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The Transition Towards a Fossil Free Freight Transport Sector – Policy Evaluations and Effects of Proposed Policy Instruments

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ABSTRACT

The overall aim of this thesis is to improve the knowledge about how policy instruments can contribute to effective and efficient reductions of greenhouse gas emissions in the freight and maritime transport sectors. Paper I addresses this aim by analysing how policy evaluations contribute with information about whether policy instruments in the freight transport sector have been successful in achieving their targets and how to improve or correct already implemented ones. A meta-evaluation of ex-post climate policy evaluations is carried out, and by analysing the outcomes and quality of the evaluations, the study investigates whether estimated effects of policy instruments can be compared between evaluations and if the results are appropriate to use for evidence-based decision making. The study shows that there is a lack of systematic climate policy evaluation which hinders reliable conclusions about the effects of policy instruments. Consequently, there is a need for more systematic monitoring and evaluation of implemented policy instruments and the study suggests that evidence-based decision making can be improved by adjusting current policy evaluation guidelines and by introducing an evaluation obligation. Paper II addresses the overall aim by developing a modelling tool, referred to as the Swedish Energy Transition of Shipping (SETS) model, that can be used for policy scenario analyses of shipowners' investment decisions in the Swedish maritime transport sector over the time period 2020-2045. The main contribution of the developed SETS model is that it can take into account data for individual ships and their operational patterns when estimating the impact of potential policy instruments. Hence, the model can contribute to an improved understanding of how proposed policy instruments can affect future greenhouse gas emission reductions in the maritime transport sector.

Keywords: Policy instruments, Greenhouse gas emissions, Freight transport, Policy evaluation, Evaluation criteria, Maritime transport, Scenario analyses.

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Gothenburg, May 2023
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LIST OF PUBLICATIONS

This thesis contains the following appended publication and working paper:

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- Takman, J., Sedehi Zadeh, N., Trosvik, L., & Vierth, I. (2020). Triple F Systemövergripande uppföljning 2020 – Uppföljning av hur godstransporter närmar sig det svenska klimatmålet 2030. Triple F leverans 2020.2.11.
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List of acronyms

BAU	Business as usual
CO_2	Carbon dioxide
CO_2e	CO_2 equivalents
EC	European Commission
ETD	Energy taxation directive
EU	European Union
EUA	EU allowances
EU ETS	European Union Emissions Trading System
GHG	Greenhouse gas
GT	Gross tonnage
HFO	Heavy fuel oil
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
LBG	Liquified biogas
LNG	Liquified natural gas
MGO	Marine gas oil
TTW	Tank-to-wake
UN	United Nations
WTW	Well-to-wake

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CHAPTER 1

Introduction

This chapter provides a brief background to the research in this thesis and presents the research aim and main objectives. The chapter also describes the scope and limitations of the research and presents the thesis outline.

1.1. Background

Climate change is one of the greatest challenges of our times. In the sixth assessment report from the Intergovernmental Panel on Climate Change (IPCC) of the United Nations (UN), the overarching message is that observed increases in greenhouse gas (GHG) concentrations unequivocally are caused by human activities and that "global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades" (IPCC, 2021). To avoid detrimental effects on the environment and society, a rapid reduction of GHG emissions is therefore essential (IPCC, 2022).

The transport sector accounts for about one-quarter of the global carbon dioxide (CO_2) emissions and it is one of the main contributors to GHG emissions due to its high reliance on fossil fuels (IEA, 2021a; 2022a). Freight transport, including heavy duty trucks, rail, and shipping, accounts for about one-third of the global GHG emissions in the transport sector (IEA, 2021b). Over the last two decades, global GHG emissions from freight transport have increased by about 37% due to global economic growth, increased international trade activity and population growth, and the demand for freight transport is forecasted to increase (IEA, 2022a; ITF, 2019). Freight transport is often referred to as a "hard-to-abate" sector, especially the maritime transport sector, due to the high dependence on fossil fuels and the forecasted increase in freight demand. For example, the current fuel mix in the maritime transport sector relies almost entirely on fossil fuels (DNV, 2022). Furthermore, ships have a relative long lifetime of about 20-35 years (Hoffmann, 2020), which means that investments in newbuilt ships made today will stay long in the ship fleet and have an impact on the possibilities of achieving future targets of GHG emission reductions.

To curb climate change, several countries have adopted targets for GHG emission reductions within the transport sector. For example, Sweden has the target to reduce GHG emissions from domestic transport (excluding aviation) by 70% by 2030, compared to 2010 levels, and to reach net zero GHG emissions by 2045 (SOU 2016:47). In the European Union (EU), the European Climate Law includes a legally binding climate neutrality target of net zero GHG emissions by 2050 and a target of at least 55% net GHG emission reduction by 2030 compared to 1990 levels (EC, 2021a). To support the transition towards climate neutrality and to achieve necessary reductions of GHG emissions from freight transports, the use and implementation of policy instruments that can encourage a transition towards renewable fuels and an improvement of operational and technical energy efficiency are needed (IEA, 2021b). In the EU, the European Commission (EC) proposed a package of policy initiatives in the European Green Deal in 2019 (EC, 2022), where emissions within the transport sector mainly are targeted in the proposed Fit for 55 package. For example, as part of the package, a revision of the EU Emissions Trading System (ETS) was proposed (EC, 2021b), and a political agreement was reached on 18 December 2022 to reform the EU ETS and to include emissions from maritime transport (EC, 2022).

To ensure that targets of GHG reductions are achieved at the lowest cost for society, policy instruments should be effective and efficient. However, although there exist numerous climate policy instruments in the freight transport sector, evaluations of them have been found to be lacking in many ways (ITF, 2022; Takman et al., 2020; Takman & Gonzalez-Aregall, 2021), which limits the understanding about the performance of currently implemented policy instruments and the continuous adaptation and improvement of them.

From an ex-post point of view, policy evaluations can contribute with useful information for policy makers. For example, policy evaluations can provide analyses about whether policy instruments have been successful in achieving their targets and which policy instruments to implement in the future as well as how to improve or correct already implemented ones. However, previous literature has found that there is a gap between evaluation theory and how ex-post policy evaluations are performed in practice (Huitema et al., 2011), that there is a risk of selective or biased policy evaluations (Bovens et al., 2008; Mastenbroek et al., 2016; Schoenefeld et al., 2018), and that comparisons between policy evaluations are difficult due to the evaluations' methodological differences (Harmelink et al., 2008; Haug et al., 2010). To draw reliable conclusions about the performance of policy instruments and to ensure evidence-based decision making, it is essential that evaluations have adequate methodological quality and legitimate analyses.

From an ex-ante perspective, it is also relevant to analyse the potential effects of proposed policy instruments. For example, in the maritime transport sector, the investments in newbuilt ships made today and in the coming years will have an impact on the possibilities of achieving future climate targets. Therefore, it is important to understand how the ship fleet composition may develop during the coming years and what effects policy instruments may have on shipowners' investment decisions. This can provide an understanding of how implemented and planned policy instruments can contribute to the achievement of climate targets and whether there is a need for additional or more stringent policy instruments.

1.2. Aim and objectives

The overall aim of this thesis is to improve the knowledge about how policy instruments can contribute to effective and efficient reductions of GHG emissions in the freight and maritime transport sectors. To analyse this overarching research aim, two more specific research questions are addressed within this thesis:

Research question 1:	Do policy evaluations of climate policy instruments in the freight transport sector contribute to reliable conclusions about the performance of policy instruments?
Research question 2:	How will proposed climate policy instruments affect shipowners' investment decisions in renewable fuels?

Research question 1 is analysed in paper I by carrying out a meta-evaluation of policy evaluations with the aim to understand how already implemented policy instruments perform and whether they contribute to climate targets in an efficient and effective way.[1] Research question 2 is analysed in paper II by developing a scenario modelling tool, referred to as the Swedish Energy Transition of Shipping (SETS) model, that can be used to analyse effects of proposed policy instruments on shipowners' future investment decisions.

