers

This group addresses the barriers between different organizations:

Split incentives addresses a situation where different stakeholders think about possible benefits to themselves by using energy-efficient measures [20]. If stakeholders cannot foresee such benefits, they may not support the uptake of measures [29]. Investors may only care about capital cost as they are not responsible for operational costs [57]. Usually ship owners pay for technologies whereas charterers pay for fuel. Charterers may not be willing to share capital expenses as they may operate ships temporarily. In cases that ship owners operate vessels, they may still hesitate to invest as they may pass increased fuel prices to shippers through bunker adjustment factors (BAF) [51].

In charter contracts one or two speeds or fuel consumptions are identified. If vessels violate these figures by a margin, charterers can claim against ship owners. There may be no bonus for ship owners who show a better performance. These restrictions may not apply in bad weather conditions. Still, operators may maintain the speed instead of saving fuel [58]. Crew may not save fuel as they are not paid for it. Demurrage costs leave no incentive to slow steam and save fuel instead of spending days at ports. It is also more convenient for agents that ships spend more time at ports. Oil companies may prefer the same; it may be more costly to not have an available vessel than to spend more on fuel.

However, trade-off between the fuel saved by slow steaming and additional vessels required to maintain transport capacity should not be overlooked [15]. The cost of the additional vessels, the shortage of seafarers [15], and possible increased emissions from building additional vessels [59] should be considered.

The ownership of vessels can act as a barrier. It is easier to do installations on ships owned by an organization than on chartered ships. However, there are cases where ships are chartered for more than a couple of months, and technologies like measurement equipment are installed onboard.

Difference in risk perception by various stakeholders can act as a barrier. Different stakeholders perceive risk differently in the context of technology development. While some, such as the investors may consider risk as an investment which may fail or not, others, such as non-governmental organizations (NGOs) may perceive risk as hazard [62]. This difference may lead to disagreement regarding the adoption of innovative energy-efficient measures.

3.1.5. Technological barriers

Incompatibility between technologies and ship types is a barrier. For instance, kites do not fit fast ships [51]. Due to the innovative nature of energy-efficient technologies and their *immatureness*, they may diffuse slowly [17]. Usually mature technologies are preferred over the new ones [64]. In the EMIP I project a list of energy-efficient measures was presented to the involved companies. The observation was that all new technologies were subject to future assessment due to, for example, *technical risk* [20]. Ship owners usually do not want to be front-runners.

If stakeholders foresee that energy-efficient measures will have *interference with main processes*, they may hesitate to invest [56]. During market boom, ship owners may hesitate to take ships out of service for long times to install energy-efficient technologies [15]. Thus, there may be a time lag between the time that a measure is introduced to the market and its installation [48].

The complexity of measures is another barrier. The more complex a measure is, the more knowledge and investment may be needed to install and operate it. Thus, the measure may be rejected [56]. For instance, measurement equipment should be calibrated periodically, which requires competence for calibration and checking the accuracy of data during various operations. Wave radar technology, which aims at more energy-efficient navigation, serves as another example. The effectiveness of it depends on factors, such as ship hull, propeller, and competence to use the outputs of this technology in a limited period of time. All these make the technology more complex to utilize.

If stakeholders foresee *improvement likeliness* and future better/cheaper technologies, they may delay investments [61].

Incompatibility between technologies and operations is another barrier. There are cases where energy-efficient technologies are introduced which work under special operational conditions. However, later conditions are changed, and the technologies are not useful anymore. For instance, shaft generators are designed for full speed operations. When vessels slow steam the initial benefits of these technologies cannot be captured any longer unless frequency converters are used. This makes it difficult to look ahead of time and invest.

Mutually exclusive energy saving measures may hinder the adoption of some of them. For instance, slow steaming reduces the effectiveness of energy-efficient measures that aim at decreasing wave making resistance (e.g., bulbous bows) [15].

3.1.6. Policy barriers

Conflicting regulations imposed by regulators like the International Maritime Organization (IMO) occur. For instance, engine manufacturers slow down the combustion process to comply with NO_x emission regulations, which leads to increased fuel consumption. There are conflicts among regulations of emissions to sea and air, too. Ballast water treatment systems reduce pollution to sea but increase fuel consumption. It is not allowed to clean ship hulls in ports, and consequently fuel consumption may increase due to the increased roughness of ship hulls.

3.1.7. Geographical barriers

As an example, a ship may operate in a *piracy area* and may be forced to have top speed to be secure, which in turn increases fuel consumption. Thus, regardless of the benefits of saving fuel, it cannot be prioritized due to the need for security.

The route dependency of energy efficiency is another barrier. Some energy-efficient measures are only effective in specific routes [51]. For instance, kites are only useful in windy areas.

3.2. Step 2: analyzing the barriers and determining their criticality

While some participants in the present study found it necessary to deal with all barriers at once, others agreed on the importance of prioritizing barriers and dealing with the most critical ones due to the lack of time and resources. Although in this study the identified barriers are not prioritized, the involved participants mentioned the barriers that they considered the most and least important to deal with:

The inaccuracy of information, *incompatibility between technologies and operations*, *the lack of credibility and trust in the source of information*, *not using information*, *not maintaining information*, *split incentives*, and *immatureness* are the barriers which were most emphasized by the participants in this study. Despite the importance of *limited access to capital* in foundries [39,42], *interference with main processes* in pulp and paper industry [40], and *the lack of time* in manufacturing firms [60], they are not deemed as main barriers to energy efficiency in shipping by the participants.

There may be several barriers that hinder the adoption of energy saving measures simultaneously. Different stakeholders may define different criteria for prioritizing barriers. They may also weigh the identified criteria differently. Thus, it is deemed important to include the viewpoints of various stakeholders in this step. For instance, charterers may put more weight on ‘the impact of barrier removal on energy efficiency’ criterion [65] as by saving fuel they can reduce operational costs. However, crew may put more weight on ‘the effort needed for alleviating a barrier’ criterion [65] as they might need to practice new skills and change job routines in order to reduce a barrier.

In the EMIP II project different stakeholders emphasized different barriers as illustrated in Table 1. In the project the participants worked in collaboration regarding research on energy efficiency. Meanwhile they have different job positions, and they work in different companies. The viewpoints of the various stakeholders show that the prioritization of barriers is complex if the prioritization is to be made outside a specific company.

If a structured approach to prioritizing the barriers and associated work is needed, AHP can be used. A decision hierarchy for AHP is illustrated in Fig. 4, which can be used to rank the barriers.

3.3. *Step 3: assigning possible measures for overcoming the most critical barriers*

In this study several measures for overcoming different barriers are put forth.

3.3.1. *Information barriers*

Sharing information and experiences (e.g., about using shaft generators) among everyone in the industry can solve *the lack of information* barrier. The flow of information may be facilitated in companies that have all parties in-house as benefits will be within the company. Disseminating knowledge makes it possible to compare different approaches that are taken to address similar problems and pinpoint differences that are merely due to the lack of knowledge about better available solutions.

The relevant stakeholders should be educated to use information equipment continuously to solve the *not maintaining information* barrier. Showing energy consumption at various speeds can help to distinguish savings due to technologies and slow steaming from each other. Consequently, *the inaccuracy of information* can be reduced. If one can do accurate measurements and gather data, *changing staff* might not be a problem as the data will always be available to refer to.

3.3.2. *Economic barriers*

Sensitivity analyses to check the effects of possible future variations (e.g., the effect of variation in fuel prices on the economic feasibility of an investment) could decrease *external* and *business risks* prior to decision making.

By top focus on budget, the *imperfect budgeting* barrier can be solved. Lifting up costs from bottom level in the whole organization and not only in separate departments can help to allocate budget in a better way. This prevents having departments with lots of costs while others benefit extra budget. Having a strong management on top can facilitate bringing these departments together.

3.3.3. *Intra-organizational barriers*

To overcome the *organizational culture* barrier various solutions can be suggested. Possible future emission regulations and demands (e.g., CO_2 tax, obligation to show energy consumption/emissions per unit of transferred cargo, etc.) could act as incentives and force shipping to get prepared by investing in energy-efficient measures. Awareness about energy can be raised in organizations by workshops. Forming voluntary/indirect competitions among vessels is another practiced solution. Vessels can report their fuel consumption, and the most efficient vessel receives money for welfare as prize. Besides, if vessels receive a report about the energy performance of different vessels, they compare themselves with the similar vessels and try to improve.

Hiring more people in addition to the energy manager to work with energy efficiency can solve *the lack of time*. However, convincing those in top management to hire more people for such posts may not be straightforward.

Crew should be trained to use available information to solve the *crew's lack of competence* barrier. Besides, crew's competence should be quantified somehow.

3.3.4. *Inter-organizational barriers*

Regarding *split incentives*, crew's responsibility regarding saving energy can be increased. 'Smart contracts' may be another solution [55]. The idea is to change charter contracts in a way that risks and benefits are shared among charterers and ship owners. In such contracts speed choice is more flexible, and the chartering cost of vessels is closer to fuel cost; as such ship owners get motivated to invest in energy-efficient technologies, and operators get stimulated to run vessels in an energy conserving manner.

3.3.5. *Technological barriers*

To solve the *immatureness* barrier state-of-the-art technologies should be tested to understand their pros and cons; this could be done by companies wishing to be pioneers at the expense of risk-taking, by demonstration projects financed by external funding, or by research grants for doing scientific works in this area. Collaborating with charterers about energy efficiency can be another solution. However, at least a one year period of chartering seems necessary to get their support. Another solution may be to have an agreement with equipment manufacturers that provide energy-efficient systems to install their products on vessels. This can be of mutual benefits: equipment manufacturers can test their equipment and ship owners can benefit from possible energy savings without paying for the whole capital investment.

To reduce the *technical risk* technologies could be first examined on a handful of vessels owned by a ship owner. If the results were good, the same technology can be installed on the rest of the fleet.

Table 1
The focused barriers by different stakeholders in the EMIP II project.

Stakeholders	Information barriers	Economic barriers	Intra-organizational barriers	Inter-organizational barriers	Technological barriers	Policy barriers	Geographical barriers
Ship owning company 1			✗	✗		✗	
Ship owning company 1	✗		✗	✗	✗		
Ship owning company 2	✗	✗	✗	✗			
Ship owning company 2	✗		✗	✗	✗		
Ship owning company 3	✗	✗	✗	✗	✗		
Ship owning company 4		✗	✗	✗			
Ship owning company 4	✗		✗	✗	✗	✗	
Ship owning company 5	✗		✗	✗		✗	✗
Equipment supplier company 1			✗	✗			
Equipment supplier company 1	✗		✗	✗	✗		
Equipment supplier company 2	✗		✗	✗			
Research institute	✗		✗	✗	✗		

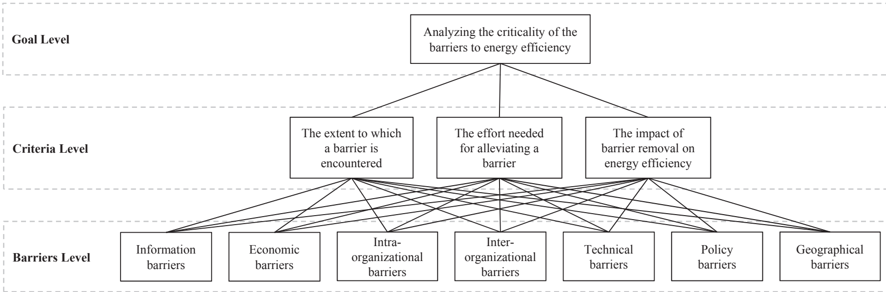

Fig. 4. Prioritizing the barriers to energy efficiency by AHP, adapted from Ref. [65].

Technologies, such as main engines should be efficient in a range of operational profiles instead of in a specific point to solve *incompatibility between technologies and operations*. This requirement should be communicated to manufacturers. Offered technologies should be studied under different scenarios to realize their flexibility. However, as few manufacturers control the market, they sell anyway. More pushing from decision makers may solve this problem. Additionally, when technologies are proven to be useful and their benefits cannot be harnessed any longer due to operational changes, the technologies should be modified to fit into new operations.

3.4. Step 4: assessing the influence of overcoming some barriers on the status of the others

The consequences of reducing the barriers should be carefully assessed. As an example, the interactions among different information barriers can be illustrated: By using measurement equipment, the change in the energy consumption of a ship after using an energy-efficient measure can be realized. By providing adequate and accurate information, *the lack of information*, *the inaccuracy of information*, and *moral hazard and principal-agent relationships* barriers could be overcome. If this information is specific, vivid, and simple, and if it is provided close to the time of investment and decision making, *the improper form of information* barrier can also be dealt with [20]. In the next step, the effect of solving/reducing these barriers on the others could be explored. By overcoming the four barriers mentioned and by providing feedback on the results of using the energy-efficient measure, the stakeholders will be more informed and the *adverse selection* barrier will be decreased. Besides, by using accurate measurement instruments and providing suitable and vivid feedback about the energy consumption, *the lack of credibility and trust in the source of information* barrier will be solved. Consequently, the stakeholders would continue/stop investing in that measure as they now have a clear knowledge about it. By transferring the gained information about the pros and cons of the measure to other ship owners/(energy) managers, they may also start/stop investing in the same measure as now there is some evidence suggesting it to be promising or not.

3.5. Step 5: documenting results and follow-up

As an outcome of the former steps some barriers may be dealt with. Accordingly, the uptake of some cost-effective energy-efficient measures could be facilitated. The knowledge gained through the previous steps should be documented to refer to later. Besides, the accumulated knowledge could be transferred to other organizations as a basis for solving their energy-related problems. Some changes are happening in shipping; some ship owners require gathering data in the same manner both in vessels operated internally and externally; in this way sharing information could be facilitated. Moreover, some ship owners, like those involved in the EMIP II project, collaborate to share their experiences with energy-efficient measures.

4. Conclusions

In this article a framework for overcoming barriers to energy efficiency is proposed. The framework consists of five iterative steps and focuses on continuous improvement in energy efficiency. The framework is mainly designed to be used by ship owners and (energy) managers. However, due to its generic structure it may be applied to industries other than shipping. Researchers and policy makers can also benefit from the framework as it makes challenges to energy efficiency more apparent.

The following steps were taken to construct the framework: First, literature on barriers to energy efficiency, which mainly addresses other industrial sectors than shipping, was reviewed to form the taxonomy. Then, the framework was designed, and interactions among barriers were considered. To corroborate the framework feedback from those in the shipping industry was must-have. Feedback on its relevance, usefulness, and possible modifications and improvements was given at meetings with 12 participants of the EMIP II project during winter and spring 2013. These participants work in five ship owners in Norway, two equipment suppliers, and a research institute.

Various barriers are encountered in shipping. Different participants had different and sometimes incompatible views about barriers. This is due to their unlike job positions, ranging from environmental performance manager to naval architect, and work environments; different companies face different barriers, and there is no one-size-fits-all set of barriers. The framework can be tailored to individual needs.

The participants considered *the inaccuracy of information*, *incompatibility between technologies and operations*, *the lack of credibility and trust in the source of information*, *not using information*, *not maintaining information*, *split incentives*, and *immatureness* as the most important barriers to deal with. The incapacity to measure energy consumption accurately makes it difficult to justify investments. For instance, when several energy-efficient measures are used simultaneously the contribution of each to fuel saving is hard to identify. Besides, when the energy consumption of a ship is stated the effect of, for example, market recession in savings is usually not mentioned. These inaccuracies plus changes in weather conditions, routing, and so on may make savings invisible and hence make it more difficult to trust in energy-efficient measures and adopt them.

There are also other problems hindering energy efficiency in shipping. For example, equipment, such as measurement instruments may be installed onboard ships without being utilized. This may be due to the misconception that the mere installation of equipment saves fuel. However, the equipment should be utilized and maintained to fit new operations. Additionally, the problem of 'who pays for technologies and who gets fuel bill?' exists in shipping. Usually ship owners pay for technologies while charterers pay for fuel bills. Therefore, not all stakeholders find incentives to focus on energy efficiency. Finally, the lack of funding to test immature energy-efficient measures may hinder their adoption.