1.3. Scope and limitations

Paper I has a wide scope in terms of covering policy instruments globally in the whole freight transport sector, while it is limited to only including climate policy instruments. Thus, the paper excludes analyses of policy instruments aimed at adjusting for other environmental issues than GHG emissions. In contrast to previous similar studies, paper I focuses also on the evaluation *quality*, in addition to the *outcomes* found in policy evaluations. To analyse these aspects, commonly applied evaluation criteria are assessed and classified according to an assessment scale for each included evaluation. By examining which types of policy instruments that are evaluated and the outcomes and quality of evaluations, paper I aims to identify whether estimated effects of policy instruments can be compared between evaluations and if the results are appropriate to use for evidence-based decision making.

By focusing on the Swedish maritime transport sector, paper II has geographically and sector-wise a narrower scope compared to paper I. However, the paper contributes to the literature by developing a modelling tool that, in comparison with previous related studies, can take more aspects into account about ships and their operational patterns. More specifically, paper II aims to use the developed model to analyse tendencies of how policy instruments in the EU (the European Green Deal and the Fit for 55 package) can contribute to a transition towards fossil free fuels in the Swedish maritime transport sector.

[1] A meta-evaluation is defined as a systematic review of evaluations to determine the quality of their methods and findings (Cooksy & Caracelli, 2005).

What both papers have in common is the focus on reductions of GHG emissions and the effects of policy instruments.

1.4. Thesis outline

The thesis is structured as follows. Chapter 2 presents the theoretical framework and provides a more comprehensive background to the research. Chapter 3 describes the methods used in the two papers and the data used in the analyses. Chapter 4 presents the main results from the two papers, which then are discussed in Chapter 5. Conclusions are summarised in Chapter 6 along with a description of future work and research.

CHAPTER 2

Theoretical framework

This chapter presents the main concepts and theories related to the research in this thesis, including market failures, policy instruments, and policy evaluation theory. This is followed by a description of the potential solutions and barriers affecting GHG emission reduction for the Swedish maritime transport sector and an overview of its regulatory context.

2.1. Market failures and policy instruments

2.1.1. Market failures

The research in this thesis is based on concepts and theories within welfare economics and environmental economics. Welfare economics is the study of how the allocation of resources and goods affects social welfare (Perloff, 2014), and environmental economics is the study of the cost-effective allocation, use, and protection of the world's natural resources (Kolstad, 2011). Both of these are based on microeconomic theories about how individuals and firms make decisions with the aim to maximise their utility, which can be used to understand how the welfare in society (i.e., the sum of all actors' utility) can be maximised (Perloff, 2014).

The concept of market failure describes a situation where the market does not lead to an optimal use of society's resources. It is thus a "failure" compared to the level of welfare that could have been achieved in a "perfect market". The most common example of market failures in the transport sector is the existence of external effects, also referred to as externalities. Externalities are positive or negative effects that occur when an economic transaction affects the utility or welfare of a third party in a way that is not compensated for through prices or market mechanisms (Perloff, 2014). An example of negative externalities is when actors (e.g., firms or individuals) in society emit greenhouse gases that affect other actors in society negatively, while not compensating for the damage that occurs.

In the presence of an externality, the total cost for society is greater than the private cost for the actor since all factors are not taken into account when the value of the good or service is calculated.[2] Hence, the price on the market does not reflect the societal cost, but only the private cost for the actor causing the emissions. Assuming that the firm acts in a competitive market without any form of internalisation of external effects, the firm will produce products to maximise its profits. In the competitive equilibrium, this will not maximise societal welfare because the firm does not have to pay for the harm that it causes and it will therefore produce more than what is optimal for societal welfare (Perloff, 2014). If the market price does not reflect the real societal price (i.e., such that the externality is considered), there will be a loss of efficiency (Perloff, 2014).

In general, achieving an efficient allocation in the presence of externalities involves making sure that actors are faced with the correct prices for their decisions and actions (Varian, 1992). To solve the market inefficiencies of externalities, there are several possible solutions of government intervention that can increase societal welfare (Perloff, 2014). One solution is to use a corrective tax that corresponds to the external costs, which often is argued as the most efficient policy instrument to achieve emission reductions.

2.1.2. Policy instruments

Policy instruments can be used to adjust for a market failure by giving actors incentives to account for the unintentional effects, or external effects, that their choices contribute to (Sterner & Coria, 2012). For GHG emissions, the main problem is that, without policy instruments, actors do not generally have incentives to internalise the cost of emissions in their production and consumption decisions. By implementing policy instruments, such market failures can be adjusted and welfare in society can be increased.

Given a specific target of GHG emission reductions, a cost-effective policy instrument has the ability to achieve the target at the lowest possible cost to society. Alternatively, for a given cost, a cost-effective policy instrument can achieve the greatest possible reduction in GHG emissions. If a policy instrument is not cost-effective, it means that more resources than necessary are used and that emission reductions take place in a more expensive way for society than necessary. More specifically, cost-effectiveness means that the private marginal cost of reducing emissions (i.e., the cost of reducing emissions with an extra unit, e.g., an extra kilo of greenhouse gases) is the same for all actors. In general, actors' private marginal cost is lower for the "first" measures to reduce emissions and higher for reducing the "last" emissions (Söderholm & Hammar, 2005). For example, actors can often use relatively cheap measures to reduce a small part of their emissions (e.g., by using eco-driving techniques), while large reductions are often significantly more expensive as they may require investments in new technology (e.g., by investing in new vehicles). When the marginal cost is the same for all actors, the responsibility is distributed in such a way that actors who can reduce their emissions relatively easily and cheaply reduce their emissions more than actors who find it relatively difficult and expensive to reduce their emissions. The total societal cost of achieving a certain

[2] The private cost for firms includes the cost of production, such as costs of labour and energy, but it does not include the cost for the negative effects from pollution they may cause. The social cost can thus be defined as the private cost plus the cost of the harms from the externalities that the firm causes (Perloff, 2014).

emission reduction can thus be minimised by replacing relatively expensive reduction measures with relatively cheap measures from another actor (Söderholm & Hammar, 2005).

Policy instruments are often divided into two groups: market-based and non-market-based policy instruments (Sterner & Coria, 2012). Market-based instruments can be described as using market mechanisms and operating through market prices, whereas non-market-based instruments instead include all other types of instruments that do not use market mechanisms. Taxes, subsidies, and emissions trading are examples of market-based policy instruments, whereas legislations, prohibitions, environmental classifications, or different types of standards are examples of non-market-based policy instruments (Sterner & Coria, 2012).

Market-based policy instruments generally have better opportunities to achieve cost-effectiveness than non-market-based policy instruments. For example, the main advantage of a tax is that if it is equally high for all actors, it has the ability to contribute to cost-effective emission reductions as all actors will reduce their emissions to the point when the tax level is equal to the marginal cost of emission reduction (Jenkins, 2014). A tax that corresponds to the external costs to which the emissions contribute, the Pigovian tax, is often argued as the most cost-effective solution to achieve emission reductions (Pigou, 1920). Even if the optimal tax level, the Pigovian tax, often is difficult to set, taxes are still cost-effective if the tax level is the same for all actors (Söderholm & Hammar, 2005; Sterner & Coria, 2012). Other advantages of a tax on GHG emissions are that it can provide incentives for actors to invest in research and development (R&D) to find innovative ways to reduce emissions (both in the short and long term if the tax level is long-term stable) and that it is technologically neutral. Disadvantages of taxes are that the size of the total emission reduction that will be achieved is uncertain, that they are often politically difficult to implement (especially global taxes), and that there is a risk of emissions leakage (to other countries or sectors that are less regulated or have lower taxes) unless border adjustment measures are implemented (Sterner & Coria, 2012).

Subsidies can either be a form of payment to actors that can cover their costs for emission reductions or a payment per unit of emissions reduced. In the case where subsidies are paid per unit of reduced emissions, it can be compared to a form of a “negative tax”, where actors instead of paying a tax per unit of emissions are paid for each unit of emissions that is avoided. In theory, subsidies provide the same incentive for actors to reduce emissions as a tax, but there are also a number of differences. For example, subsidies do not fulfil the principle that “the polluter pays”, as all individuals in society instead pay for subsidies through the country’s tax revenue. In other words, all individuals in society have to pay for the specific reduction in emissions that the subsidy leads to, which places relatively large information requirements for how and where the subsidy is used in order to maximise welfare in society (Sterner & Coria, 2012). If there had been cheaper ways to achieve the same emission reduction, it means that the money saved could have been used differently with higher welfare in society as a result. An advantage of subsidies is that they generally generate relatively little political resistance from society, which makes them easier to implement than, for example, taxes (Sterner & Coria, 2012). Subsidies can be justified to use to help the market diffusion of new technological solutions with the potential to reduce GHG emissions (Sterner & Coria, 2012).

Emissions trading systems are based on political decisions about a maximum permitted amount of emissions that may be emitted (e.g., of GHG emissions). Actors that emit greenhouse gases are then allowed to trade emission rights (i.e., a right to emit a certain amount of greenhouse gases) so that their emissions correspond to the number of emission rights that they submit for a given time period. The main advantages of emissions trading systems are that they have the ability to achieve cost-effectiveness and that the total emission reduction that will be achieved is certain because it was decided in the system through the available amount of emission rights. A disadvantage of emissions trading systems is that there is a risk of fluctuating prices for emission rights, which makes it more difficult for actors to plan future investments in emission-reducing technologies and may therefore reduce incentives to invest in R&D to find innovative ways to reduce emissions. Additionally, there is also a risk of emissions leakage if there are no border adjustment measures to complement the emissions trading system. Furthermore, emissions trading systems often have complex designs and require large resources to be designed, implemented, and operated. Finally, emissions trading systems, just like taxes, have high information requirements so that the optimal level of the number of available emission rights can be set (Sterner & Coria, 2012).

Non-market-based policy instruments are, as previously mentioned, policy instruments that do not directly operate through market mechanisms and generally do not achieve cost-effectiveness. The advantages of non-market-based policy instruments, such as bans or technical standards, are that it is relatively easy to control the actors' compliance with requirements, which also provides control over total emission reductions that will be achieved. However, the main disadvantage is that all actors are forced to make the same change and that the actors' marginal cost will be different, which means that emission reductions do not take place where it is cheapest to achieve cost-effectiveness (Sterner & Coria, 2012). Other disadvantages include monitoring and enforcement costs, and that they provide low incentives for actors to invest in R&D to find innovative ways to reduce emissions as there are few incentives to reduce emissions more than the standard requires.

2.2. Policy evaluation

According to Crabb and Leroy (2008), a policy evaluation can be defined as "a scientific analysis of a certain policy area, the policies of which are assessed for certain criteria, and on the basis of which recommendations are formulated" (p.1). Similarly, Vedung (2017) defines a policy evaluation as a "careful, retrospective assessment of merit, worth, and value of the administration, output and outcome of government interventions, which is intended to play a role in future practical action situations" (p.3). Below follows a description of different branches of policy evaluation research and its main purposes, followed by examples of previous policy evaluations.

2.2.1. Theoretical framework of policy evaluation literature

There are different branches of policy evaluation research, for which Turnpenny et al. (2009) developed a categorisation of policy evaluation literature, which later was extended and applied by Adelle et al. (2012). The motivations, or types and purposes of the literature, are by Turnpenny et al. (2009) divided into four categories: 1) policy evaluation designs and guidelines, 2) policy instrument evaluation and evaluation of the quality of policy evaluations, 3) learning and policy change from policy evaluations, and 4) motivation and politics for evaluating policy instruments.

The first type of literature considers the methods and the design of policy evaluations, as well as guides and handbooks for practitioners who perform evaluations. It also includes literature focusing on various types of tools that can be used in policy evaluation, such as cost-benefit analyses, econometric techniques, impact assessments, or multicriteria analyses (Adelle et al., 2012; Turnpenny et al., 2009). Examples of policy evaluation guidelines are those provided by the EC and the Organisation for Economic Co-operation and Development (OECD), which are aimed to be used by policy evaluators when managing and evaluating existing legislation. According to the EC (2017), an ex-post policy evaluation should be an evidence-based judgement of the extent to which a policy instrument fulfils certain evaluation criteria. The evaluation should look for causality between the policy instrument and the observed changes and it should consider *why* and *how much* something has changed on account of the policy instrument, rather than just assessing *what* has happened (EC, 2017). The OECD recommends six evaluation criteria to be used to support consistent policy evaluations, where they argue that the criteria should be related to the aim and context of the specific evaluation and should not be applied in a fixed way for all evaluations (OECD, 2021).

The second type of literature considers the performance and operation of policy evaluation designs by evaluating their quality against different evaluation criteria. A challenge within this literature type has been how to conceptualise and measure the quality of evaluations. For example, quality has in some literature been measured by comparing the contents of policy evaluations with official policy evaluation guides, while in other literature, this approach is extended to include the process of the evaluation. Most of the studies in this literature type provide recommendations to policy makers on how to improve the performance of the evaluation systems, but few are found to address or question underlying political motivations or the framing of the evaluations (Turnpenny et al., 2009). Related to the research in this thesis, there are relatively few studies that systematically compile and assess the effects and results of climate policy evaluations in practice, despite an increased implementation of climate policy instruments (Michaelowa et al., 2018) and an increased recognition of the value of policy evaluations (Fujiwara et al., 2019). There are a few exceptions, such as Haug et al. (2010), Huitema et al. (2011), Auld et al. (2014), and Fujiwara et al. (2019), which provide systematic reviews of ex-post climate policy evaluations, which are further described below in section 2.2.2.

Whether policy evaluations have contributed to improvements is considered in the third type of literature, which aims to search for evidence that policy evaluation has led to policy change via processes of learning (Adelle et al., 2012; Turnpenny et al., 2009). For example, Hildén (2011) examines how policy evaluations have contributed to learning and how knowledge is generated and used at the level of a national government by using the evolution of long-term climate strategies in Finland and the relationship between evaluations and changes in policy. Hildén (2011) finds that although ex-ante and ex-post evaluations have contributed to learning, mandatory evaluations are to a large extent constrained by policy makers and the learning is therefore mainly limited to a predefined framing of the issues. Independent evaluations, which are less constrained and have greater possibilities to contribute to reflexive learning, are however less likely to enter the policy cycle. To increase learning also from independent evaluations, Hildén (2011) argues that policy processes should be more transparent and that background material should be accessible for external analyses.

Finally, the fourth type of literature considers the politics of policy evaluation and aims to explore the motivation for evaluating policy instruments (Adelle et al., 2012; Turnpenny et al., 2009). There are according to Bovens et al. (2008) two politically related obstacles that can affect the quality and outcome of policy evaluations. The first is that policy evaluations may uncover critical problems of the evaluated policy instrument, which may call for legislative repeal and create a risk of selective, biased, or even absent evaluations (Bovens et al., 2008; Mastenbroek et al., 2016). The other obstacle is that policy evaluations can be hindered by the evaluability of the policy instrument. That is, the quality may depend on how easy or difficult it is to evaluate a policy instrument, which for example can depend on data availability (Bovens et al., 2008).

2.2.2. Examples of policy evaluations

Although there are relatively few studies that systematically compile and assess the effects and results of climate policy, there are some exemptions. For example, Haug et al. (2010) examine to what extent climate policy evaluations provide evidence on which to base future policies. Their meta-analysis includes an examination of a number of ‘dilemmas’ connected to the policy making of climate policies, including aspects of policy objectives, governance, timing, instrument types, distribution of costs and benefits, as well as implementation and enforcement. When the dilemmas are ‘adequately addressed’ in the evaluation studies, Haug et al. (2010) argue that they may serve as a valuable basis for policy making. The main findings are that most reviewed evaluations addressed the effectiveness of the policy instrument, that few used a quantitative assessment, and that evaluations often used a variety of techniques which generated different results (Haug et al., 2010). Huitema et al. (2011) also provide a meta-analysis of ex-post climate policy evaluations, in which the evaluations are categorised according to a series of evaluation criteria in order to draw conclusions about the emerging patterns of policy evaluations in the EU. Huitema et al. (2011) find that there is a gap in the literature between evaluation theory and how ex-post policy evaluations are performed in practice. They also find that non-commissioned policy evaluations are more likely to challenge established goals than commissioned ones and that governmental bodies, which often have a specified policy agenda, are less likely to challenge established goals in policy evaluations than other actors. Using the same evaluation criteria as Huitema et al. (2011), Fujiwara et al. (2019) provides a relatively similar meta-analysis, but reviews more recent ex-post climate policy evaluations. In line with both Haug et al. (2010) and Huitema et al. (2011), they find that most policy evaluations include analyses of the effectiveness and goal achievement of the policy instrument, but that few policy evaluations analyse levels of reflexivity (the challenging of established goals) or public participation in the evaluation process. Auld et al. (2014), which use a similar method as Haug et al. (2010), Huitema et al. (2011), and Fujiwara et al. (2019), find that policy instruments that have flexibility mechanisms or well-defined time frames tend to be associated with more positive policy evaluations.