Despite the importance of *limited access to capital* in foundries [39,42], *interference with main processes* in pulp and paper industry [40], and *the lack of time* in manufacturing firms [60], they are not considered as critical barriers by the participants. *The low priority of energy efficiency* can act as another barrier in some sectors, such as manufacturing [60]. However, this is not an issue in shipping, either. Shipping is quite energy intensive, and energy cost has a big share in operational costs. Thus, top management and charterers are concerned about energy consumption. Still, this concern is not reflected on operational practice, which is problematic. For instance, the chartering party may discuss the importance of saving fuel as fuel cost may form about 80% of the charterer's expenses. However, this concern is not necessarily reflected on how this party deals with fuel consumption. In some cases there are other problems that leave no space to focus on energy performance.

Future work should be conducted, for example, to study the viewpoints of more stakeholders, such as authorities, classification societies, agents, captains, crew, and charterer parties, who are not included here. Different stakeholders may encounter dissimilar barriers, and the benefit to all of them should be considered. They may also define different criteria with different weights for prioritizing barriers.

In Norway, the fisheries are important to the national economy. However, operating in harsh waters makes the fishing fleet quite energy demanding [70]. This fact coupled with the increase in fuel price and imposed and possible future emission taxes endanger the economic profitability of fisheries [71]. Thus, energy efficiency and barriers should be explored in the fishing fleet by using the proposed framework.

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Article III

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Article IV

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Article V

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Second International Symposium on Fishing Vessel Energy Efficiency
E-Fishing, Vigo, Spain, May 2012

Emission Reduction in the Norwegian Fishing Fleet: Towards LNG?

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***Abstract*— The continued operation of fisheries is fundamental to Norway's economy bloom. However, there are some obstacles against fulfilling this. Firstly, operating in harsh waters makes the Norwegian fishing fleet quite energy intensive. This fact coupled with the recent increase in fuel prices and introduced taxes on emissions cast doubt on the economic profitability of the Norwegian fishing sector. Secondly, Norway is committed to a greener environment due to several regulations the fulfillment of which is high on the agenda. Key legislations driving emissions reduction in this sector are Marine Pollution (MARPOL) Annex VI regulations which introduce stringent limits on sulphur dioxide (SO_2) and nitrogen oxides (NO_x) emissions in the Emission Control Areas (ECAs) which come into force on 2015 and 2016, respectively. Besides, nowadays fish food consumers and other stakeholders are not only concerned with the quality of fish, but also with the environmental footprints associated with its production. Therefore, there are various economic and environmental drivers in favor of reducing adverse environmental impacts associated with fishing in Norway.**

Fishing vessel owners willing to continue operation in ECAs after 2015 and 2016 will need to modify their ships and/or the way they operate them. There are several management and technical options in this favor. Among the technical options available there are those focusing on modifying engine systems, including switching to alternate fuels, such as Liquefied Natural Gas (LNG). LNG has proved technical feasibility in 26 LNG-fueled ships in operation, namely 15 ferries, 5 offshore support vessels, 3 coast guard vessels, 1 product tanker and 2 LNG tankers, of which 25 are in operation in Norway. This paper discusses the challenges and benefits related to the implementation of LNG-fuelled engines in the Norwegian fishing fleet as a step towards emission reduction.

Keywords- fishing fleet; Norway; emission reduction; LNG

I. INTRODUCTION

Having access to some of the world's richest fishing resources makes Norway the second largest fish exporter around the world [1]. Fisheries are a central contributor to Norway's economy after oil and gas [2]. Thus, maintaining the competitiveness of fisheries in food market is crucial.

Traditionally, some issues such as the decreasing stock size of target stocks, biological impact on by-catch stocks, ghost-fishing, and the effects of some types of fishing gears on ecosystem, e.g. the effects of bottom trawlers on sea bed, have been the main focus while studying environmental impacts of fisheries. These could be considered as some of the direct impacts of fishing. On the contrary, the contribution of fishing to environmental effects above the ocean level, i.e. indirect impacts of fishing, has been underestimated so far. Indirect impacts are connected to the use of fossil fuel, antifouling, and refrigerants [3, 4].

The operation of fishing gears in rough and icy waters makes the Norwegian fishing fleet quite energy demanding. High energy consumption is a challenge for this fleet. On one hand, increase in oil prices and the introduction of taxes on emissions have put financial burdens on the fishing sector [5]. On the other hand, fuel consumption during fish catching is a significant contributor to the global warming potential of the Norwegian fishery [3]. This is illustrated in Figure 1 which shows the carbon footprint of different Norwegian seafood products at the different stages of their life cycle. Besides, the contribution of fishing to climate change is just one of the several potential impacts of fishing on the environment. Other impacts include acidification, toxicity etc. [6]

Norway has to comply with different international environmental agreements, such as Gothenburg Protocol and Marine Pollution (MARPOL) Annex VI regulations, which aim at reducing various emissions including sulphur dioxide (SO_2) and nitrogen oxides (NO_x). Besides, nowadays fish food consumers and other stakeholders are not only concerned with the quality of fish, but also with the environmental footprints associated with its production [7]. Therefore, there are economic and environmental drivers in favor of reducing adverse environmental impacts associated with fishing in Norway.

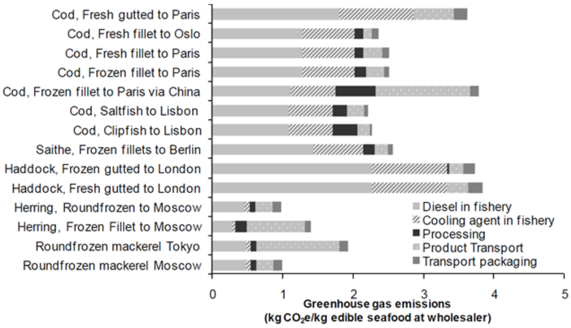

Figure 1. The total carbon footprint of the Norwegian seafood products from capture fisheries [3]

With regard to Figure 2 which shows the fuel use coefficient, i.e. kilogram of fuel per kilogram of fish landed, for different segments of the Norwegian fishing fleet in the period of the years 1980-2005, trawling is the most energy demanding fishing method [5]. That is, trawlers emit the most in their fishing stage among various fishing types. Thus, by reducing emissions from trawlers Norway could take a step forward to fulfill its commitment to emissions limitations. One possible way to reduce emissions is to introduce ship engines consuming Liquefied Natural Gas (LNG).

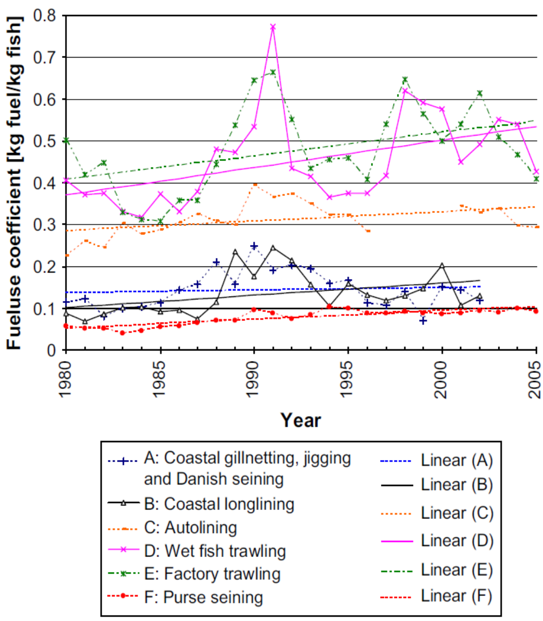

Figure 2. The fuel consumption of different segments of the Norwegian fishing fleet in 1980-2005 [5]

The objective of this article is to discuss the implementation of LNG in the Norwegian fishing fleet as a means to reduce emissions to air. Throughout the article the status of the shipping sector is discussed as fishing vessels constitute a part of it. That is, they could be influenced by changes in the shipping sector and they could follow the technological amendments made in other parts of this sector. The article is structured as follows: first the present environmental regulations imposed on the shipping industry, with emphasis on the Norwegian fishing fleet, are discussed. Then, some of the possible measures to be taken to be able to pursue operation in the current situation are stated. Finally, as an example a rough estimation of emissions from using different fuels, namely Marine Gas Oil (MGO) and LNG, to capture fish by a Norwegian coastal trawler are compared. In this way some of the benefits attained by using LNG in fisheries are illustrated.

II. REGULATIONS FOR MARITIME EMISSION REDUCTIONS

Regarding the Intergovernmental Panel on Climate Change (IPCC) the greenhouse gas (GHG) emissions of the shipping industry are estimated to be 10 fold the amount in 1995 by the year 2050 [8]. Moreover, the shipping industry emits NO_x, SO_x, and particles [9]. Considering environment, different policies are adopted worldwide; among them emission restrictions are imposed on the shipping industry and more is to come [10]. MARPOL Annex VI aims at implementing a progressive reduction in the emissions of SO_x, NO_x and particulate matter in global scale and more stringently in designated Emission Control Areas (ECAs). In Sulphur Emission Control Areas (SECAs), which includes the North Sea, the English Channel and the Baltic Sea, sulphur content in fuel oil should be reduced to 0.1% by the first of January 2015 [11]. Furthermore, gradual reductions in NO_x emissions from marine diesel engines are required. In the case that IMO member states submit a proposal for Nitrogen Emission Control Area (NECA), the most stringent limitation on NO_x emissions would come into force by the first of January 2016 [12].

In addition to MARPOL Annex VI regulations there are other drivers in favor of reducing environmental footprints from the shipping and fishing industry, namely

- Energy Efficiency Design Index (EEDI), which applies to new ships; however, only following ship types are included: bulk carrier, gas carrier, tanker, container ship, general cargo ship, refrigerated cargo carrier, combination carrier [10],
- Ship Energy Efficiency Management Plan (SEEMP), which applies to all ships [10],
- The European Union (EU) staff working paper entitled “Pollutant emission reduction from maritime transport and the sustainable waterborne

transport toolbox", which suggests several incentives/disincentives in favor of a greener shipping industry in the EU [10], and

- The Gothenburg Protocol which covers energy producing units such as domestic shipping (including fisheries) [13].

III. COMPLIANCE OPTIONS WITHIN THE ENGINE TECHNOLOGY

Emissions from fishing fleets contribute to air pollution significantly [14]. Regarding to what was stated earlier ship owners are forced to modify their ships if they wish to continue trade in ECAs, which are shown in Figure 3, by 2015 and 2016. The Norwegian fishing vessel owners are not exempt from this as Norway is among ECAs. Additionally, with regard to the Gothenburg Protocol and National Emission Ceilings (NEC) Directive, the total NO_x emissions of Norway should not surpass 156000 tons from 2010 onwards [13]. Various management and technical modifications can be introduced to achieve this goal; some of the technical modifications concentrate on modifying engines. Three options exist from this point of view, namely

A. Switching to low-sulphur MGO or Marine Diesel Oil (MDO) [10],
B. Using exhaust gas scrubber for ships running on Heavy Fuel Oil (HFO) [10], and
C. Switching to alternate fuels, such as LNG [10].

Figure 3. ECAs [9]

A. *Switching to low-sulphur MGO or MDO*

It is possible to refine HFO to the extent that it contains 0.1% sulphur; however, refineries do not find it economically viable as they can produce higher priced products like MGO with the same production cost. MGO and MDO with less than 0.1% sulphur could be supplied, and do not require major changes in the fuel system and the retrofitting of the engine. MGO does not require extra volume for storage tanks, as well. Thus, using MGO will result in small investments costs at most. However, switching to these fuels has some drawbacks. First of all, low sulphur fuels are limited and rising demand may affect their prices. Second, the viscosity of MGO is less than that of MDO and HFO. For operation in a two-stroke diesel engine the viscosity should be more than a minimum. Besides, fuel injection pump wear may force even a higher viscosity, unless a more tolerant modern common-rail system is used. Fuel cooler requirements are related to the viscosity as well. Finally, these fuels require the change of lubrication oil after two weeks of operation [9, 10].

B. *Using exhaust gas scrubber for ships running on HFO*

"End of pipe" solutions consist of using scrubbers for the SO_x and particulate matter removal by using chemicals or seawater plus using either Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) for NO_x cleaning [10].

Scrubbers have both advantages and disadvantages. As an advantage by using scrubbers the ship could run on high sulphur HFO and there would be no need to modify or replace engine. Moreover, SO_x emissions will be eliminated and particulate matter emissions will be reduced. Thus, scrubbers could be easily retrofitted to comply with regulations in ECAs [9, 10].

As a drawback while installing scrubbers, several alterations should be implemented onboard as they need additional tanks, pipes etc. which result in additional investment cost and space needed subsequently. In addition, the waste should be disposed of at special places and this could be charged in the future. Besides, CO_2 emissions are not reduced. Scrubbers used in SECAs should be IMO certified which means additional paperwork. HFO availability in ports in the future is of question as well [9, 10].

With SCR method nitrogen and water vapor would be emitted instead of NO_x. The success of this system depends on maintaining a specific exhaust gas temperature and not having high sulphur content in the exhaust gas. It is possible to optimize the system further by modifying the engine. However, this means increased investment [15].

By using EGR exhaust gas is recirculated into the charge air. In this way the oxygen content of the cylinder and the specific heat capacity are reduced and increased, respectively. These lead to lower combustion temperatures and subsequently less NO_x emissions. However, the sulphur content of heavy fuel oil can result in the corrosion of components [16].

C. *Switching to alternate fuels, such as LNG*

LNG is produced by liquefying natural gas at about -162˚C and due to this low temperature it should be stored in cryogenic tanks. LNG is mainly composed of methane. There are two main engine types running on LNG, namely dual fuel engines and LNG lean-burn mono fuel engines, which are explained further [17]:

1) *Dual fuel engines, four-stroke Otto engines*

Dual fuel engines can run in either gas mode or conventional liquid fuelled diesel mode. The working principle is based on Otto cycle in gas mode; injection of a small amount of fuel oil, usually less than 1% of total fuel, together with the compression heat is used as the ignition source. Operation on fuel oils is based on diesel cycle [17].

2) Dual fuel engines, two-stroke diesel engines

These engines work by high pressure gas injection together with pilot diesel oil. They can run on fuel oil only or on a mixture of gas and fuel oil. The engine has no or almost no methane slip. However, it cannot fulfill the most restrict NO_x regulations without the installation of EGR or SCR. Various engine makers are working on solving this drawback [10].

3) Single fuel gas engines

Gas engines of the Otto/Miller type with spark ignition run only on gas. Lean-burn mixture, i.e. with high air-fuel ratio, drives a spark ignition. High efficiency and low emissions are ensured at the expense of losing the possibility to use fuel oil [10].

Shifting to LNG fuel has some pros and cons. First of all, LNG use is foreseen to have the lowest present value costs compared to conventional fuels considering a 20-year long life time for a ship [9].

Second, by using LNG for propulsion purposes, the shipping sector will be a new market for LNG terminals [9].

Third, of interest specifically for fishing fleets is the possibility to take advantage of the low LNG temperature. To put it in simple words, it can be used to cool down fish storage tanks [10], resulting in the less usage of conventional refrigeration systems. This in turn can reduce the energy and consequently the cost of freezing fish. If this can be implemented in fishing vessels, it will result in additional emission reduction as well considering that current refrigeration systems are significant contributors to emissions (Figure 1).

Fourth, by using LNG the emissions of NO_x are reduced by 80-90% and 10-20% for Otto cycle and diesel cycle processes, respectively; NO_x reduction is beneficial from economic view in addition to environmental view. That is, the Norwegian authorities have established a NO_x-tax equal to 16.43 NOK (ca. 2 EUR) per kilogram of NO_x emitted from 1 January 2011[13]. On the other hand, the Government has introduced a NO_x-fund to turn the collected tax back to the industry in support of NO_x-mitigating measures. Thus, many of the currently running ships on LNG have received more than 50% of the extra cost by support from the fund. It is possible to get monetary support of up to 75% of the investments to decrease NO_x emissions [10, 18]. SO_x and particles emissions are almost eliminated as well.