There is also literature which systematically reviews evaluations of policy instruments aimed at other aspects than climate. For example, Mastenbroek et al. (2016) conduct a meta-evaluation of ex-post legislative evaluations in the EU evaluation system. The EC has committed itself to a producing systematic high-quality EPL evaluations to enhance effectiveness, accountability, legitimacy and enforcement (Mastenbroek et al., 2016). However, Mastenbroek et al. (2016) argue that the EC also may have incentives not to evaluate legislations since evaluations may “lead to undesired policy change or repeal”. The results of this meta-evaluation indicate that the coverage of ex-post legislative evaluations is inconsistent and that they are mainly performed as an obligation.

2.3. The Swedish maritime transport sector

The Swedish maritime transport sector contributes with about 8.5 million tonnes of CO_2-equivalent (CO_2e) emissions (in 2021) and the emissions have increased by about 15% since 2010 levels. CO_2e emissions from domestic maritime transport have decreased slightly since 2018, while CO_2e emissions from Swedish international maritime transport have continued to increase (Swedish Environmental Protection Agency, 2023a; 2023b). The majority of Swedish maritime transport travels internationally. For example, 86% of all cargo handling in Swedish ports in 2021 involved international traffic (Transport Analysis, 2022). It is also at the international level that Swedish GHG emissions from maritime transport is mainly regulated, and there are few nationally implemented policy instruments aimed to reduce their GHG emissions.

2.3.1. Solutions and barriers for GHG emission reduction

Possible solutions for shipping companies to reduce GHG emissions include both technical and operational solutions. For example, solutions include retrofitting to more energy efficient engines, implementing waste heat recovery systems, improving hull design, reducing speed, and improving routing and scheduling (Bouman et al., 2017; Zhu et al., 2018) as well as changing to renewable fuels (Kanchiralla et al., 2022; Malmgren et al., 2021). The fuel use from ships contributes to the main part of ships’ emissions, which makes the abatement solutions important considerations for shipowners to be able to comply with environmental policy instruments, where the choice of propulsion system is the most critical part to reduce emissions (Zhang & Yin, 2021).

The current fuel mix in the maritime transport sector relies almost entirely on fossil fuels (DNV, 2022). Conventional marine fuels, such as marine gas oil (MGO) and heavy fuel oil (HFO), are used in internal combustion engines (ICEs). Paper II analyses the following solutions of alternative propulsion systems and fuels: 1) biofuels (e.g., hydrotreated vegetable oil (HVO) and bio-methanol) in ICE, 2) battery electric propulsion, 3) electro-methanol (e-methanol) produced from the Nordic electricity mix in ICE, 4) liquified natural gas (LNG) in ICE, 5) liquified biogas (LBG) in ICE, 6) electro-methane (e-methane) in ICE, and 7) hydrogen in fuel cells.

The climate emission factors for the different propulsion systems and fuels are presented in Table 1. Conventional fuels have the highest emission factors, both from the tank-to-wake (TTW) and the well-to-wake (WTW) perspectives. LNG has the second highest emission factors and has from the WTW perspective almost as high emissions as conventional fuels. The lowest climate emission factors can be seen for the energy carriers electricity, hydrogen, and e-methanol. Moreover, the energy carriers can be associated with emissions of air pollutants that may affect the environment and health, but these are excluded in the scope of this thesis.

Table 1. Climate emissions factors for different energy carriers (tonne/MWh fuel). Sources: Copied from paper II, where values are based on Brynolf (2014), Malmgren et al. (2021) and Brynolf et al. (2023).

Energy carrier	**Tank-to-wake**		**Well-to-wake**
	CO_2	**CO_2e**	**CO_2e**
Conventional fuels	0.28	0.28	0.33
Biofuels (HVO/bio-methanol*)	0.00	0.00	0.13
Electricity	0.00	0.00	0.03
E-methanol	0.00	0.00	0.10
LNG	0.20	0.25	0.31
LBG	0.00	0.05	0.16
E-methane	0.00	0.05	0.16
Hydrogen	0.00	0.00	0.08

*The CO_2 and CO_2e emissions from tank-to-wake are the same for HVO and bio-methanol when not considering the biogenic CO_2 emissions.

Ship investments are complex decisions for shipowners, which are affected by numerous factors and barriers. For example, a transition towards zero-carbon fuels includes significant capital investment, long payback periods, limitations of availability in global bunkering infrastructure, higher fuel prices, and a potential additional demand for onboard storage space (DNV, 2022). In addition, ships are highly heterogenous with different operational profiles, power needs, sailing distances, and have different levels of fixed and varying routes, which affect which abatement options that are technologically mature and suitable for different ship segments (DNV, 2022; Mäkitie et al., 2022). The investment decision includes considerations of operational costs, fuel and technology availability, and safety concerns (Zhang & Yin, 2021).

2.3.2. Regulatory context

Due to the international character of the maritime transport sector, it is difficult to limit the analysis to the national level. In the international regulatory context, Swedish maritime transport is affected by policy instruments both at the EU level and at the global level, where the International Maritime Organisation (IMO) is responsible for regulating global commercial shipping. The only implemented policy instruments affecting GHG emissions from maritime transport at a national level in Sweden include the Climate Leap initiative (Klimatklivet), environmentally differentiated fairway and port dues, and environmental requirements for public procurement of ships (Transport Analysis, 2022).

In the international regulatory context, Swedish maritime transport is affected by policy instruments both at the EU level and at the global level, where the UN agency IMO is responsible for regulating global commercial shipping. Table 2 summarises implemented and proposed policy instruments at the EU and global level affecting Swedish maritime transport, sorted by the year they came into force or are planned to come into force.

On the global level, the IMO has implemented different policy instruments affecting the energy efficiency of ships. The Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) came into force in 2013 (IMO, 2011). EEDI is a performance-based measure affecting the technical requirements, while complying with the SEEMP can include improvements such as weather and route planning, speed reductions, and hull maintenance (IMO, 2011; 2022). The management of efficiency performance over time is achieved through the voluntary use of a monitoring tool, the Energy Efficiency Operational Indicator (EEOI), which enables ship operators to measure the fuel efficiency of a ship in operation and to measure the effect of any changes in operation. In 2019, the IMO implemented a global data collection system about ships' fuel consumption, referred to as the IMO Data Collection System (DCS), covering all ships in international traffic with 5000 gross tonnage (GT) and above (IMO, 2016). The DCS data is the basis for the Carbon Intensity Indicator (CII) rating and the SEEMP. In 2023, IMO introduced a complementing index, referred to as the Energy Efficiency Existing Ship Index (EEXI), affecting ships that were built before EEDI came into force (IMO, 2021).

On the EU level, the only implemented policy instrument is the EU Maritime monitoring, reporting and verification (MRV) Regulation, which was implemented in 2018. According to the regulation, ships above 5000 GT calling ports in the European Economic Area (EEA) have to monitor and report fuel consumption, CO_2 emissions, and transport work per voyage on an annual basis (EC, 2015; 2021b).

The European Climate Law made the EU's climate neutrality target of net zero GHG emissions by 2050 legally binding and it also raised the ambition by setting a target of at least 55% net GHG emission reduction by 2030 compared to 1990 (EC, 2021a). To support the transition to climate neutrality by 2050, a package of policy initiatives was proposed in 2019 in the European Green Deal (EC, 2022). One of the policy initiatives is the Fit for 55 package which refers to achieving the 2030 target of reducing net GHG emissions by at least 55% compared to levels in 1990. In this package, maritime transport is mainly affected through four parts: 1) including emissions from maritime transport in the EU ETS, 2) a revised energy taxation directive (ETD) which involves an end for the historical tax exemption of marine fuels, 3) the proposed FuelEU Maritime initiative which would involve setting a stepwise limit to reducing the carbon content of the maritime fuel and a maximum limit on the GHG content of energy used by ships calling European ports, and 4) concrete targets for deploying infrastructure to support the availability of alternative fuels within the EU through the AFIR (EC, 2021b).

Table 2. Overview of policy instruments affecting GHG emissions from the Swedish maritime transport sector, sorted by the implementation year. Source: copied from paper II.

Name	**Implementation year**	**Short description**	**Source**
Energy efficiency design index (EEDI)	2013	An index applicable for ships above 400 GT which is related to the technical design of a ship. It provides a newbuilding standard to ensure a certain efficiency level (of gram CO_2 emitted per tonne-mile of work) of ship designs.	IMO (2011)
Ship Energy Efficiency Management Plan (SEEMP)	2013	A tool to assist shipowners in managing the energy efficiency of ships. It consists of three parts: I) ship management plan to improve energy efficiency (ships above 400 GT), II) ship fuel oil consumption data collection plan (ships above 5000 GT), and III) ship operational carbon intensity plan (ships subject to CII, see below).	IMO (2011; 2022)
EU Maritime monitoring, reporting and verification (MRV) Regulation	2018	Ships of 5000 GT and above, calling EEA ports, are required to monitor and report fuel consumption, CO_2 emissions and transport work per voyage on an annual basis.	EC (2015; 2021b)
IMO Data Collection System (DCS)	2019	Ships of 5000 GT and above are required to report consumption data for each type of fuel oil they use. The DCS data is the basis for the CII rating and the SEEMP part III.	IMO (2016)
Carbon Intensity Indicator (CII)	2023	The CII applies to all cargo, RoPax and cruise ships above 5000 GT. It measures how efficiently a ship transports goods or passengers (in grams of CO_2 emitted per cargo-carrying capacity and nautical mile). The ship is given an annual rating from A to E based on reported IMO DCS data. The rating thresholds becomes increasingly stringent towards 2030.	IMO (2022)
Energy efficiency existing ship index (EEXI)	2023	An index applicable for ships above 400 GT, which extends the EEDI concept to the existing fleet. The required EEXI standard is determined by the ship type, the ship's capacity and principle of propulsion and describes the CO_2 emissions per cargo ton and mile.	IMO (2021)
EU Emissions Trading System (ETS)	2024	The current design of the EU ETS is proposed to be reformed to include emissions from maritime transport.	EC (2021b)
FuelEU Maritime Regulation	Not decided	The FuelEU Maritime regulation aims to increase the demand and deployment of renewable alternative transport fuels and zero-emission technologies by setting gradually increasing maximum limits on the yearly GHG intensity of the energy used by a ship.	EC (2022; 2023)
Energy taxation directive (ETD)	Not decided	A revision of the ETD is proposed to align the taxation of energy products with EU energy and climate policies. The ETD contains minimum levels of taxation based on energy content and environmental performance of the fuel.	EC (2021c; 2022)
Alternative Fuels Infrastructure Regulation (AFIR)	Not decided	The regulation aims to set targets for the expansion of infrastructure for alternative fuels. It is proposed that at least 90% of container and passenger ships above 5000 GT must have access to shore power supply in ports in the main ports by 2030, and that there must be access to LNG bunkering by 2025 at the latest.	EC (2021d)

The EU reached a political agreement on 18 December 2022 to reform the EU ETS and to include emissions from maritime transport (EC, 2022). The extension of the EU ETS to maritime transport applies to 100% of emissions from intra-EU/EEA voyages, half of the emissions from extra-EU/EEA voyages and emissions occurring at berth in EU ports (EC, 2021b). The coverage is initially, from 2024, proposed to include ships that are included in the EU MRV. The emissions in scope for surrendering EU allowances (EUA) will be gradually phased in, starting with 40% of emissions in 2024, 70% in 2025, and 100% from 2026 and onwards. The EU ETS is proposed to initially cover CO_2 emissions and be extended in 2026 to also cover other GHG emissions.

The proposed revision of the ETD regards the current exemption of fuel used by ships from taxation and is proposed to align the taxation of energy products with EU energy and climate policies (EC, 2021c; 2022). The ETD contains minimum levels of taxation, varying between different energy products, based on energy content and environmental performance of the fuel. For example, renewable fuels are proposed to have a lower tax level than fossil fuels. The taxes are proposed to be introduced on a lower level in 2023 and to be gradually increased over a ten-year period until 2033. In contrast to the proposed coverage of the EU ETS, all ships will be affected by the ETD regardless of their GT through the fuel price (the bunker distributors are responsible for complying with the ETD).

The FuelEU Maritime regulation aims to ensure that the GHG intensity of fuels used by the maritime transport sector gradually will decrease over time (EC, 2022). A provisional political agreement was reached on 23 March 2023 (EC, 2023). It is proposed to come into force in 2025 and to apply to all ships above 5000 GT in respect to energy used during the stay within a port in a member state, the energy used on intra-EU voyages, and half of the energy used on extra-EU voyages (EC, 2021e). The Directive 2014/94/EU on the deployment of alternative fuels infrastructure, which has been in place since 2014 to promote investments in infrastructure of alternative fuels within the EU, has within the Fit for 55 package been proposed to be repealed and to be updated as a regulation instead of a directive. The AFIR is aimed to set concrete targets for deploying infrastructure, which means that it will be binding for EU member states to provide such infrastructure. It is proposed at least 90% of container ships and passenger ships above 5000 GT will have access to shore-side electricity supply in the main sea ports by 2030 and that there must be access to LNG bunkering by 2025 at the latest (EC, 2021d).

CHAPTER 3

Data and methodology

This chapter presents the data and methodologies used to answer the research questions and to analyse the objectives of this thesis. Based on the work in paper I, a framework of a meta-evaluation of policy evaluations is presented, including a description of systematic search methodology and relevant evaluation criteria. Based on the work in paper II, the scenario modelling tool for the energy transition of shipping is presented, including the model methodology and policy scenario analyses.

3.1. Meta-evaluation of policy evaluations

3.1.1. Systematic search for policy evaluations

Paper I used a systematic review to collect policy evaluations to include in the meta-evaluation, meaning that the search is undertaken according to a fixed plan or system to identify and select relevant literature (Moher et al., 2009). In contrast to a non-systematic literature review, a systematic review facilitates the identification of all relevant research evidence that fulfils certain criteria set out in a search protocol, which can reduce the risk of a biased search for literature (Adelle et al., 2012). The main drawback of using the method of a systematic review is according to Auld et al. (2014) that the conclusions from the evaluations may be affected by the evaluators' choices about, for example, inclusion and evaluation criteria. However, the benefits include that it offers an approach that is designed to provide an overview of findings in the literature, that it facilitates a critical analysis of the existing evidence, and that it helps to identify research gaps in the literature (Auld et al., 2014).

The systematic search for policy evaluations included both white and grey literature, where white literature refers to papers published in peer-reviewed journals and grey literature is defined as literature produced by institutions not controlled by commercial publishers, such as governments, academia, businesses, and industry. The grey literature can include unpublished papers, conference articles, and government and agency reports (Gokhale, 1997). The search strategy, which is based on the methodologies described by Tsafnat et al. (2014) and Moher et al. (2009), can be described by the following steps:

(1) Preparation:	decision of databases and keywords to be used in the search,
(2) Retrieval of items:	searching in databases with the aim to find all relevant items,
(3) Screening:	removing duplicates, then screening titles and abstracts to remove irrelevant items,
(4) Eligibility:	screening full text for relevance and removing items that do not fulfil inclusion criteria,
(5) Snowball:	following citations of included items to find additional items.

The search procedures in paper I for steps (1) and (2) above are slightly different for the searches of white and grey literature. For the search of white literature, three comprehensive scientific databases were used: Web of Science, Scopus, and ScienceDirect. The search terms were aimed to capture literature including the following four areas: policy instruments, the freight transport sector, GHG emissions, and evaluations. The searches were limited to the time span January 2000 to September 2021 and were chosen because there were few policy evaluations prior to 2000 and the searches for policy evaluations ended in September 2021. For the search of grey literature, a database of policy instruments was used as a basis for the searches. The policy database was compiled in a previous research project (in Takman et al. (2020)) and includes policy instruments aimed at reducing GHG emissions from freight transport over the time period 2010-2020. For each listed policy instrument in the database, a search was made in paper I for the name of the policy instrument together with each of the three search terms *evaluation*, *assessment*, and *impact*. All relevant search hits were then compiled in a document, even if they later were found to not fulfil the inclusion criteria.