Fifth, up to now no requirements about GHG emissions are imposed on the shipping industry. However, the introduction of some sort of CO_2-tax in the near future seems likely. In this case reduced GHG emissions would be of economic interest in addition to environmental interest. LNG contains less carbon and consequently a gas fueled engine emits less CO_2. On the negative side, while running on Otto cycle process some methane slip occurs in dual fuel engine [10, 9]. Methane is an effective GHG with a radiative impact equal to 23 times of the value corresponding to CO_2 on a weight basis over a 100-year perspective. Methane is the second largest contributor to anthropogenic GHG emissions after CO_2 and contributes to about 16% of the total GHG emissions on a CO_2-equivalent basis. As a result, controlling methane emissions is of significant importance for GHG mitigation [19]. Engine manufacturers expect to overcome this problem. However, despite methane slip, LNG could reduce net GHG emissions by about 15-20% compared to conventional fuel oils. Methane slip is not a problem for engines operating on gas in the diesel cycle [9, 10].

Sixth, another drawback of LNG is that it imposes about 10-20% additional investment cost for infrastructure [9, 10].

Finally, LNG needs purpose-built or modified engines and a complicated system of special fuel tanks, a vaporizer, and double insulated piping due to properties of LNG and to ensure safety. These result in a need for more storage room in comparison to conventional fuel oil tanks. This may or may not reduce the cargo capacity, depending on ship type, fuel tank type and the potential of locating LNG tanks on-board [9, 10].

IV. INTRODUCING LIQUEFIED NATURAL GAS IN THE NORWEGIAN FISHING FLEET

Out of the compliance options mentioned, shifting to LNG fuelled engines is getting more attention from an environmental perspective [9]. The safety and technical feasibility of LNG as a fuel for shipping are proven by 26 ships in current operation, i.e. 15 ferries, 5 offshore support vessels, 3 coast guard vessels, 1 product tanker and 2 LNG tankers, the 25 of which are operating in Norway [20, 21]. Switching to LNG is expected to continue increasing in the shipping sector provided that required bunkering facilities will be in place. There are nine LNG production plants in North Europe, the five of which are based in Norway; moreover, fourteen of the Norwegian small-scale land-based terminals are organized to deliver LNG to ships while four of them are operating as bunkering stations today. In addition to these terminals, LNG bunker vessels plus offshore terminals are supposed to be crucial segments of LNG infrastructure within SECAs in the future [10].

LNG's safety and technical feasibility are well proved in different ship types, and there seems to be no barrier to introduce it in fishing vessels too. Basically, all fishing vessel types could be suitable for running on LNG fuel. However, with regard to high capital investment needed for using LNG and limited available bunkering facilities at the present time, the first adopters will be the ones having a regular route near coast which are also capable of capturing large amounts of fish in a shorter time. Coastal trawlers could be a possible nominee.

First of all, operating on a specific route makes it easier to predict the fuel needed per voyage and to secure bunkering as bunkering spots are limited at the present time. It also makes the fishing vessels "secure" customers for bunkering terminals which in turn motivates investment in expanding terminals [10]. Second, operating near coast makes it possible to have smaller LNG storage tanks and to allocate more space to fish tanks and other facilities needed for fishing. Third, as the capital investment of shifting to LNG is about 10-20% more than that of operating on conventional fuels, it is of major interest to ship owners to shorten the pay-back time. Therefore, by using LNG in coastal trawlers, which could capture large amounts of fish in each hauling, the possibility of attaining a shorter pay-back time is more. Finally, the Norwegian trawlers consume the most amount of energy in comparison to other fishing vessel types as stated earlier; thus, by propelling trawlers by a cleaner fuel, a degree of emission reduction could be obtained. This could help Norway to comply with environmental regulations mentioned and to reduce environmental impacts in turn.

To get a view of the environmental benefits of running the Norwegian coastal trawlers on LNG, a rough calculation is done to compare emissions from operating on MGO and LNG fueled engines. With regard to Figure 2, the mean fuel use coefficient of wet fish trawlers, which are mainly of coastal type, is 0.45. Although there is a significant variation in the amount of this coefficient from year to year, the mean value is used for the calculations hereafter. The fuel used for calculations of the energy coefficient is MGO with lower heating value of 42.8 Mega Joule/kilogram MGO [5]. The amounts of NO_x and CO_2 emissions in the Norwegian fishing vessels in average are 0.064 and 3.17 kilogram/kilogram MGO, respectively [22]. Besides, total amount of fish caught by 44 trawlers in 2010 was 267582 tonnes [23]. Two assumptions are made. Firstly, although this group of trawlers consists of both coastal and ocean going trawlers, the average amount of fish caught is allocated to each vessel. Secondly, the amount of fish caught in 2010 is considered to stand for the amount of fish captured each year. Therefore, each coastal trawler is estimated to capture 6081.41 tonnes of fish per year. Additionally, as stated earlier by shifting to LNG NO_x and CO_2 emissions are expected to be reduced about 80-90% and 15-20%, respectively [9,10]. Thus, the emissions of each Norwegian coastal trawler currently running on MGO and the expected emissions by switching to LNG would be as shown in Table I.

Thus, by switching to LNG it is expected to abate emissions from the Norwegian fishing sector substantially.

TABLE I. EMISSIONS OF EACH NORWEGIAN COASTAL TRAWLER

		Current MGO's Emissions	Expected LNG's Emissions
Emissions per Catch	NO_x (kg/kg fish)	0.029	0.003-0.006
	CO_2 (kg/kg fish)	1.426	1.144-1.215
Total Emissions	NO_x (tonne)	175.145	17.514-35.028
	CO_2 (tonne)	8675.131	6940.104-7373.861

As a basis for a rough comparison reference [17], which compares environmental footprints of different fuel alternatives in a Ro-Ro vessel, is used. Only the transportation phase of cargo is considered as a guideline to do a simple calculation of CO_2 and NO_x emissions of a typical MGO- and LNG- fuelled coastal trawler.

It should be emphasized that the results are a rough estimation. First of all, emissions from the MGO- fueled engine are computed based on an abstract trawler with mean characteristic values. Second, emissions from a MGO- fuelled Ro-Ro vessel [17] are considered. Third, no LNG-fuelled trawler is constructed up to now, so the data for emission amounts from another LNG-fuelled vessel type, namely a Ro-Ro ship [17] is used. And finally, the emissions are only representative of emissions from the fish catching phase. For precise comparison of the two fuels the impacts from their whole life cycle should be estimated.

Emissions of the fuels are illustrated and compared in Table II, regarding to which by shifting from the conventional MGO to LNG 88.571% and 13.474% reduction in emissions of NO_x and CO_2 could be attained, respectively.

TABLE II. EMISSIONS OF A NORWEGIAN COASTAL TRAWLER BASED ON THE DATA FROM A RO-RO VESSEL

	MGO's Emission	LNG's Emission	Emission Reduction % ((MGO's Emission – LNG's Emission) /MGO's Emission) *100
kg NO_x/kg fish	0.070	0.008	88.571
kg CO_2/kg fish	3.451	2.986	13.474

Considering MGO as fuel, Tables II represents larger values in comparison to Table I. As it was stated it is due to the fact that Table I and II are based on emission data from the Norwegian fishing vessels and a Ro-Ro vessel, respectively. Thus, it is believed that the data in Table I are more realistic regarding the problem at hand. With regard to LNG, no conclusion could be drawn at present as no LNG-fueled fishing vessel exists to be used as a basis for comparison. However, by referring to literature [9,10] and the rough estimations in Table II it is expected that shifting to LNG would be beneficial from an environmental point of view.

186000 tonnes of NO_x emission in 2010 were 19% higher than the emission ceiling Norway had promised to meet due to international agreements according to Norway's statistics [24]. According to Table I if by switching to LNG in each Norwegian coastal trawler its NO_x emissions could be reduced by 80%, the amount of NO_x emissions corresponding to each vessel would be reduced by about 140.117 tonnes. Thus, by introducing LNG in 10 Norwegian coastal trawlers, Norway's NO_x emissions would be reduced by about 1%, which could be of importance.

V. CONCLUSION

The Norwegian fishing fleet is quite energy demanding due to the harsh environment it operates in. Thus, the fishing phase is an energy intensive step in the life cycle of a Norwegian seafood product. Among various fishing gears, trawling consumes the most amount of energy per kilogram fish caught. Besides, Norway is committed to several regulations in favor of reducing emissions from the shipping industry. Therefore, the Norwegian authorities have introduced taxes to force emission reduction and funds to support measures leading to a greener environment. Moreover, environmental footprints of a seafood product are important to its consumers while deciding to choose between different products. These environmental and economic incentives force modifying the Norwegian fishing fleet to ensure less environmental impacts associated with it.

A possible modification is to alter the conventional fuel used for propulsion by other kinds of fuels with less emission, such as LNG. Successful operation of 26 LNG-fueled ships of various types, 25 of which operate in Norway, is an indicator of technical feasibility of this option.

In this paper with regard to the limited number of bunkering stations and ways available at the moment and the high capital investment needed for LNG-fuelled vessels, the Norwegian coastal trawlers are suggested to be the best nominee for switching to LNG fuel. In this way in addition to adhering to the emission limitations in force, they could ensure a less pay-back time for the high investment made. Moreover, by a rough calculation it is shown that by shifting from MGO to LNG in a typical Norwegian coastal trawler it is expected to reduce its CO_2 and NO_x emissions significantly. Considering trawlers as an important portion of the Norwegian fishing fleet, this emission reduction could be of substantial interest. It is shown that by introducing LNG in 10 Norwegian coastal trawlers Norway's NO_x emissions could be reduced by 1% roughly.

Despite the several benefits of LNG mentioned, there are still some obstacles which need to be overcome to expedite adoption of LNG propulsion; Further improvement in bunkering facilities and in designs leading to less space allocated to LNG tanks.

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Article VI

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LNG-fuelled fishing vessels: a systems engineering approach

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Abstract

Air emissions from fishing vessels must be reduced to comply with progressively tightening environmental regulations. Among the available solutions, liquefied natural gas (LNG) fuel may represent a promising solution, particularly from an environmental perspective. However, the use of LNG as a marine fuel creates different types of hazards than those that exist for traditional fuels. In addition, the higher complexity, safety requirements, and space needed for LNG installation increase the capital cost. This article uses a systems engineering approach to clarify the technical aspects of LNG-fuelled systems, their potential implementation costs, and the expertise and training needed to operate them safely. Ship owners can use such an approach to aid decision-making and trade-off analyses. Naval architects may also benefit from better information management. Finally, the crew may better understand the logic behind the safety actions they are instructed to take.

Keywords

LNG; Fishing vessel; Ship design and operation; Systems engineering; Safety; Cost

1 Introduction

Except for airborne transportation, fishing vessels are responsible for the largest portion of the energy consumed in and emissions resulting from the seafood product value chain (Avadí and Fréon, 2013; Parker et al., 2015; Winther et al., 2009). Although considerable differences in energy efficiency exist among different types of fishing vessels (Jafarzadeh et al., 2016), since 1990, global fisheries have consumed a median value of 639 litres of fuel per tonne of fish (Parker and Tyedmers, 2015). In 2000, fishing vessels accounted for approximately 1.2% of worldwide oil consumption and produced 134 million tonnes of carbon dioxide (CO_2). These values are likely underestimates, given that energy inputs for the provision of fuel, vessels, and fishing gears were not considered (Tyedmers et al., 2005). Furthermore, the CO_2 estimate only accounts for emissions from energy use and excludes greenhouse gas (GHG) emissions from refrigerants on board (FAO, 2012). Hence, the regulations imposed on fishing vessel emissions have become increasingly strict. In 2011, the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI was revised to control GHG emissions by introducing the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) (IMO, 2013a). The EEDI does not currently apply to fishing vessels, but it may apply in the future (Bazari and Longva, 2011). The SEEMP applies to fishing vessels of 400 GT and above (Hop, 2016). Additionally, the Kyoto Protocol covers domestic shipping and regulates GHG emissions in Norway and other involved countries. In 2012, this protocol was revised to set new caps (UNFCCC, 2014).

Because fishing vessels emit sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) (Lin and Huang, 2012), the MARPOL Annex VI regulations also aim at reducing these emissions globally and more stringently in emission control areas (ECAs). These regulations apply to all ships. Vessels of 400 GT and above require an International Air Pollution Prevention (IAPP) Certificate to demonstrate their compliance with these regulations. The Flag Administration may establish other measures to ensure the compliance of smaller vessels (DNV, 2008; Hop, 2016; IMO, 2013b). Additionally, the Gothenburg Protocol regulates NO_x emissions in Norway and other involved countries. In 2012, this protocol was revised to set caps for 2020 (UNECE, 2014). To fulfil the NO_x cap, Norway introduced a NO_x tax and a fund that applies to domestic shipping and fishing. The Norwegian state and 15 business organizations (e.g., the Norwegian Fishermen's Association) signed a NO_x agreement, which means that the organizations will adopt emission-reducing measures and pay a smaller amount to the NO_x fund instead of the NO_x tax. The fund supports measures that reduce NO_x (EFTA, 2011; Høibye, 2012; NHO, 2013; Åsen, 2013).

In Norwegian waters[1], fishing vessels contributed to approximately 10.2% of the fuel consumed by ships in 2013 (DNV GL, 2015b). Compared to passenger ships (22.3%) and offshore supply vessels (15.7%) (DNV GL, 2015b), fishing vessels were the third most fuel-intensive shipping segment in Norway. Fuel is one of the primary costs associated with fishing, and the proportion of the cost that it represents varies among fisheries (Sumaila et al., 2008). Various factors affect fuel consumption and fuel cost, such as the target species and harvesting method. For example, in 2012, fuel and lubrication oil accounted for approximately 5–38% of the operational costs for Norwegian shrimp trawlers, whereas the mean value for the entire fleet was 10% (these calculations were based on a dataset from the Directorate of Fisheries (2014)). In addition, seafood consumers are becoming aware of the environmental consequences of fishing, and the environmental impact of seafood products may influence the market share (Fet et al., 2010).

Regulations and agreements act as incentives to reduce emissions from fishing vessels and develop greener fisheries. Ship owners have different options regarding compliance with the regulations (Jafarzadeh et al., 2012; Martelli et al., 2016; Notti and Sala, 2013). Among these options, the use of liquefied natural gas (LNG) as an alternative fuel is gaining increasing attention, particularly from an environmental perspective (Benvenuto et al., 2013; DNV, 2011; LR, 2012). However, the use of LNG as a marine fuel creates different hazards than traditional fuels, such as cryogenic temperatures and increased fire intensity, creating an explosion risk. To ensure safety, it is necessary to consider different and/or additional safeguards when using LNG (Davies and Fort, 2013). In addition, the higher complexity, safety requirements, and space needed for LNG installation increase the capital cost of LNG-fuelled vessels compared to their oil-fuelled counterparts (Chryssakis et al., 2015; Tzannatos et al., 2015). Lower operational expenses should compensate for the additional investment costs to ensure profitability.

Powering fishing vessels with LNG may be a solution for reducing air emissions from the fleet (Altosole et al., 2014; Danish Maritime Authority, 2012); however, environmental improvements should not come at the cost of safety and profitability; otherwise, the ship owners may prefer other solutions over LNG. The objective of this article is to present a systematic approach for a feasibility analysis of LNG in the fishing fleet and thus increase knowledge regarding the requirements, costs, and benefits of LNG-fuelled ships for the ship owners, naval architects, and crew. A systems engineering (SE) process is used to clarify the technical aspects of LNG-fuelled systems, their potential implementation costs, and the expertise and training needed to operate them safely. Ship owners can use this knowledge in parallel with other decision-making processes to determine whether LNG fuel is the appropriate choice. They may also use this approach to plan for harnessing the environmental benefits of LNG without exposing the crew and fishing vessels to higher risk.