The search procedures for steps (3) to (5) were the same for both white and grey literature, where the full text of each search hit was screened for inclusion in the meta-evaluation. For a search hit to be included, it needed to fulfil the following selected inclusion criteria:

- The evaluated policy instrument must be aimed at reducing GHG emissions in the freight transport sector (although it can cover additional sectors).
- The policy instrument must be implemented as a public tool employed to correct for market failures and/or to reach objectives in society, thus excluding private measures.
- It must be an evaluation of actual outcomes of ongoing or terminated policy instruments, thus excluding ex-ante evaluations.
- The evaluation must include an analysis of at least one of the six outcome evaluation criteria (described below in Table 4), thus excluding status reports and other descriptive reports.
- The evaluation must evaluate the impact on GHG emissions, although the impact does not have to be expressed in quantitative terms.
- The publication year of the evaluations must be sometime over the period 2000-2021.

After all search items were compiled, the items' titles and abstracts were reviewed to exclude those that were not relevant, and the rest were marked as potentially relevant. The potentially relevant items were then reviewed in detail to examine whether they fulfil the inclusion criteria in the meta-evaluation.

3.1.2. Meta-evaluation and assessment scale

To be able to analyse and draw conclusions about the policy evaluations included in the meta-evaluation, the evaluations' content was in paper I compiled by using a template comprising information about the evaluation, the evaluated policy instrument, and the evaluation criteria. For example, the compiled information about the evaluations includes authors, title, abstract, type of study, publication year, and source. More specific information about the evaluations includes the affiliation of authors and whether the evaluation was commissioned or not. The template also includes information about the evaluated policy instrument, such as the type of policy instrument, which transport modes that are affected by the policy instrument, and the time period that the policy instrument has been in force. The compiled information about the policy instrument and evaluation type was mainly used for the analysis of trends over which types of policy instruments that are evaluated and which types of evaluations that are made.

The template also includes evaluation criteria related to the evaluations' outcomes and quality, which were used for the analyses of the quality and the outcomes of the evaluations, whether policy instruments are evaluated on equal grounds, and whether the effects of policy instruments can be compared between different evaluations. Table 3 presents the four most commonly discussed evaluation criteria measuring the quality of evaluations, here referred to as quality criteria, and Table 4 presents the definitions of the six most common evaluation criteria related to the analysis of results and findings, here referred to as outcome criteria.

The four quality criteria, described in Table 3, were based on criteria used by Mastenbroek et al. (2016), Huitema et al. (2011), and Crabb and Leroy (2008) and were chosen to measure the replicability of evaluations and the robustness and complexity of their methods. The six outcome evaluation criteria, described in Table 4, were chosen based on recommendations in policy evaluation guidelines by the EC (2017) and the OECD (2021). The evaluation criteria in these policy evaluation guidelines overlap, except for the criteria of "EU added value" and "sustainability" which are specific to the EC (2017) and the OECD (2021) guidelines, respectively, of which the former is excluded in this study since it only applies for policy instruments implemented in the EU.

Table 3. Quality criteria based on criteria included in Mastenbroek et al. (2016), Huitema et al. (2011), and Crabb and Leroy (2008). Source: copied from Trosvik et al. (2023).

Criteria	Definition
Internal validity	Using the same data again, can the results be replicated? Is there enough information provided in the evaluation to be able to replicate the results (data sources and descriptions of the method)?
Reliability	Are references and data sources clearly presented and described? Are the variables in the data explained?
Robust methodology	Is the choice of methodology well-motivated and are potential weaknesses with the method mentioned/discussed?
Complexity	Are side effects and causality analysed (in relation to the outcome variables and the scope of the evaluation)?

Table 4. Outcome criteria based on policy evaluation guidelines by the EC (2017a; 2017b) and the OECD (2021). Source: copied from Trosvik et al. (2023).

Criteria	Definition
Effectiveness	This criterion involves an examination of the interventions' effects and the extent to which it achieves (or progresses towards achieving) its objectives. In cases where the intervention does not achieve its objectives, the effectiveness analysis should include an identification of factors hindering progress. The extent to which the observed effects can be linked to the intervention should also be analysed. Examples of questions to answer in the evaluation to fulfil this criterion include: Is the intervention achieving its objectives? What have been the effects of the intervention?
Efficiency	This criterion considers the relationship between the resources used for the intervention and the resulting effects and changes generated by the intervention. The evaluation of this criterion involves an examination of the extent to which the intervention delivers results in a timely and cost-effective way. Examples of questions to answer in the evaluation to fulfil this criterion include: How well are resources being used? To what extent has the intervention been cost-effective? To what extent are the costs of the intervention justified, given the effects it has achieved?
Relevance	This criterion involves an examination of the extent to which the objectives of the intervention are adequately defined, realistic and feasible, and whether they respond to the needs and problems in society. Examples of questions to answer in the evaluation to fulfil this criterion include: Is the intervention doing the right things? How well do the objectives of the intervention correspond to the needs?
Coherence	This criterion includes concepts of complementarity, harmonisation, and co-ordination. It involves an examination of how well the intervention works together with other interventions and actions. This may include internal coherence (i.e., coherence within institutions and with other interventions with similar objectives) and external coherence at different levels (i.e., coherence with other interventions and coherence with national and international obligations). Examples of questions to answer in the evaluation to fulfil this criterion include: How well does the intervention fit? To what extent is the intervention coherent internally and externally?
Impact	This criterion considers the ultimate significance, going beyond the effectiveness criterion and the immediate results, and involves an examination of the extent to which the intervention generates more transformative holistic effects. Such effects may include social, environmental, and economic effects or indirect consequences of the intervention, or enduring changes in systems or norms. An example of a question to answer in the evaluation to fulfil this criterion is: What difference does the intervention make?
Sustainability	This criterion involves an examination of whether the benefits (e.g., economic, social, or environmental benefits) of the intervention are likely to continue over the medium and long term. An example of a question to answer in the evaluation to fulfil this criterion is: Will the benefits last?

To analyse and compare the content of the policy evaluations, the policy evaluations' assessments of the evaluation criteria were in paper I described both in a qualitative way and through an assessment scale in the template. The assessment scale was used as a tool to compare how different evaluation criteria have been addressed across evaluations. The assessment scale, presented in Table 5, includes three levels depending on how the policy evaluations address the different evaluation criteria.

Table 5. The assessment scale used for each evaluation criterion in the meta-evaluation.

Assessment scale	Description
▬	Not included: the evaluation criterion is not analysed or discussed
□	Lower detail: the evaluation criterion is mentioned or discussed shortly, i.e., only parts of the aspects in the definition of the criterion are analysed or discussed
■	Higher detail: the evaluation criterion is analysed in detail, i.e., all aspects in the definition of the criterion are analysed or discussed

3.2. The Swedish energy transition of shipping (SETS) model

This section first presents the data and model development, followed by a formulation of policy instrument scenarios.

3.2.1. Data description and model development

In paper II, the SETS model is developed with the aim to be able to analyse which investment options shipowners are most likely to choose in different policy instrument scenarios, based on the assumption the shipowners will choose the lowest cost investment option. The investment options are presented in Chapter 2 of this thesis and can be described as the shipowners' choice of fuel and propulsion system and include retrofitting an existing ship and changing fuel type. In the model, a ship dataset is used in combination with different inputs and assumptions to estimate the lowest cost investment options for shipowners, which then are used to estimate the fuel consumption of different fuel types and resulting emissions in the ship fleet. Policy instrument scenarios are developed to analyse tendencies in how policy instruments affect shipowners' investment decisions.

The base ship dataset used in the model was delivered by the Swedish Meteorological and Hydrological Institute (SMHI) (Windmark, 2020). In collaboration with the Swedish Maritime Administration, SMHI has developed the so-called "Shipair shipping model" to improve statistics on domestic fuel usage and emissions from maritime transport (Windmark et al., 2017). The Shipair model is based on Automatic Identification System (AIS) data, which is a global system that identifies vessels and their movements. The Shipair model area consists of three sea basins: North (Baltic Sea, north of Åland), South (Baltic Sea, south of Åland), and West (Skagerrak/Kattegat). The dataset contains information about ship routes for 4331 ships in 2019 in the Shipair model area. For each ship, the data includes routes until the accumulated distance exceeds 90% of the ships' total travelled distance over the year, or a maximum of ten routes. Hence, the dataset misses some information about the ships' routes and travelled distance, but it can still provide useful information about their movements.