The remainder of this article is organized as follows. A brief background on LNG as a marine fuel is presented in Section 2. Then, Section 3 presents the SE and the systematic approach to LNG implementation. Section 4 provides details via an analysis of a shrimp trawler. Section 5 presents a discussion of the results, and Section 6 presents the conclusions.

2 LNG-fuelled vessels

Natural gas, which is mainly methane, liquefies at -160°C, and its volume is reduced to 1/600 of its gaseous state, thus making it more space efficient for storage and transportation on ships (Wang and Notteboom, 2014). There is extensive experience with LNG use in terms of the use of boil-off gas in LNG carriers. Since 2000, other vessel types, such as ferries and offshore supply vessels, have also used LNG fuel (Chryssakis et al., 2015). Three engine types can use LNG as fuel (Einang, 2013):

- Pure gas engines or lean-burn spark-ignited gas (LBSI) engines

[1] Norwegian waters include the Norwegian economic zone, fishery protection zones around Svalbard and Jan Mayen Islands, the Loop Hole (i.e., Smutthullet) in the Barents Sea, and the Banana Hole (i.e., Smutthavet) in the Norwegian Sea (DNV GL, 2015b).

- Low-pressure dual fuel (LPDF) engines
- High-pressure dual fuel (HPDF) engines

LBSI engines use only gas, whereas LPDF and HPDF engines can run on both gas and diesel fuel. LBSI engines operate on the Otto cycle, in which a spark plug initiates the combustion process. LPDF engines operate on the Otto cycle in gas mode, in which pilot fuel oil starts the combustion process. The gas supply pressure is low in both LBSI and LPDF engines, with pressures of approximately 5–6 bar for four-stroke engines and 10 bar for two-stroke engines. Therefore, gas can be provided either directly from a pressurized storage tank or by a compressor. HPFD engines use the diesel cycle in gas mode. Gas is injected at high pressure into the cylinder (i.e., approximately 300 bar) after the pilot fuel oil has ignited. An additional high-pressure gas compressor or a LNG pump is needed to provide such a high pressure. In addition, special piping and a safety system are required (Boulougouris and Chrysinas, 2015; DNV GL, 2015a; Æsøy et al., 2011).

In March 2016, 77 LNG-fuelled ships were in operation, and 85 new ships were under construction, with planned deliveries within 2022. These numbers exclude LNG carriers and inland waterway vessels. Of the operating vessels, 69% operate in Norway (DNV GL, 2016). LNG-fuelled vessels may potentially reduce emissions, but several aspects are important during the design and operation phases, which are discussed in the following sub-Sections.

2.1 Environmental aspects

LNG-fuelled ships emit almost no SO_x and PM; LNG emits up to 90% less NO_x compared to heavy fuel oil due to the lower peak temperature of combustion. The amount of NO_x emissions depends on the engine design: a pure gas Otto cycle engine can comply with the most stringent NO_x cap, whereas a gas engine based on a diesel cycle, which uses oil pilot ignition, cannot comply. Nevertheless, the latter still emits less NO_x than conventional oil-fuelled engines. LNG emits approximately 25% less CO_2 than conventional engines due to its higher hydrogen-to-carbon ratio compared to diesel (LR, 2015; Wang and Notteboom, 2014).

Methane has a stronger GHG effect than CO_2 and can leak during the production, transportation, and use of natural gas. Such leakage can offset some of the benefits gained from switching to LNG from a lifecycle perspective (Bengtsson et al., 2011; Brynolf et al., 2014; Buhaug et al., 2009; DNV, 2011; LR, 2015). Most LNG-fuelled engines operate on the Otto cycle, which results in a methane slip of 2–3%. A total methane leakage of 5.5% during the entire life cycle would cause the GHG emissions from LNG to be equivalent to the corresponding value for diesel fuel (Chryssakis et al., 2015).

2.2 Economic aspects

Newly built LNG-fuelled ships require 20–25% more capital investment compared to oil-fuelled vessels (Wang and Notteboom, 2014). The cost range depends on ship design, engine type, and fuel tank size, among others. Converting an existing vessel is even costlier. Therefore, LNG appears more feasible for newly built ships (Wang and Notteboom, 2014). LNG tanks are one of the largest capital expenses for LNG-fuelled vessels (DNV GL, 2014). The vacuum-insulated C-type tank is the most commonly used of the tank types available[2] (Rolls-Royce, 2016). For a similar energy content, LNG requires approximately 1.8 times larger tanks compared to marine gas oil (MGO). When adding tank insulation and considering a maximum filling ratio of 95%, this difference is approximately 2.3 fold. Among other components, additional bulkheads, void spaces, access trunks, and vents increase the difference to 3–4 fold (Bagniewski, 2010; Kraack, 2014). In addition, restrictions on the location of LNG tanks exist for safety reasons. For instance, whereas MGO can be stored in wing tanks, LNG tanks are distanced from shipside by B/5[3] or 11.5 m, whichever is less (IMO, 2015b). Therefore, LNG tanks occupy space that could be used for other purposes, such as a fish hold or cargo. LNG tanks are also costly

[2] For an overview of tank types, see Boulougouris and Chrysinas (2015).

[3] "B is the greatest moulded breadth of the ship at or below the deepest draught (summer load line draught) (refer to SOLAS regulation II-1/2.8)" (IMO, 2015b).

because they must be constructed from materials suitable for cryogenic temperatures (e.g., stainless steel) and require insulation (Boulougouris and Chrysinas, 2015).

Lubrication oil in pure gas engines does not become contaminated, and purifiers and oil changes are typically not required. Gas engine rooms also stay considerably cleaner than conventional engine rooms, which leads to lower maintenance (Rolls-Royce, 2016). However, specially trained crew is needed because a gas system is more complex than a conventional system. The complexity also adds to the cost of spare parts (Mohn, 2012). Components are costlier for high-pressure gas supply systems compared to their low-pressure counterparts. In addition, more energy is consumed to produce high pressures, leading to higher costs (WinGD, 2015).

Although there are different views regarding the future price of LNG, the majority of studies are optimistic about its future price advantage (Wang and Notteboom, 2014). Possible fuel or emission taxes, such as the NO_x tax in Norway, can increase economic interest in LNG. Solving current bunkering problems can also foster its adoption (DNV, 2011; Wang and Notteboom, 2014).

2.3 Safety aspects

The development of the LNG supply chain in Europe (EIA, 2013) has led to several studies on risks related to LNG handling. For instance, Cozzani et al. (2011) identified and analysed accident scenarios related to LNG handling. Tugnoli et al. (2010) and Paltrinieri et al. (2015) warned about the presence of potential hazards and risks posed by new LNG technologies, which may be well known to academics but are ignored by professionals. In addition to the potential for fires and explosions (e.g., pool fires, a vapour cloud explosion, and flash fires), a series of hazards resulting from the specific properties of LNG have been reported, such as:

- Rapid phase transition: a phenomenon occurring when the temperature difference between a hot liquid and cold liquid is sufficiently large to drive the cold liquid rapidly to its superheat limit, resulting in spontaneous and explosive boiling of the cold liquid (Reid, 1983).
- Cryogenic burns and cryogenic damage: hazards due to the cryogenic temperatures of LNG (Woodward and Pitblado, 2010).
- Asphyxiation: immediately after the release of LNG, a dense vapour cloud forms around the area of the spill close to the ground, leading to an asphyxiation hazard (Woodward and Pitblado, 2010).

The world LNG carrier fleet has implemented LNG risk management (Chryssakis et al., 2015). However, the majority of the world fleet, including fishing vessels, has no experience with handling LNG. This segment regards alternative fuels for economic and environmental benefits, but managing risk related to new potential accident scenarios might be challenging (Chryssakis et al., 2015). Fishing vessels are dangerous work environments, as demonstrated by Lindøe (2007), who compared the fatal accident rates of the fishing and offshore petroleum industries from 1990 to 2005. The fatality rate of fishermen was 12-fold higher than the corresponding value for offshore workers on average. If helicopter accidents are excluded, this difference increases to 25 fold. Several factors may explain the higher fatality rate in fishing compared to offshore industry. McGuinness et al. (2013) state that the main fatality modes in Norwegian fisheries are vessel accidents (e.g., collisions, groundings, foundering, capsizing) and man overboard. However, we aim to address the overall safety strategy in the sector. In fact, one explanation for this gap in safety levels may be the different competence of the workforce and safety management systems (Lindøe, 2007). Despite a recent decrease in its fatal accident risk, fishing is still the occupation in Norway most exposed to risk (McGuinness et al., 2013). Switching to LNG must not make fishing even more dangerous.

Safety must be built into the system, and safety during operation depends both on the design and effective operational control. Ship owners and fishing vessel crew may not be familiar with the safe handling of LNG. Everyone involved in the operation must understand their responsibility and the safety rationale behind the system design. If the crew understand the purpose of the safety programmes, they are more likely to commit to them. Understanding the safety rationale will also foster the avoidance of unintended system changes that lead to hazards (Leveson, 2011).

3 A SE approach to the design and safe operation of LNG-fuelled ships

Verification of the technical and operational aspects of LNG-fuelled systems and their potential implementation costs and benefits is a challenging decision problem with an interdisciplinary nature. A SE approach is used to address this problem. Classical engineering practices typically deconstruct a system to its formative elements to aid understanding. However, systems thinking prioritizes the study of a system as a whole. It recognizes system level behaviours, interactions, and structural characteristics that are missed by focusing on individual elements instead of "the big picture" (Driscoll, 2010). For instance, safety is a system property, not a component property. As such, safety must be controlled at the system level, not at the component level. Systems thinking may assist in understanding system dynamics and preventing system accidents (Leveson, 2004, 2011).

A SE approach starts with the desired goal of the system and stakeholder requirements. Then, it identifies system functions, processes, structures, and elements that can fulfil the desired goal (Driscoll, 2010). The approach suggested in this article and shown in Figure 1 is based on Dahl (2001) and Oliver et al. (1997). The process has been adapted to fishing vessels and LNG in particular. It comprises six sequential steps and one iteration loop, with input from INCOSE (2015), Kossiakoff et al. (2011b), Long and Scott (2011), and Sproles (2001, 2002):

1. The process begins with understanding the problem and highlighting its importance.
2. Next, relevant information that may help solve the problem is compiled. Available information may be in different forms (e.g., text, models, and stakeholder knowledge).
3. Early in the process, measures of effectiveness (MOEs) are defined. MOEs are a subset of the requirements imposed on the system. They are the yardsticks used to assess alternative solutions, and success of a system depends on their fulfilment. These measures are useful for assessing complete systems and may also be used as monitoring tools in the early and late phases. For example, they can monitor progress during the system development process. They can also monitor the system through its lifetime to verify whether it still fulfils the needs for which it was designed.
4. In the next step, the user requirements, behaviour, and structure of the system are clearly defined. Model-based systems engineering (MBSE) is used to capture, investigate, share, and manage the available information. Using models, MBSE supports system requirements, design, analysis, verification, and validation during various life cycle phases, such as the conceptual design phase. The MBSE approach consists of three parts. Each part views the system from a different perspective:
   - First, the requirements imposed on the system are organized. The *requirement analysis* model is a hierarchy that starts from the source documents and ends in system components. It aims at clear identification and traceability between documents, requirements, functions, processes, and the system components.
   - Next, the functions that the system must perform to fulfil the requirements are identified, i.e., *functional behaviour*. This model orders functions into processes by looking at their sequence and how inputs (e.g., the occurrence of unwanted events) activate functions.
   - Finally, the functions are translated into the hardware and software components that are necessary to carry out the functions. The *architecture* model breaks the system down into its components, both physically and logically, and delineates their relationships. In the concept development stage, such a model can help to embody the system concept and provide a tangible and physical form for the system to be built. It can make the system more understandable for its stakeholders.
5. Once the alternative architectures or designs have been created, a trade-off analysis uses stakeholder-defined criteria (i.e., the MOEs) to evaluate and compare system designs. The aim is to identify the system design that most closely matches the stakeholders' objectives.
6. When a feasible and near-optimal architecture has been identified, an implementation plan is produced.

When necessary, iteration is performed back to Step 2. The approach and its steps are demonstrated for a fishing vessel in the following section.

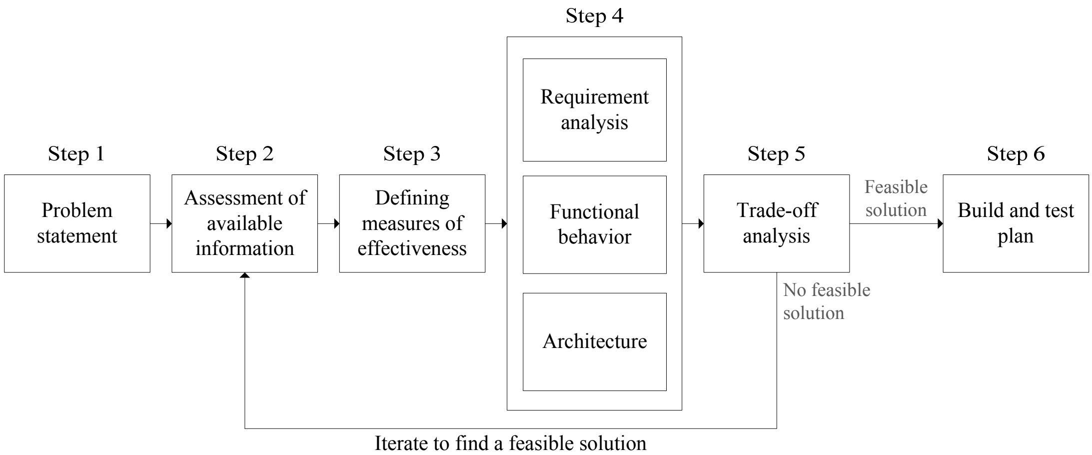

Figure 1: Modified SE process (adapted from Dahl (2001); Oliver et al. (1997))

4 Application to fishing vessels with LNG propulsion

4.1 Step 1 - Defining the problem

The use of LNG on energy-demanding vessels with high catch and regular coastal routes, such as coastal demersal trawlers in Norway, appears more environmentally and economically attractive for several reasons (DNV, 2012; Jafarzadeh et al., 2016; Jafarzadeh et al., 2012; Winther et al., 2009):

- Natural gas and bunkering stations are available in Norway.
- It is easier to predict fuel consumption for vessels with specific routes. It also makes the vessels reliable and provides regular customers for bunkering stations.
- Coastal vessels require smaller LNG tanks and can allocate more space to fish holds.
- Demersal trawlers consuming a considerable amount of energy and produce considerable pollution.
- The Norwegian NO_x tax and fund system promotes switching to LNG propulsion.
- Extreme cold from the LNG regasification process can be recovered for cargo cooling, and thus, fuel consumption and associated emissions can be reduced in this manner.

Technology transfer of LNG-fuelled propulsion from other types of vessels (e.g., offshore oil and gas supply vessels) to fishing vessels may be relevant but requires re-innovation (i.e., “adaptations to use”) to make the technology operable in the new context of fishing. In addition, a mere technology transfer is not adequate; competence and knowledge regarding the technology must also be fully transferred, which may be challenging (Olsen and Lindøe, 2009).

4.2 Step 2 - Relevant information for building and operating the system

4.2.1 System boundaries

The system in this study consists of the technical, operational, and economic aspects of a LNG-fuelled fishing vessel. Technical aspects range from the components (e.g., pressure relief valves) to design considerations (e.g., collision distance between the LNG unit and shipside). Operational aspects range from the daily tasks of the crew, including maintenance, to emergency preparedness and handling. Economic aspects cover capital and operational costs and benefits. From a SE perspective, operators and stakeholders are parts of the system environment imposing interface requirements that must be satisfied by the system.

A context diagram is a communication tool that depicts the system, its environment, and the interactions between them (Kossiakoff et al., 2011b). This diagram does not depict the internal details of the system. Instead, it highlights the external factors that may be relevant to the system’s operation, and should thus be considered while developing the system. It is a starting point for defining the system’s mission and operating environment.

The interactions between the system and environment show system inputs and outputs in the form of receiving and sending data, signals, material, and energy or an action that affects the system or environment. Relevant information about these interactions should be compiled (Kossiakoff et al., 2011a, b; Oliver et al., 1997).

The system environment includes different stakeholders, such as the ship owner, crew, bunkering station, material suppliers, equipment manufacturers, and naval architect. Figure 2 is a reduced context diagram. For example, the ship owner may have specific requirements regarding the space and arrangement needed for the fishing gear and fish holds. However, the system may impose requirements on the location and size of the LNG tanks, among other things. Considering all of these requirements, the gas system should be optimized to avoid interference with normal operation of the vessel. The economic implications of these requirements should also be evaluated. As another example, the crew has specific duties, such as navigating the vessel or handling the fishing gear. However, the system requires some routine and emergency operations for the safe handling of the LNG. LNG-related training should consider normal fishing operations. The cost of various training schemes should also be evaluated.

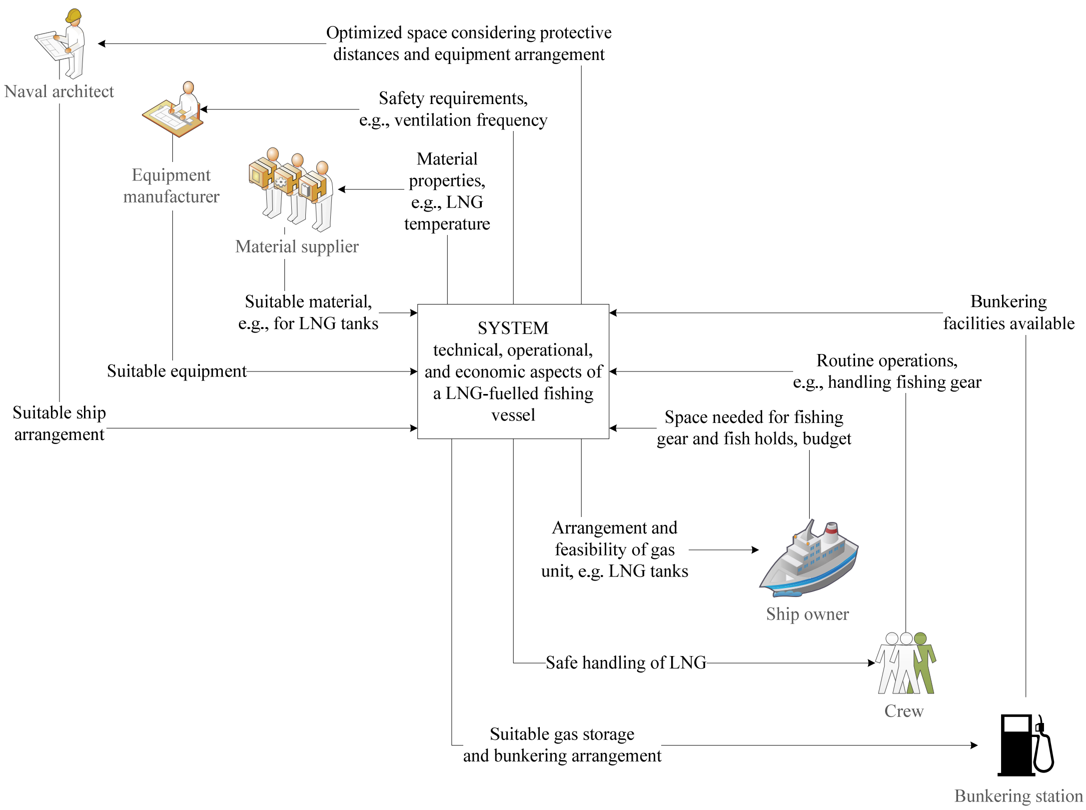

Figure 2: Reduced context model

4.2.2 Regulatory framework

Because the technical and operational aspects of a LNG-fuelled fishing vessel are part of the system, the regulations and guidelines that address the design and operation of LNG-fuelled ships are relevant information. These regulations also have cost implications because they impose additional requirements, such as the installation of gas detectors and safety training.

In June 2015, the International Maritime Organisation (IMO) adopted the mandatory International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). The IGF Code will come into force in

2017. Until then, the Interim Guidelines on Safety for Natural Gas-Fuelled Engine Installations in Ships have been adopted. Concurrently, Regulation V/3 was added to the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). Similarly, Section A-V/3 was added to the STCW Code and includes new compulsory minimum requirements for the training and qualification of personnel on ships subject to the IGF Code[4]. These amendments will also come into force in 2017 (Danish Maritime Authority, 2015; IMO, 2015a, b).

The IGF Code mainly addresses the technical requirements for LNG-fuelled ship design. However, it also addresses operations, drills and emergency exercises. For example, it requires that the IGF Code and maintenance procedures be provided on board the vessels. Section A-V/3 of the STCW Code addresses the training and qualifications of the crew in greater detail. It identifies two levels of training, basic and advanced based on personnel's responsibilities (IMO, 2015c).

Both levels of training require some knowledge of the IGF Code. Among other things, basic training requires basic knowledge on ships subject to the IGF Code, fuel systems, and fuel storage systems. It also requires an understanding of safety requirements and safety management on these ships. The advanced training, among other things, requires an understanding of the hazards and control measures associated with fuel system operations. In addition, it demands proficiency in the use of the IGF Code (IMO, 2015d). Therefore, the technical and operational regulations are closely linked, and the crew should understand how safety is built in the system to operate it properly.

In addition to these binding regulations, other organizations provide relevant information on the safe operation of LNG carriers or LNG-fuelled ships. For instance, the Society of International Gas Tanker and Terminal Operators (SIGTTO) specifies and promotes best practices to maintain confidence in the safety of the liquefied gas industry. Among other things, SIGTTO publishes guidelines for safe cargo handling on LNG carriers (SIGTTO, 2014). In 2013, the Society for Gas as a Marine Fuel (SGMF) was established. SGMF is a non-governmental organization that promotes safety and industry best practices for the use of gas as a marine fuel. Among other things, it publishes safety guidelines for LNG bunkering (SGMF, 2016).

4.2.3 Environmental taxes and fund

In Norway, a fishing vessel with a total engine power of more than 750 kW operating within 250 nm (nautical miles) offshore is liable to be taxed on NO_x emissions. Although vessels in direct traffic between Norwegian and foreign ports are exempted from the tax, a vessel will not be considered in direct traffic if engaged in fishing during the course of the voyage (Directorate of Customs and Excise, 2015; Norwegian Maritime Directorate, 2014).

The tax rate in 2016 is 21.17 NOK (2.45 USD)[5] per kg NO_x (Skatteetaten, 2016). If the vessel adopts a NO_x reduction measure, such as LNG fuel, it can pay a lower rate to the NO_x fund instead of the NO_x tax. As of 2016, the reduced rate is 4 NOK (0.46 USD) per kg NO_x for fishing vessels (NHO, 2016b).

In addition, the NO_x fund provides financial support for NO_x reduction measures. The support rate varies for different measures. In 2016, the support for LNG-powered ships is 375 NOK (43.35 USD) per kg NO_x reduced. This support is limited to 80% of the additional cost for the measure (NHO, 2016a).

Norwegian fishing vessels either are exempt from the basic tax on mineral oil or have the tax refunded (i.e., "grunnavgift" in Norwegian). Fishing in distant waters is also exempt from CO_2 and SO_x taxes in Norway.

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[4] The STCW Convention consists of three sections: (i) the articles, which outline the legal responsibilities of the involved parties, (ii) the annex, which provides technical details on how the responsibilities mentioned in the articles should be met, and (iii) the STCW Code, which specifies the technical details contained in the annex (ITF, 2013).

[5] NOK and USD respectively stand for Norwegian Krone and US Dollar. An average 2016 exchange rate (1 USD ≈ 8.65 NOK) is considered (Norges Bank, 2016).

However, fishing in Norwegian coastal waters (i.e., within 250 nm ashore) is subject to 0.28[6] and 0.133[7] NOK (0.03 and 0.02 USD) per litre of MGO for CO_2 and SO_x emissions, respectively. LNG-powered fishing vessels are exempt from these taxes (GFF, 2016; Norwegian Directorate of Taxes, 2016).

4.3 Step 3- Measures of effectiveness

The goal of the IGF code is "to provide for safe and environmentally friendly design, construction, and operation of ships and, in particular, their installations of systems for propulsion machinery, auxiliary power generation machinery and/or other purpose machinery using gas or low-flashpoint fuel as fuel" (IMO, 2015b). The main purpose of the STCW Convention is "to promote safety of life and property at sea and the protection of the marine environment by establishing in common agreement international standards of training, certification and watchkeeping for seafarers" (IMO, 2016). If a candidate solution cannot comply with these, it should be rejected. For this reason, the following MOE has been defined:

- Compliance with safety requirements

Implementing safety measures can reduce the risk of severe accidents and improve safety. However, these measures incur cost and may be reduced by the stakeholders to minimum protections. On the other side, LNG has the potential to reduce the operational cost (see Section 2.2). As a result, the following MOE is also considered:

- Life cycle cost (LCC)

The new system should meet the functional requirements at a reasonable cost over its anticipated lifetime. The system life cycle includes various stages, ranging from conceptualization and design to operation and system retirement (Pohl and Nachtmann, 2010). In many cases, it may not be necessary to perform a complete LCC analysis. Instead, an estimation of the major cost elements is sufficient (Norsok Standard, 1996).

As a minimum, these MOEs should be considered while evaluating an LNG solution. Stakeholders may also consider other MOEs.

4.4 Step 4 - Model-based SE

Various requirements are imposed on the system. Some requirements, such as those imposed by the IGF Code, are related to technical requirements. Others, such as those imposed by Section A-V/3 of the STCW Code are operational (see Section 4.2.2). In addition, there may be financial requirements. For instance, ship owners may require a specific payback time for a LNG investment. Although models can be established based on all of these requirements, the remainder of this sub-Section focuses on models based only on technical and operational requirements.

4.4.1 Requirement analysis

The IGF Code, Section A-V/3 of the STCW Code, and the SIGTTO guidelines are the main sources for the requirement analysis model, which is illustrated in Figure 3. Although the SIGTTO guidelines mainly address the safe operation of LNG carriers, they may be relevant to the operation of LNG-fuelled ships, such as SIGTTO (2000, 2002, 2011). Other sources (e.g., port regulations and national laws) may impose additional requirements on the system in specific cases.

The IGF Code addresses "provisions for the arrangement, installation, control, and monitoring of machinery, equipment, and systems using low-flashpoint fuel". Section A-V/3 of the STCW Code covers the "minimum

[6] Upon bunkering, coastal fishing vessels pay 0.92 NOK/L (0.11 USD/L) for the CO_2 tax. Later, they can be refunded for 0.64 NOK/L (0.07 USD/L). Therefore, the net value paid is 0.28 NOK/L (0.03 USD/L) (GFF, 2016).

[7] The SO_x tax depends on the sulphur content of the fuel. This rate applies to mineral oils with 0.05–0.25% sulphur.

requirements for the training and qualifications of the masters, officers, ratings, and other personnel on ships subject to the IGF Code". These two form the upper hierarchy guidelines in the requirement model, as illustrated in Figure 3.

These guidelines are divided into four primary safety-related requirements, as shown in Table 1. These requirements are not comprehensive; other requirements may be added to the list based on the IGF and STCW Codes. Each of the primary requirements includes several secondary requirements, which trigger different barrier functions in the system. Barrier functions specify the tasks or roles of barriers (PSA, 2013).

The system requires various barrier elements, i.e., measures or solutions that are instrumental in fulfilling a barrier function (PSA, 2013). The requirement analysis model links the requirements to the corresponding barrier functions and barrier elements.

For example, regarding Figure 3, Primary requirement 1 includes several secondary requirements, such as "*Minimize the probability of damage to fuel tanks and piping*". Different barrier functions are needed to satisfy this secondary requirement, such as "*Protecting tanks and pipes against collision, grounding, and mechanical damage*". Different technical and operational barrier elements carry out this barrier function, such as "*Specified minimum distances from the ship shell plating […]*".

Table 1: Primary requirements based on the IGF Code and Section A-V/3 of the STCW Code

Primary requirement	Definition	Number tag used in bowtie diagrams (Figures 5 and 6)
1	Prevent leakage and overpressure in the gas fuel storage, bunkering arrangement, and gas piping system.	1
2	Contain leakage and/or reduce overpressure to the highest extent.	2
3	Prevent fire and explosion in the fuel containment and machinery space.	3
4	Mitigate accident consequences.	4

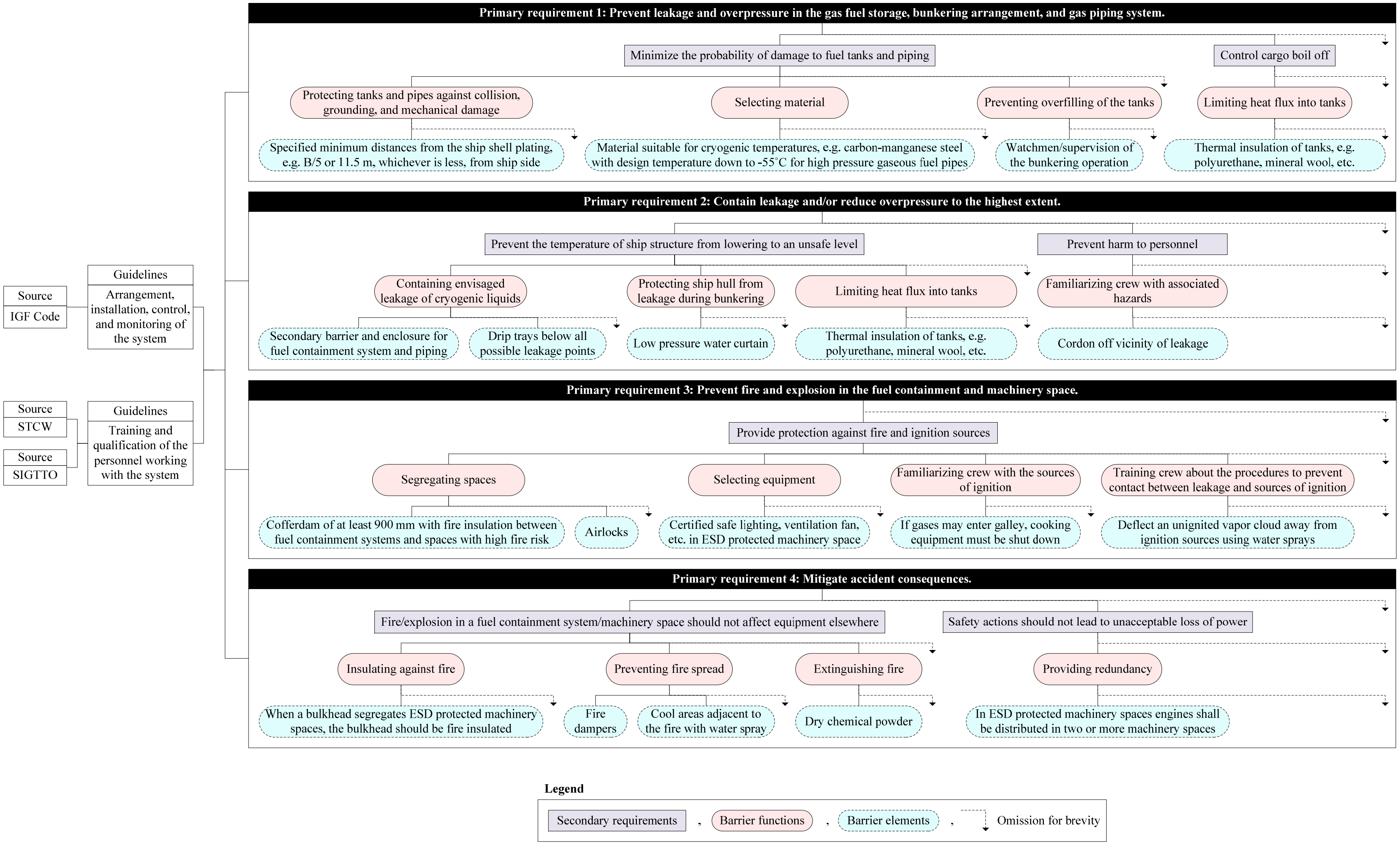

Figure 3: Reduced requirement analysis based on IMO (2015b, 2015d); SIGTTO (2000, 2002, 2011). "Breadth (B) means the greatest moulded breadth of the ship at or below the deepest draught (summer load line draught)" (IMO, 2015b).