There are 11 ship types included in the dataset, which are presented in Table 6. The descriptions of the ship types are based on the StatCode5 classification, which is the industry-standard ship type coding system (IHS Markit, 2017). Private recreational vessels are not included in the data. In addition to the 11 ship types included in the data set, paper II also divided the included ships into smaller segments to be able to use different scenarios for different ship segments. More specifically, the ships were divided into 57 ship segments depending on whether the ship travels in domestic, international or mixed (i.e., both domestic and international) traffic, is above or below 5000 GT, and whether it is used in publicly chartered traffic.

The dataset consists of both dynamic data, such as position, speed, and operating mode, and static statistical parameters, such as vessel identity, size, and year of vessel construction. Based on the ships' IMO number or MMSI number, the Shipair dataset was in paper II also matched with information from a commercial database, delivered by IHS Markit (2020) to get additional information about the ships.

Table 6. Description of ship types. Source: Windmark (2020).

Ship type	Description (according to Statcode5)
Tanker ship (TA)	Vessels carrying liquefied gas, chemicals, oil and other liquids
Bulk carrier (BU)	Vessels carrying bulk dry, bulk dry/oil, self-discharging bulk dry, and other bulk dry
Cargo ship (CA)	Vessels carrying general cargo, passenger/ general cargo, refrigerated cargo, and other dry cargo
Container ship (CO)	Vessels carrying containers
Ropax (RP)	Vessels carrying passenger/Ro-Ro cargo
Passenger cruise (PC)	Passenger cruise ships
Passenger ferry (PF)	Passenger ships
Fishing vessel (FI)	Vessels for catching fish and other fishing
Service ship (SS)	Vessels for offshore supply and miscellaneous (e.g., research vessels, towing/pushing vessels, icebreakers, and dredging vessels)
Vehicle carrier (VE)	Vessels carrying Ro-Ro cargo
Other ships (OT)	All other ships (W: Inland waterways, X: Nonmerchant ships, Y: Non-propelled ships and Z: Non-ship structures)

The developed SETS model can be divided into five steps, which are briefly described below. Figure 1 presents an overview of the model by summarising the main parts of the five steps along with the model inputs. The inputs to the model, represented by the rectangles outside the boxes in the figure, include assumptions about future investment costs, fuel costs, infrastructure and distribution costs, energy efficiencies of different propulsion systems (propulsion system efficiencies), emission factors, price of emission allowances (where emission factors influence the fuel costs, represented by the dashed arrow in the figure). In addition, assumptions are made for different ship segments regarding transport demand and the lifetime of ships.

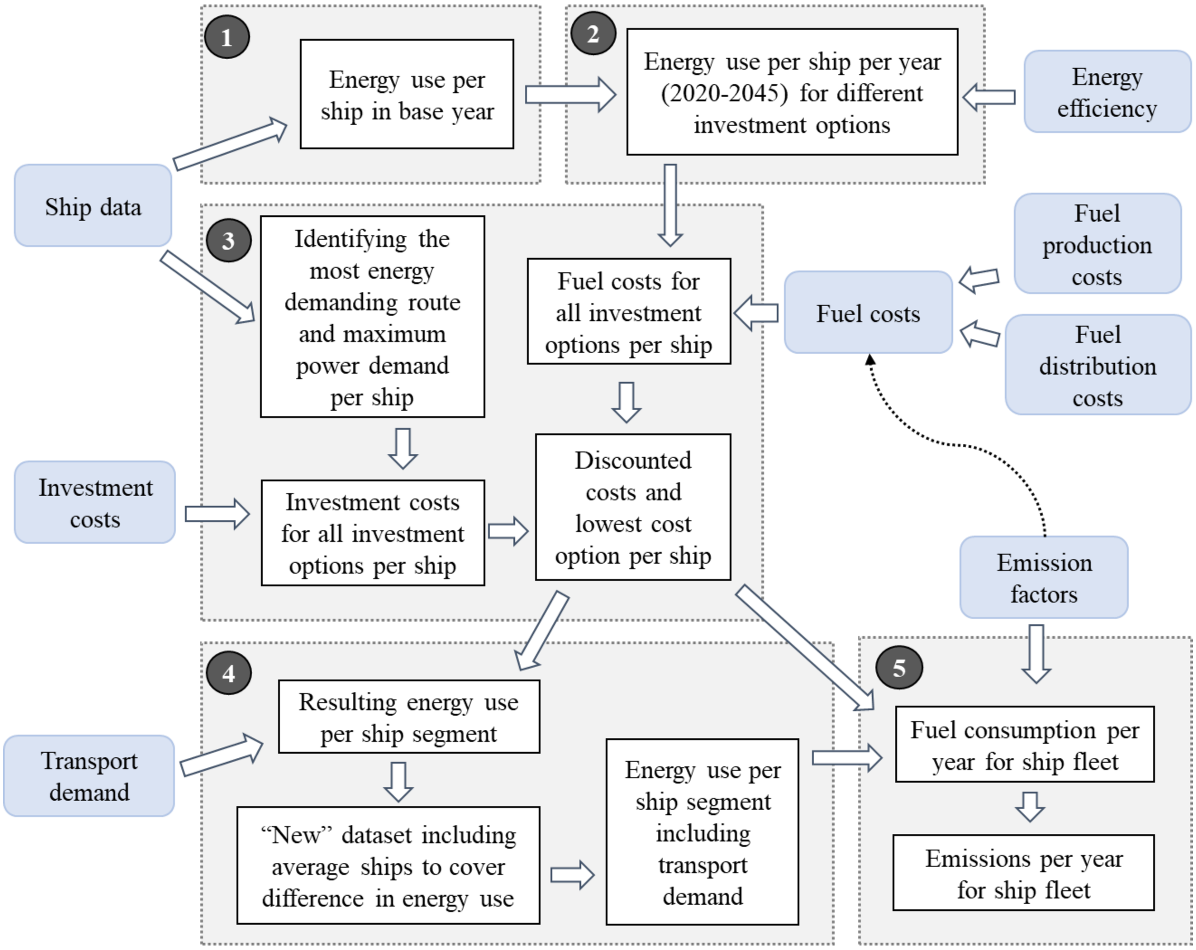

Figure 1. Model structure overview, describing steps 1-5 in the model (represented by the five boxes) and the inputs to each step (represented by the rectangles outside the boxes). The dashed arrow illustrates that the emission factors also influence the fuel costs in step 3. Source: copied from paper II.

Step 1: Estimation of the energy use per ship in the base year

The first step in the model consists of an estimation of the energy use per ship for the base year. The methodology follows an approach in IMO (2020), which considers ship specific information regarding ships' engine capacity, engine load, design speed, average speed per route, travel time per route, number of trips per route, and the specific fuel oil consumption of conventional fuel.

Step 2: Estimation of energy use for investment options for 2020-2045 per ship

In the second step, the future energy use per ship for all possible investment options in the model is estimated for the time period 2020-2045. To be able to calculate the costs for each investment option in the third model step, an estimate of each ship's future energy use for all investment options is needed. The investment options are described in Chapter 2 and include eight alternatives (conventional marine fuel, biofuels, battery electric propulsion, e-methanol, LNG, LBG, e-methane, and hydrogen). The estimation of future energy use is based on assumptions about propulsion system efficiencies for each investment option.

When a ship reaches its expected end of lifetime, it will have to choose to invest by latest that year. To make the model size manageable, the number of available investment options is reduced by assuming that every other year is an "investment year", that is, a year when the shipowners are able to make a decision in the model. The first investment year is in 2022, resulting in 12 investment years in total and 96 investment options (eight investment options and 12 investment years). For example, to estimate the future energy use of an investment of conventional fuels in ICE in 2022, the propulsion energy need (from the base year) is divided by the propulsion system efficiencies to estimate the energy use needed for the new propulsion system. Hence, the energy use will for the years 2020-2021 be the same as the base year and the following years 2022-2045 will have the new energy use in that option.