4.4.2 Functional behaviour

Figure 4 illustrates some representative elements of the functional behaviour model. Primary requirement 1 and its barrier functions are in place to prevent leakage and overpressure. If these functions are not successful in meeting this requirement, Primary requirement 2 and its barrier functions address the occurrence of leakage and/or overpressure. If leakage cannot be controlled, Primary requirement 3 and its barrier functions prevent fire and explosion. If these functions also fail, Primary requirement 4 and its functions minimize accident consequences.

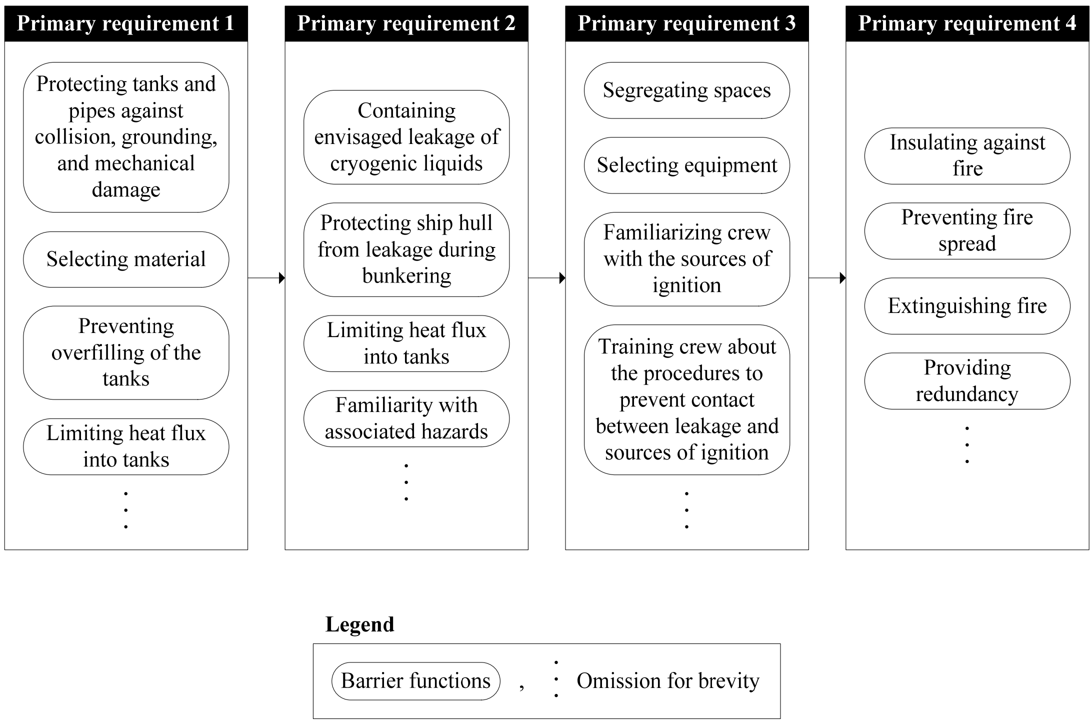

Figure 4: Reduced functional behaviour based on IMO (2015b, 2015d); SIGTTO (2000, 2002, 2011). Table 1 defines the primary requirements.

A bowtie diagram complements the functional behaviour model by showing that the fulfilment of the single safety requirements may prevent an accident on several levels, which are not sequential, even though Figure 4 might indicate the opposite. A bowtie diagram is a graphical illustration of an accident scenario, starting from accident causes and ending with the consequences. While centred on a critical (or top) event, the composition of a bowtie diagram may be described as a Fault Tree on the left-hand side and an Event Tree on the right-hand side (Khakzad et al., 2012). The former identifies the possible events that could cause the critical event, whereas the latter shows the possible consequences of the critical event. Safety barriers[8] may be employed on both sides to stop the development of the accident scenario. As shown in Figure 5, barrier functions and, in turn, barrier elements are enforced by the primary requirements previously defined in Table 1.

[8] Safety barriers are technical, operational, and organizational means to reduce the possibility for occurrence of an error/hazard/accident or limit its consequences (PSA, 2013). Systems engineers can identify the safety barriers necessary to ensure safety and effectively communicate them to ship owners, designers, and crew who, in turn, must enforce them.

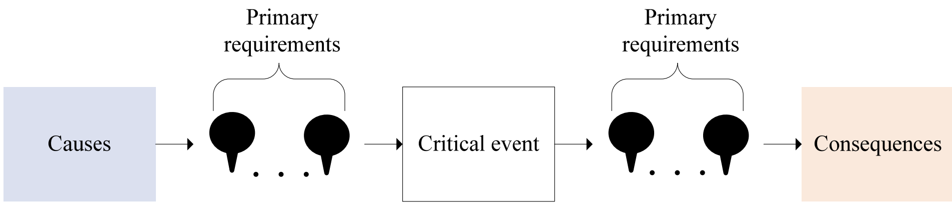

Figure 5: Bowtie diagram

Figure 6 shows representative results from a bowtie analysis performed on a LNG carrier, considering leakage as the critical event. This bowtie diagram was obtained by applying a common bowtie analysis technique (i.e., Methodology for the Identification of Major Accident Hazards (Delvosalle et al., 2006)). Such analysis is qualitative. In order to perform quantitative modelling (as addressed in CPR (2005)), detailed data on the arrangement of the fishing vessel are needed. The number tags on the diagram indicate where some representative barrier functions are located, i.e., where the action of some primary requirements shown in Table 1 may stop the unwanted events. However, the number tags show only certain barrier functions. More specifically, only the barrier functions included in Figure 4 are illustrated in Figure 6. After deriving a complete functional behaviour model, barrier functions and their corresponding number tags can be assigned to other branches of the bowtie diagram.

The bowtie analysis in Figure 6 clarifies the scope of the primary requirements and their barrier functions. In addition, the bowtie analysis provides an overview of potential accident scenarios to be prevented and raises awareness about the potential consequences if the safety MOE is not fulfilled. For instance, Primary requirement 1, among other things, has functions that prevent the critical overpressure of a LNG tank. If these functions fail, the tank pressure can potentially raise until leakage (i.e., a critical event) occurs. At this point, some Primary requirement 2 functions can contain the leakage and avoid the formation and evaporation of pools. Failure of this function exposes the leaked LNG/natural gas to ignition – instant ignition may also occur, but the risk of exposure to possible ignition sources increases as the LNG spreads further. The goal of Primary requirement 3 functions is the prevention of ignition, and a serious catastrophic event, such as a vapour cloud explosion may occur if they fail (Vílchez et al., 2011). The goal of Primary requirement 4 functions is to minimize the consequences of such an accident. Failure of these functions may lead to a domino effect and extensive damage. Figure 6 does not consider whether sufficient barriers are in place for the critical event, but it can be used as an input for such an analysis.

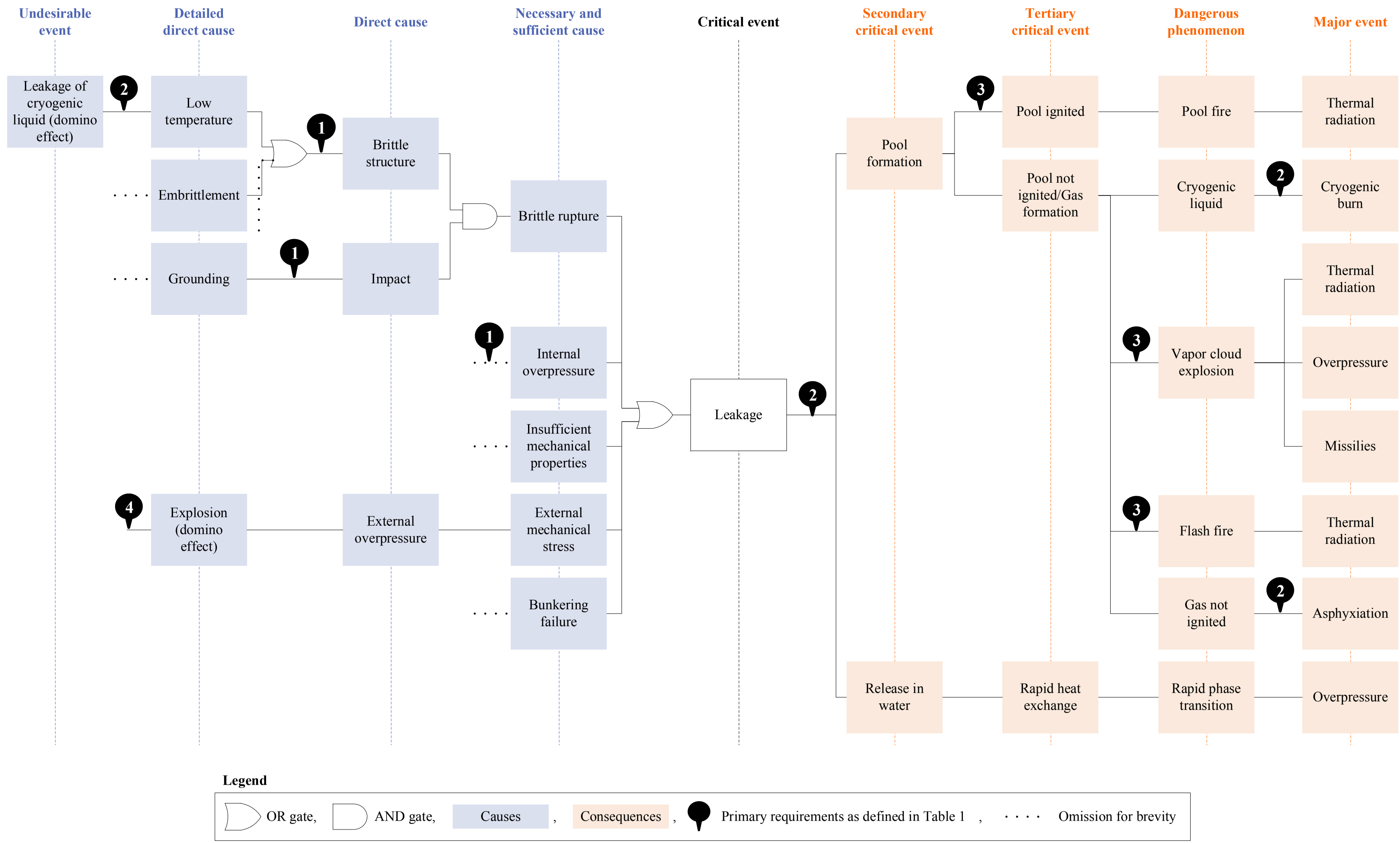

Figure 6: Bowtie diagram concerning the leakage of a LNG tank on a carrier ship adapted from Paltrinieri et al. (2015)

4.4.3 Architecture

Figure 7 shows the reduced architecture model. In this study, the main component is the overall system, which is composed of technical and operational safeguards (i.e., barrier elements) on a LNG-fuelled fishing vessel. This diagram provides an overview of the barrier elements that are included in the system to ensure safety.

In the case under study, different barrier elements can fulfil the safety requirements of the system. For instance, one of the requirements under Primary requirement 1 is to "Control cargo boil-off". This requirement involves controlling boil-off and overpressure, which could damage the tank. Various barrier functions work together to fulfil this requirement, such as the "Limiting heat flux into tanks" function. Such heat flux may occur during normal operations or unwanted events, such as a fire on the ship. One of the barrier elements that can limit the heat flux is proper "Thermal insulation of tanks […]". Designers have different options for thermal insulation, such as polyurethane and mineral wool (SIGTTO, 2011). The same holds for the other requirements, functions, and barrier elements. For instance, different training plans may be considered. Different final safety systems may be established based on the choices made by the designer, and thus, various alternatives may be considered for a LNG-fuelled ship.

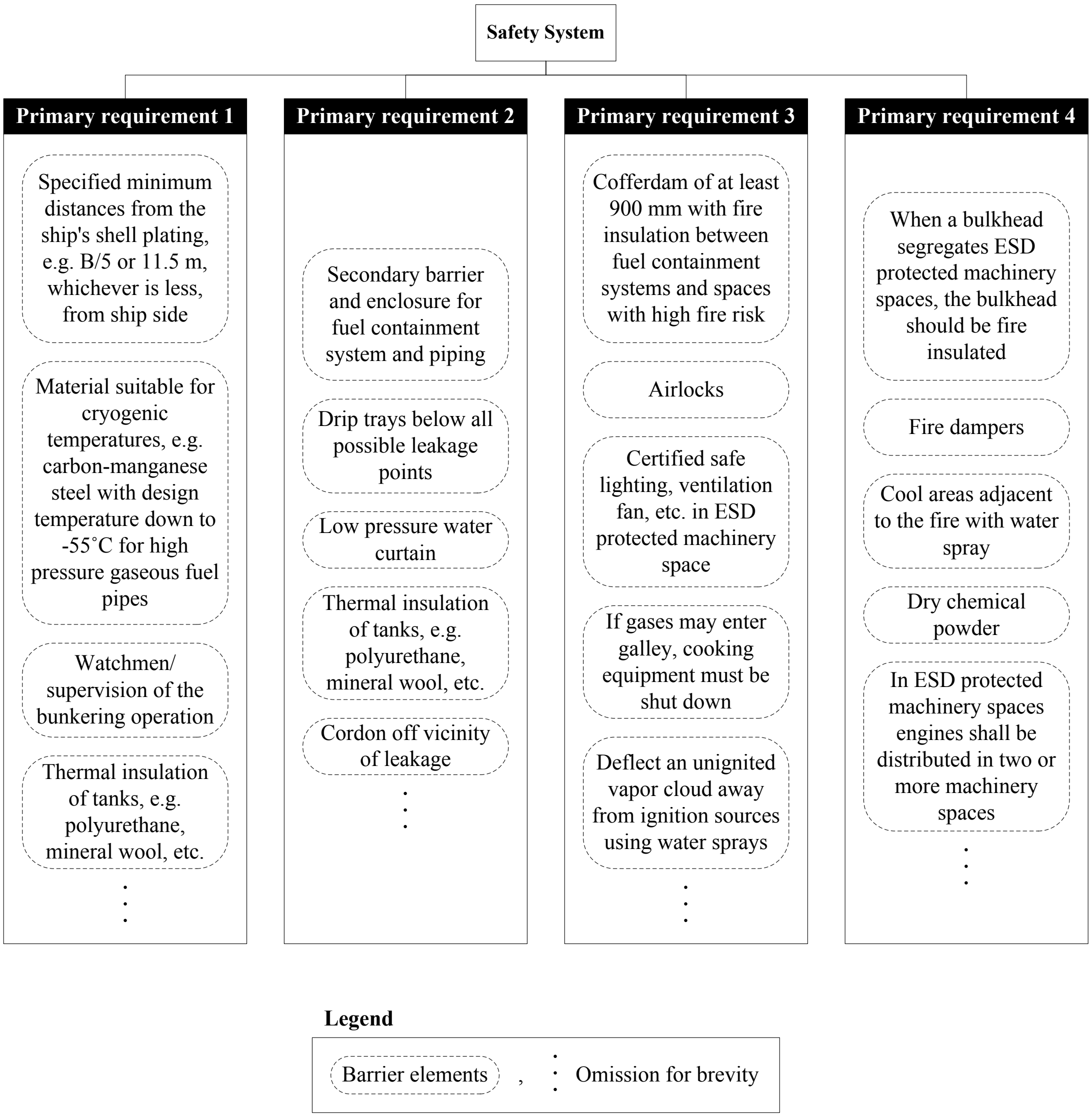

Figure 7: Reduced architecture based on IMO (2015b, 2015d); SIGTTO (2000, 2002, 2011). Table 1 defines the primary requirements.

4.5 Step 5 - Trade-off analysis

Two MOEs were defined in Section 4.3: (i) compliance with safety requirements and (ii) the LCC. The trade-off analysis uses these MOEs as criteria to evaluate and compare alternative designs for an LNG-fuelled vessel. If no feasible solution was found, iteration back to Step 2 is performed (see Section 3) to gather additional information that may lead to new alternatives that were not initially considered. The MOEs may also be revisited to improve decision-making.

Different alternatives are possible. For example, one alternative is to elongate the vessel to accommodate the gas unit. Another alternative is to reduce the size of the fish hold to create space for the gas unit. These alternatives and other possible options should be evaluated and compared with respect to the MOEs. For illustration, the remainder of this sub-Section evaluates the LCC of the former alternative by means of the net present value (NPV) technique. We assume compliance with safety requirements because their evaluation is out of the scope of this study.

To evaluate the feasibility of the investment in LNG, it is compared with the baseline MGO investment. We are mainly interested in the additional/fewer capital and operational costs associated with powering the vessel with 100% LNG rather than MGO. Other lifecycle stages are not considered. The following costs have been considered:

- Difference between the cost of a conventional diesel engine and a gas engine,
- Cost of the LNG tank,
- Cost of elongating and modifying the ship hull to fit in the LNG tank while keeping the fish hold capacity intact,
- Support from the NO_x fund,
- Difference between the MGO and LNG fuel costs, and
- Difference between the environmental taxes.

4.5.1 Vessel characteristics

A coastal shrimp trawler operating in Norway was selected as the vessel for consideration. It was assumed that a new vessel with the characteristics shown in Table 2 was built in 2016. A 25-year lifetime of the vessel was assumed.

This vessel was chosen for the following primary reasons:

- Because the vessel operates within 250 nm of shore and its engine power is greater than 750 kW, it is liable to NO_x, SO_x, and CO_2 taxes (see Section 4.2.3). Therefore, LNG fuel can reduce these costs.
- Considering a MGO density of 0.86 kg/L (NP, 2013) and the fuel consumption and catch data in Table 2, the fuel use coefficient[9] of the vessel was approximately 2.13 kg fuel/kg fish in 2012. This amount is considerably higher than the corresponding value for the Norwegian fishing fleet without a shrimp catch (i.e., below 0.3 kg fuel/kg fish) (Jafarzadeh et al., 2016). Therefore, this vessel consumes relatively large amounts of fuel to catch fish. The vessel may save on fuel costs by using LNG.

Table 2: Characteristics of a coastal demersal trawler operating in Norway. The values are derived from Directorate of Fisheries (2014), except for depth, which is assumed.

Characteristic	**Value**
Length overall (m)	33.18
Breadth (m)	7.20
Depth (m)	5.96
Gross tonnage	279
Main engine power (kW)	760
Days at sea in 2012	280
MGO consumption in 2012 (L)	407,030
Catch in 2012 (kg)	164,454

[9] In fisheries, a fuel use coefficient (kg fuel/kg fish) can indicate the energy efficiency. High fuel use coefficients indicate low energy efficiency and vice versa (Jafarzadeh et al., 2016).

4.5.2 Engine

For operation on MGO, an engine with 760 kW that complies with Tier II of MARPOL Annex VI regulations on NO_x emissions (see IMO (2014a)) was chosen. This engine cost approximately 1.85 MNOK (0.21 MUSD)[10] in 2016 (Engine suppliers, 2016).

An 845 kW engine was chosen based on the gas engines available in the market. The engine is approved for marine applications. The gas engine cost approximately 3.75 MNOK (0.43 MUSD) in 2016 (Engine suppliers, 2016). This price covered the engine, its control and monitoring system, and the gas valve unit. Therefore, the gas engine was approximately 100% more expensive than the conventional engine. The price difference is **1.90 MNOK (0.22 MUSD).**

4.5.3 LNG tank

The following steps were performed to estimate the LNG tank cost:

- First, the fuel consumption for a round trip was estimated.
- Second, the LNG tank volume was estimated.
- Finally, the cost was estimated based on the tank volume.

Fuel consumption for a round trip

Fiskeriportalen (2016) provided an overview of the dates that Norwegian fishers land their catch. The length of each voyage in 2015 has been estimated assuming that the vessel has been operating between two consecutive landing dates. Six days is the average round-trip length.

Using the days at sea and the fuel consumption data in Table 2, the average MGO consumption for a round trip was calculated as **8.72 m³** of MGO. The energy consumed during a round-trip can be estimated using Equation (1) together with MGO and the diesel engine characteristics shown in Table 3:

$$E_r\ (kWh) = \frac{FC_r(m^3) \times \rho(\frac{g}{m^3})}{sfc(\frac{g}{kWh})} \tag{1}$$

where *E*, *FC*, ρ, and *sfc* are the energy consumption, fuel consumption, density, and specific fuel consumption of the engine, respectively. The subscript *r* indicates a round-trip. The energy necessary for a round-trip is **35.17 MWh**.

If the vessel consumes 100% LNG instead of MGO, the LNG required for a round trip can be estimated using Equation (1) and the LNG and gas engine characteristics (Table 3). The LNG consumption for a round trip is approximately **15.55 m³.**

The approach taken for estimating fuel consumption was simplified due to lack of data on the operational profile of the vessel. In cases where detailed data is available, modelling and simulation of power system of vessels under different operational profiles may reduce inaccuracies (Baldi et al., 2015; Figari and Soares, 2009; Jafarzadeh et al., 2014; Martelli et al., 2013; Martelli et al., 2014).

[10] MNOK and MUSD respectively stand for million NOK and million USD.

Table 3: Characteristics of LNG and MGO fuels and their corresponding engines

Parameters	Amount	Source
Round trip (days)	6	This study
Gas engine power (kW)	845	(Engine suppliers, 2016)
Average sfc of gas engine [a,b] (g/kWh)	198.99	(Engine suppliers, 2016)
LNG density (g/m^3)	45×10^4	(IGU, 2012)
Energy content of LNG (MWh/tonne)	13.80	(Skjervheim, 2012)
Marine diesel engine (kW)	760	(Directorate of Fisheries, 2014)
Average sfc of conventional engine [a] (g/kWh)	213.30	(Engine suppliers, 2016)
MGO density (g/m^3)	86×10^4	(NP, 2013)
Energy content of MGO (MWh/tonne)	11.90	(Skjervheim, 2012)

[a] The gas engine is more energy efficient than the diesel engine at higher powers. However, the opposite is true for lower powers. The average specific fuel consumption (sfc) in the entire power range has been considered due to a lack of data on the operational profile of the vessel.

[b] The engine supplier provided the fuel rate in the gaseous state (Nm^3/h). "N" refers to the normal state (0˚C, 1 atm). We assumed 1 tonne LNG equivalent for 1,300 Nm^3 gas (IGU, 2012) while converting fuel rates to sfc (g LNG/kWh).

LNG tank volume

Depending on the relief valve setting, the usable capacity of LNG is approximately 80–85% of the tank volume (Boulougouris and Chrysinas, 2015). Considering a round-trip LNG consumption of 15.55 m^3 and a usable capacity of 85% (Jetlund, 2016), the gross volume of LNG tank is approximately **18.30 m^3**.

LNG tank dimensions

The next step was to estimate diameter and length of the tank. The IGF Code states that "the fuel tanks shall be located at a minimum distance of B/5 or 11.5 m, whichever is less, measured inboard from the ship side at right angles to the centerline at the level of the summer load line draught" (IMO, 2015b). In addition, "the lowermost boundary of the fuel tank(s) shall be located above the minimum distance of B/15 or 2.0 m, whichever is less, measured from the moulded line of the bottom shell plating at the centerline" (IMO, 2015b).

A simplified case was considered and is shown in Figure 8. It is assumed that the breadth in Table 2 represented the moulded breadth. Because trawlers use the vessel's deck for fishing operations, the tank was positioned below deck. Considering the vessel's breadth and depth (Table 2), the maximum breadth of the tank with insulation could be **4.32 m** (i.e., vessel breadth minus B/5 from each side of the ship), whereas the maximum depth of the tank with insulation could be **5.48 m** (i.e., vessel depth minus B/15). Because the tank is cylindrical, a diameter of **4.32 m** with insulation was chosen.

The insulation of tanks typically has a minimum thickness of 25 cm (Jetlund, 2016). We assumed a 30 cm thickness for the insulation and the inner and outer steel walls (Wold, 2016). Therefore, the tank diameter without the insulation and walls is **3.72 m**. Considering the LNG tank size (i.e., 18.30 m^3) and diameter (i.e., 3.72 m), the tank is approximately **1.68 m** long.

The pressure build-up unit, LNG vaporizer, tank connections, and tank valves are included in a gastight space welded to the outer tank, termed a cold box (ECE, 2014). The size of the cold box varies with the valve and vaporization installations. It is typically installed at the extension of the tank with an additional length of, for example, 1.5–3 m (Jetlund, 2016). In this study, a cylindrical extension of 1.5 m was assumed. Therefore, the length of the tank, including the cold box, was increased to **3.18 m**. Table 4 summarizes the LNG tank dimensions.

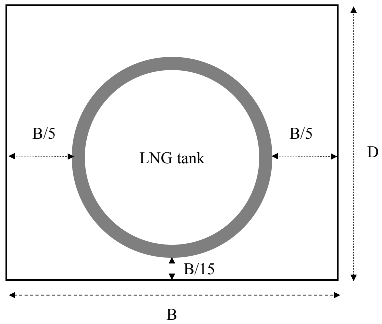

Figure 8: Section view of the LNG tank within the vessel. B and D denote the breadth and depth of the vessel, respectively. The shaded area represents the insulation and walls.

Table 4: LNG tank dimensions

Item	Amount
Usable capacity of the LNG tank (%) (Boulougouris and Chrysinas, 2015; Jetlund, 2016)	85
LNG tank diameter without insulation and tank walls (m)	3.72
Insulation and inner and outer wall thicknesses (cm) (Jetlund, 2016; Wold, 2016)	30
LNG tank length (m)	1.68
LNG tank length including the cold box (m)	3.18
Gross tank volume [a] (m^3)	18.30
Insulated LNG tank volume [b] (m^3)	24.67

[a] 85% usable capacity of LNG was considered. This value excludes the insulation, walls, and cold box.

[b] Excluding the cold box

LNG tank cost

In 2016, the cost of an LNG tank ranged from approximately 40 kNOK/m^3 (4.62 kUSD/m^3)[11] gross volume for larger tanks (e.g., 1,000 m^3) to 150 kNOK/m^3 (17.34 kUSD/m^3) gross volume for smaller tanks (e.g., 20 m^3). These costs included expenses related to the tank manufacturing (e.g., the cold box, bunker stations, bunker pipes, gas pipes, and electrical interface). However, they do not include expenses for the tank control system, the ventilation system, and other shipyard-related expenses. The cost of the LNG tank for this study was approximately **2.74 MNOK (0.32 MUSD)** (Jetlund, 2016). We assumed an additional **1.21 MNOK (0.14 MUSD)** for the gas control system, ventilation, gas detectors and shipyard installation costs (Stenersen, 2015). Therefore, the total cost was approximately **3.95 MNOK (0.46 MUSD)**.

[11] Where kNOK and kUSD respectively stand for thousand NOK and thousand USD

4.5.4 Hull modification

The vessel can be elongated to fit the tank to the vessel without reducing the catch capacity. Due to lack of data on general arrangement of the vessel, an elongation cost of 1 MNOK/m (0.12 MUSD/m) was assumed (Einang, 2016). Considering a tank length of 3.18 m (Table 4), the hull modification cost was estimated to be **3.18 MNOK (0.37 MUSD)**.

4.5.5 Fuel cost

The vessel in this study operates in the North Sea, which is a sulphur ECA. Since 2015, the vessels operating in Sulphur Emission Control Areas (SECAs) are required to use fuel with a maximum sulphur content of 0.1% (IMO, 2014b), such as low-sulphur MGO (LSMGO) or LNG.

We considered the average LSMGO prices in Bergen, Norway from January to April 2016 as the cost basis, which is 361.50 USD/tonne (Ship & Bunker, 2016). Considering its energy content (Table 3) and exchange rate in the period of interest (1 USD ≈ 8.65 NOK) (Norges Bank, 2016) the price of LSMGO was 259.72 NOK/MWh (30.03 USD/MWh).

Among other things, the LNG price depends on the bunkering type and the distance from the LNG source. For the same energy content, we assumed a 10% lower price for LNG delivered on-board a vessel along the Norwegian coast compared to LSMGO (Einang, 2016; Marhaug, 2016)

Considering the annual MGO consumption (Table 2), the energy content and density of MGO (Table 3), and the difference in fuel prices, the annual fuel cost savings from the use of LNG instead of LSMGO was approximately **108.19 kNOK (12.51 kUSD)**. For simplicity, it is also assumed that the fuel costs remained the same during the vessel's lifetime.

4.5.6 Environmental expenses and support

In this study, the environmental tax rates were assumed to be constant during the vessel's lifetime. The NO_x emissions for a MGO-fuelled vessel were calculated considering the annual MGO consumption (Table 2), the MGO density (Table 3), and an emission factor of 54 kg NO_x per tonne MGO (Stenersen, 2015). Considering a NO_x tax rate of 21.17 NOK (2.45 USD) per kg NO_x (see Section 4.2.3), the annual NO_x tax was **400.17 kNOK (46.26 kUSD)**.

It is assumed that the use of 100% LNG would reduce NO_x emissions by 90%. The vessel can pay 4 NOK (0.46 USD) per kg NO_x to the NO_x fund instead of the tax for the remaining emissions (see Section 4.2.3). By using LNG, the annual savings on the NO_x tax will be **392.60 kNOK (45.39 kUSD)**.

The vessel can also receive 375 NOK (43.35 USD) per kg NO_x reduced as support from the NO_x fund. However, the support may not exceed 80% of the additional investment costs (see Section 4.2.3): (i) the additional cost of the gas engine compared to a conventional engine (1.90 MNOK (0.22 MUSD)), (ii) the LNG tank cost (3.95 MNOK (0.46 MUSD)), and (iii) the hull modification cost (3.18 MNOK (0.37 MUSD)). Therefore, **6.38 MNOK** (0.74 MUSD) of the additional investment cost (i.e., **9.04 MNOK (1.05 MUSD)**) can be covered by the fund.

Because the vessel in this study operates in coastal waters, it is subject to a tax on CO_2 and SO_x emissions when using MGO (i.e., 0.28 and 0.133 NOK (0.03 and 0.02 USD) per litre of MGO, respectively). Considering the annual MGO consumption (Table 2), the annual CO_2 and SO_x taxes were **113.97** and **54.13 kNOK (13.18** and **6.26 kUSD)**, respectively. LNG-powered fishing vessels are exempt from these taxes (Norwegian Directorate of Taxes, 2016).

4.5.7 Net present value

In previous sub-Sections, we estimated the relative costs for a LNG investment compared to a MGO investment. For many investments, such as the case under study, the main costs are incurred upfront and other costs and benefits are incurred in the future. The value of money changes over a vessel's lifetime. The NPV technique can be used to evaluate the LCC of an investment considering the time value of money (Pohl and Nachtmann, 2010).

Inflation and uncertainty, among other things, cause future costs and benefits to be discounted to express their current value. The discount rate i depends on various factors, such as the interest rate paid by the government on treasury bonds and the prime rate charged by major banks to their best customers. Once all of the costs and benefits are determined, the present value of the costs is subtracted from the present value of the benefits to determine the NPV (Equation (2)) (Fields, 2009).

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+i)^t} \tag{2}$$

where B_t and C_t represent the additional/fewer benefits and costs of a LNG-fuel investment at time t compared to a conventional vessel, respectively, and n represents the years covered. For an investment with a positive NPV, the present value of the benefits exceeds the present value of the costs, and the investment is deemed feasible.

Figure 9 summarises the various additional capital and operational costs and benefits for the LNG investment compared to the conventional MGO investment. The capital costs include the additional engine cost, the expenses related to the LNG tank, and the hull modification cost. All of these costs are incurred when the vessel is built (i.e., t=0). The operational costs of a LNG-fuelled vessel are less than the corresponding values for a conventional vessel. Therefore, the LNG-fuelled vessel has operational benefits/savings on fuel costs and environmental taxes compared to the conventional vessel. The NO_x fund support is received in stages. For instance, NO_x reduction after a month will elicit possible partial support. The payment will be adjusted according to each emission reported toward full payment in relation to NO_x reduction achieved after 3–12 months of operation. The verification period is generally one year, and a part of the total verified support can be received every 2–3 months (Fleddum, 2016; NHO, 2016a). In the case under study, it is assumed that all of the support was received after the first year (i.e., t=1).

The calculation of the discount rate is outside the scope of this study. Here, we assume a discount rate i of 8%. We assume that n equals the vessel's lifetime (i.e., 25 years). For the case under study, Equation (2) can be expressed as Equation (3):

$$NPV = -(1.90 + 3.95 + 3.18) + 6.38\left[\frac{1}{(1+0.08)^1}\right] + (0.11 + 0.39 + 0.11 + 0.05)\left[\frac{(1+0.08)^{25}-1}{0.08(1+0.08)^{25}}\right] = 4.01\ MNOK \tag{3}$$

If the ship owner invests in a LNG-fuelled vessel instead of a conventional vessel, with an 8% discount rate, 4.01 MNOK (0.46 MUSD) in 25 years accrues. In other words, the LNG investment is economically more beneficial than a conventional investment. The payback time is 7 years.

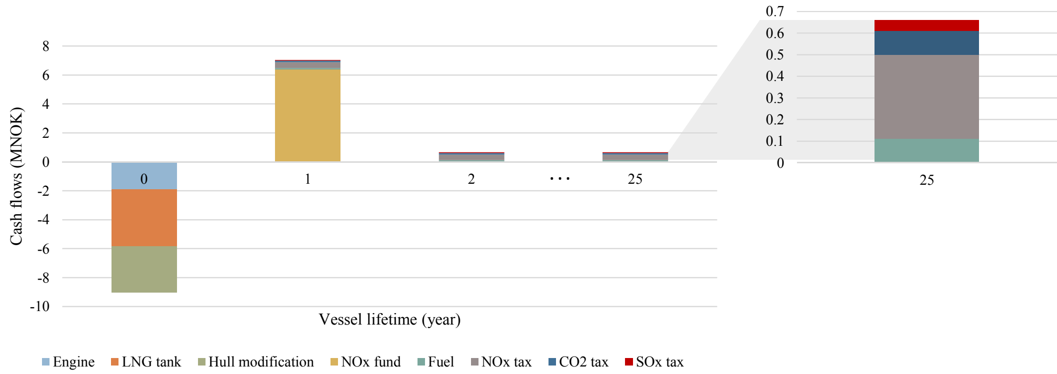

Figure 9: Cashflow for a LNG investment compared to a MGO investment during the vessel's lifetime

4.6 Step 6 - Build and test the plan

When a feasible design has been established, an implementation plan is produced. The plan accounts for the available resources for implementation, the technical risk, and subcontracting, among other details (Oliver et al., 1997). Producing the implementation plan is outside the scope of this study and is thus not further discussed.

5 Discussion

5.1 Knowledge transfer

LNG does not resemble any fuel that fishermen have experience with from either an economic perspective or a safety perspective. Still, LNG may be a viable alternative for meeting environmental regulations. LNG can reduce fuel costs in this fuel-intensive sector; however, other costs should also be considered while evaluating economic feasibility of a LNG investment. In addition, the present safety concerns in fishing increase the complexity of this issue. This article uses a SE approach to increase the knowledge of ship owners and other stakeholders regarding the financial, technical, and operational aspects of using LNG fuel.

Progressively tightening environmental regulations increase the complexity of investment decisions. Ship owners can use a holistic approach to harness the environmental benefits of LNG with a better understanding of its economic and safety implications. The SE approach can assist ship owners in decision-making and trade-off analyses. The most appropriate design for meeting environmental requirements can be selected based on defined criteria, such as the MOEs defined in Section 4.3.

Naval architects can use the SE approach to manage and organize the relevant information and regulations, such as the IGF Code, while designing a LNG-fuelled system. This approach aids in the understanding of the rationale behind the rules and may thus enhance ship design. The SE process stresses the importance of the early definition of system requirements and stakeholder criteria. In this manner, it prevents fundamental requirements from being overlooked during the downstream system design. In addition, the SE approach covers different stages of the life cycle, which allows the effects of the design on the operation to be identified early in the design process. For instance, possible interactions between the gas unit or bunkering system and the fishing operation can be identified well in advance. In the same manner, gas-related safety training can be planned with fishing operations in mind.

The link between the SE approach and the bowties shows where the action of different safety barriers can prevent undesirable events in different accident scenarios and illustrates the consequences of not satisfying the MOEs. This allows for an assessment of the overall system safety based on the relative importance of primary requirements and also helps the ship owners, designers, and crew prioritize their actions to improve the overall safety of the system and prevent accidents.

SE can also be useful operationally. Using the SE process, ship owners can realize which skills are needed for safe operations and plan crew training accordingly. Training can extend beyond educating the crew about hazards and proactive and reactive safety operations; it can also inform the crew about the reasons behind the required steps. If the crew realizes the logic behind their safety actions, they are more likely to comply with the procedures that they are expected to follow. As noted above, the crew training requirements on a LNG-fuelled ship (i.e., Section A-V/3 in the STCW Code) demand some knowledge of the technical requirements of these vessels (i.e., the IGF Code). The SE approach may facilitate the understanding of these technical requirements and their link to the operational requirements.

5.2 LCC analysis revisited

Several assumptions were made while estimating the LCC of the LNG investment in Section 4.5. For example, the fuel price was assumed to be constant during the vessel's lifetime. However, the actual future prices of MGO and LNG are highly uncertain. Different fuel price projections should be considered to reduce the investment risk.

While fuel projection is outside the scope of this study, the LNG investment was revisited considering two scenarios from DNV GL and MAN Diesel & Turbo (2015). These scenarios are shown in Figure 10. The first scenario is a high-price scenario based on mid-2014 fuel prices (Scenario I). The second scenario is a low-price scenario based on mid-2015 prices (Scenario II). In these scenarios, LNG is on average 41% and 24% less expensive than MGO for the same energy content, respectively. We assumed that MGO and LNG prices would increase at the same rate during the vessel's lifetime (i.e., from 2016 to 2041). Keeping the remaining parameters and costs unchanged (see Section 4.5), the NPV will rise to the values shown in Table 5. Therefore, the analysis is highly sensitive to fuel price dynamics, which should be considered.

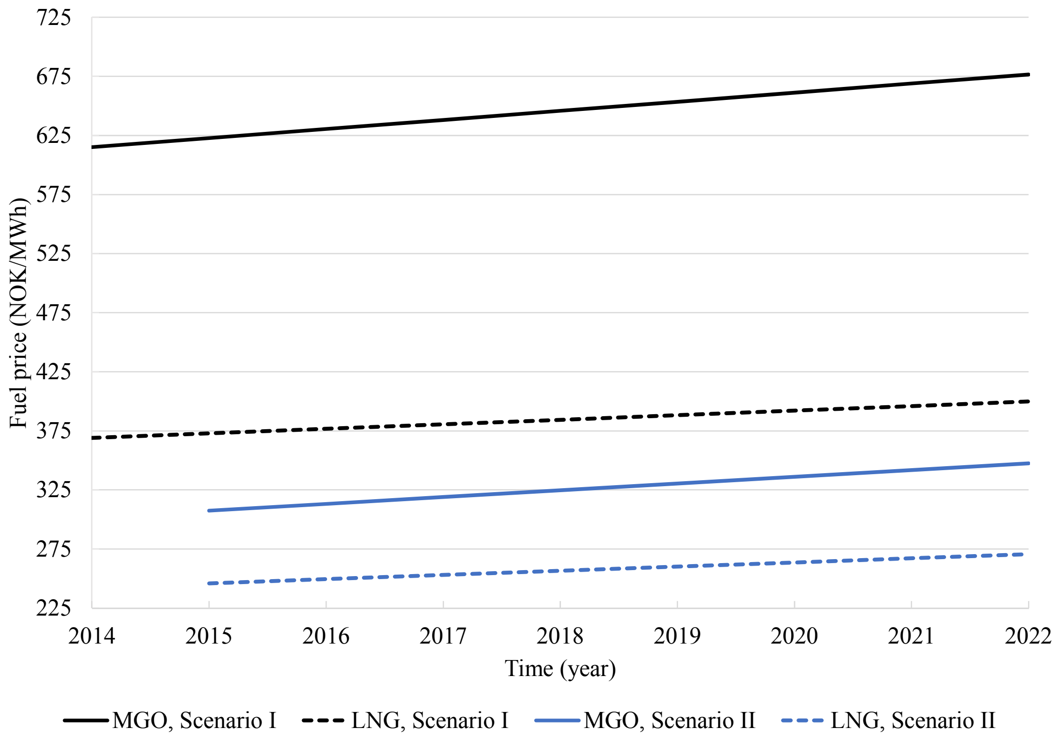

Figure 10: Two fuel price scenarios based on DNV GL and MAN Diesel & Turbo (2015). Exchange rate of 8.65 NOK/USD is used to convert values.

Table 5: Relative net present value (NPV) of the LNG investment compared to the MGO investment. The LNG investment is feasible in scenarios with positive NPV and vice versa. Case study in Section 4.5 is the base case. Scenario I and II consider high and low price projections defined by DNV GL and MAN Diesel & Turbo (2015), respectively. Scenario III considers no tax and support for emissions of nitrogen oxides.

Scenario	NPV in MNOK (MUSD)
Base case	4.01 (0.46)
Scenario I	15.76 (1.82)
Scenario II	6.60 (0.76)
Scenario III	-6.09 (-0.70)

Different scenarios for environmental tax projections may be considered in a similar manner. For instance, although LNG only reduces CO_2 emissions by approximately 25%, LNG-fuelled vessels are exempt from the CO_2 tax in Norway. For the case under study and considering the current low fuel prices, the annual economic gain from the CO_2 tax exemption is close to the annual fuel cost savings when using LNG (see Sections 4.5.5 and 4.5.6). A possible future CO_2 tax could make LNG a less desirable solution, especially if fuel prices are low.

Table 5 indicates that LNG would not be a viable option when excluding the NO_x tax and fund system (Scenario III) while keeping the other parameters and costs unchanged (see Section 4.5). In addition, the vessel under study operated in the North Sea, which is a SECA. Vessels operating in SECAs are obliged to use a low-sulphur fuel (e.g., LSMGO or LNG) or use scrubbers to clean the exhaust gas. LNG may be less desirable for a vessel that spends less time in SECAs because the vessel can use a less expensive fuel (e.g., heavy fuel oil) outside of the SECAs. Therefore, the viability of LNG may change from one region to another based on environmental regulations, taxes, and supports.

The effects of crew training and hiring on costs were not considered due to the lack of specific data. These costs may add to the expenses of the LNG investment. Maintenance costs were also not considered. Gas engines may require less frequent maintenance; however, the spare parts may be more expensive (see Section 2.2).

In this study, NPV was used for the LCC analysis. Although this technique is simple to use and provides a good overview of costs, it has drawbacks. For instance, NPV cannot evaluate the value of investing in a technology at a later stage. Acciaro (2014) suggests other methods, such as a real option analysis (ROA), for this purpose.

In this study, the LNG tank was assumed to be horizontal. However, vertical tanks are another option. In this manner, the tank may be positioned in available free spaces on the vessel. However, this option was not evaluated due to the lack of data on the ship arrangement.

In this study, the tank volume including insulation was 24.67 m^3 (Table 4), which is approximately 2.8-fold larger than the MGO tank volume (i.e., 8.72 m^3) (see Section 4.5.3). Bagniewski (2010) reported a corresponding value of 2.3 fold for the maximum filling ratio of 95% (see Section 2.2). However, it is not clear whether the minimum filling ratio of 10% was considered (i.e., a net 85% usable capacity). The thicknesses of the insulation and the inner and outer walls were also unknown. More importantly, we used Equation (1) to estimate the fuel consumption for a round trip. In other words, we investigated the actual energy needed by considering the average efficiency of diesel and gas engines. If we had instead considered the energy content of MGO and LNG as shown in Table 3, the LNG consumption for a round trip would have been 14.37 m^3 (as opposed to the current value of 15.55 m^3). Assuming this value and a usable capacity of 95% (instead of the 85% value used), the LNG tank would be 2.3-fold larger than the MGO tank.

5.3 Limitations

Despite its benefits, the SE approach has some limitations. It may be challenging to define MOEs. Different stakeholders should agree on these measures well in advance to avoid costly problems in the future. Although models enable the investigation of systems from different perspectives, the construction of accurate models is time and resource consuming. Professionals from different disciplines, such as naval architects, safety engineers, and equipment suppliers, should collaborate to collect and analyse the data. In addition, some stakeholders may be familiar with compiling and analysing data in a text and document format. It may be difficult to define the relationship between requirements, barrier functions, and barrier elements, as different pieces of information are spread across different documents. Finally, cost estimation for relatively new technologies, such as LNG propulsion, may be challenging. There are few gas engine and equipment suppliers, which causes cost data to be confidential and less accessible. The LNG price is highly uncertain and varies from one region to another. There is also room for negotiation on fuel price, both for MGO and LNG, for major fuel consumers.

6 Conclusions

This article illustrates how a SE approach can increase the knowledge of ship owners, naval architects, and the crew regarding the financial, technical, and operational aspects of the use of LNG fuel. Fishing vessels can use LNG fuel to improve their environmental profile. The vessels can comply with progressively tightening environmental regulations in this manner while satisfying customers who want “green” seafood products. Better insight into LNG economic and safety aspects may support ship owners when evaluating such available options. Moreover, naval architects may benefit from better management of the available information and the crew may improve their understanding of the safety rationale. In fact, combining a SE and bowtie analysis allows for the visualization of the potential effects when missing safety requirements.

This representative application demonstrates how an organised approach such as SE can enhance decision-making on risk prevention, the selection of feasible alternatives, and harmonisation between the system elements and environment. Specifically, this case study demonstrates that LNG may be cost efficient for coastal shrimp trawlers, but the results depend on fuel prices and environmental taxes and supports. The results may be applicable to other parts of the fishing fleet, particularly those parts of the fleet that have high fuel consumption.

The suggested approach may be broadened and applied to other ship types. Additional stakeholder requirements may be added to the SE models. The economic feasibility of alternative LNG-fuelled designs, such as the use of dual fuels (i.e., MGO and LNG) or the use of smaller fish holds for accommodating LNG tanks, may also be of interest.

7 Acknowledgments

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IMT-14-2014	Syahroni, Nur	Fatigue Assessment of Welded Joints Taking into Account Effects of Residual Stress, IMT
IMT-1-2015	Bøckmann, Eirik	Wave Propulsion of ships, IMT
IMT-2-2015	Wang, Kai	Modelling and dynamic analysis of a semi-submersible floating vertical axis wind turbine, CeSOS

IMT-3-2015	Fredriksen, Arnt Gunvald	A numerical and experimental study of a two-dimensional body with moonpool in waves and current, CeSOS
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IMT-8-2015	Oleh I Karpa	Development of bivariate extreme value distributions for applications in marine technology,CeSOS
IMT-9-2015	Daniel de Almeida Fernandes	An output feedback motion control system for ROVs, AMOS
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