Step 3: Estimation of the discounted costs for each ship and investment option

In the third step in the model, the costs for each investment option are calculated based on the estimations in step 2, including fuel costs and investment costs for the motor and fuel tank/battery. To be able to compare the sum of all costs for each investment alternative, discounted costs, DC, are calculated according to equation (1).

$$DC_i = \sum_{t=1}^{T} \frac{C}{(1+r)^t} = \sum_{t=1}^{T} \frac{FC_{i,t} + I_{i,t}}{(1+r)^t} \tag{1}$$

For a given investment option, the discounted cost of vessel i is equal to the sum of all costs, C, which includes fuel costs, FC, and investment costs, I, of vessel i at time t, discounted over the lifetime of the investment where r is the discount rate. A discount rate of five percent is used in all scenarios, except for some of the sensitivity analyses.[3] Fuel costs are based on estimates of fuel consumption in the second model step and assumptions about future fuel costs, infrastructure and distribution costs and policy instruments. Investment costs are based on ships' maximum propulsion power, route distances and assumptions about component costs and energy storage margins needed for each ship. Shipowners are assumed to choose the option with the lowest discounted cost.

Step 4: Estimation of energy use per segment including transport demand

The fourth step in the model is to estimate the total energy use per segment over the time period 2020-2045 including forecasts of the segments' future transport demand. It is assumed that all ships in the dataset already have reached their maximum transport capacity and route frequency. Hence, the only way transports can be increased is to increase the number of ships in the model. In the first part of this estimation, the total energy use per ship segment per year is estimated by summarising the energy use for all ships' lowest DC for each segment per year. Then, the assumed future energy use including changes in transport demand per ship segment is estimated by multiplying the energy use the previous year per ship segment with the assumed yearly change in transport demand. The difference between the assumed future energy use including changes in transport demand and the total energy use per ship segment is calculated, which then is used to estimate how many additional average ships that are "needed" in each segment to

[3] The same discount rate is also used in related previous studies, see e.g., Hansson et al. (2020) and Brynolf et al. (2018), but it varies in other studies between 3-11%, see for example Zhang and Yin (2021), Pomaska and Acciaro (2022), Yin et al. (2019), and Atari et al. (2019).

cover this difference (i.e., the increased transport demand). The new ships in the model are assumed to have the same characteristics and choice of investment as the average ship type in each segment.

Step 5: Estimation of fuel consumption and emissions

The last step in the model is to combine the new average ships with the original dataset and to calculate the total fuel consumption of each fuel type, based on the lowest cost investment option per ship, and the resulting emissions. Emission factors, described in Chapter 2, are used to estimate the emissions from the estimated fuel consumption.

3.2.2. Policy instrument scenarios

In paper II, the policy instrument scenarios are developed based on the proposed policy package in the EU, Fit for 55, described in Chapter 2. The proposed policy instruments were used to formulate the policy instruments scenarios, which include:

- **(BAU)** **Reference scenario:** The reference scenario is the status quo, which is a situation in which no action is taken. It is assumed that maritime transport is not affected by any new policy instruments.
- **(1)** **ETD:** The proposed ETD (affecting all ships through the fuel cost).
- **(2)** **Low EUA:** EU ETS with a low EUA price (affecting ships of 5000 GT and above).
- **(3)** **High EUA:** EU ETS with a high EUA price (affecting ships of 5000 GT and above).
- **(4)** **High EUA + subsidy:** EU ETS with a high EUA price (affecting ships of 5000 GT and above) and a subsidy for the infrastructure cost of electricity (affecting all ships through the cost).
- **(5)** **High EUA 400 GT:** EU ETS with a high EUA price (affecting ships of 400 GT and above).

In paper II, some assumptions are the same in all scenarios. First, the assumptions about transport demand, are based on forecasts by the Swedish Transport Administration (2020) and, for some segments, based on previous trends of the demand. Second, the assumptions about ship lifetime follow the average scrap age of commercial ships by Hoffmann (2020). Third, all main scenarios are based on the same fuel costs, referred to as base fuel costs. In paper II, a simplified method is used to estimate future fuel costs, where fuel costs are assumed to be the sum of the fuel distribution cost (based on Brynolf et al. (2022)) and the fuel production cost (based on Korberg et al. (2021), Axelsson and Pettersson (2014), U.S. EIA (2022), and Gustavsson Binder (2022)). Fourth, the energy use from public maritime transport is not estimated within the model since that segment can be expected to have other factors affecting investment decisions compared to commercial maritime transport, such as requirements for public procurement and climate targets set by authorities. Therefore, for ships used by public actors, assumptions about their future fuel consumption are instead based on climate strategies of public actors. Finally, it is assumed that ship operators are aware of which policy instruments will be implemented, and that these changes will affect their investment decisions through expectations about future prices on allowances, energy taxes, and subsidies. It is assumed that the ships' voyages and length of voyages are fixed over the time period included in the model, that is, it stays the same as in the base year.

The business as usual (BAU) scenario is a reference scenario, which is a situation in which no new policy instruments are implemented. In scenario 1 (ETD), the ETD is assumed to be introduced in 2023 and to be gradually increased over a ten-year period until 2033. In the scenarios, the proposed tax levels are assumed follow the proposal, where the gradual increase is assumed to be a linear over the time period 2023-2033, and then stay at the final tax rate for the rest of the model period.[4]

In scenarios 2-5, the extension of the EU ETS to maritime transport is assumed to be gradually introduced, starting with 40% of emissions in 2024, 70% in 2025, and 100% from 2026 and onwards. For simplicity, it is assumed to include TTW CO_2e emissions already from 2024 and that it applies to all voyages. Hence, this is different compared to the proposal, where other GHG emissions than CO_2 are proposed to be included first from 2026 and onwards, and where it applies to 100% of emissions from intra-EU/EEA voyages and half of the emissions from extra-EU/EEA voyages. All ships of 5000 GT and above are assumed to be affected in scenarios 2-4, and all ships of 400 GT and above are assumed to be affected in scenario 5.

The CO_2 price component in the EUA is included separately from the base fuel costs, and it is estimated for each fuel type by multiplying the emission factor for TTW CO_2e of each fuel with the assumed price of EUAs. The low price of emission allowances is assumed to be constant over the time period at 100 EUR/tonnes CO_2e (TTW). This is higher than the price assumed by the EC (2021f) in their impact assessment report, where the carbon price ranges from 45-55 EUR/tonnes CO_2e, and where they discuss forecasts of up to 89 EUR/tonnes CO_2e. However, the price for emission allowances within the EU ETS has shown a significant increase during the last years. From levels around 15-30 EUR/tonnes CO_2 during 2018-2020, the price has now (March 2023) reached levels above 100 EUR/tonnes CO_2 and is expected to be traded at around 120 EUR/tonnes CO_2 in about a year (Trading Economics, 2023). Therefore, in the low price scenario, the EUA price is assumed to stay at the current level around 100 EUR/tonnes CO_2. The high EUA price is assumed to follow a scenario by the IEA (2022b), in which the price increases to 192 EUR/tonnes CO_2e by 2045.

In addition to the main policy instrument scenarios, six sensitivity analyses are developed in paper II to analyse uncertainties in the model. For example, the sensitivity analyses include different fuel costs, the inclusion of ships with 400 GT and above with low EUA, higher storage margin of ships, higher and lower discount rates, and an adjustment of the model area.

[4] Conventional fuel is assumed to be in the tax category of “Gas oil, HFO, non-sustainable biofuels” with a tax rate of 0.9 EUR/GJ. LNG is assumed to be in the tax category of “LPG, Natural gas, non-sustainable biogas, Nonrenewable fuels of non-biological origin” with a tax rate of 0.6 EUR/GJ in 2023 and gradually increasing to 0.9 EUR/GJ in 2033. Biofuels and LBG are assumed to be in the tax category of “Sustainable biofuels and biogas” with a tax rate of 0.45 EUR/GJ. Electricity, e-methanol, e-methane, and hydrogen are assumed to be in the tax category of “Renewable fuels of non-biological origin, advanced sustainable biofuels and biogas, Electricity” with a tax rate of 0.15 EUR/GJ (EC, 2021c).

CHAPTER 4

Results

This chapter presents the main findings from the two papers in this thesis related to the research aim. The chapter first presents the findings from the meta-evaluation of policy evaluations, followed by the findings from the developed SETS model and scenario analyses of proposed policy instruments.

4.1. Evaluations of policy instruments

4.1.1. Included evaluations in the meta-evaluation

The systematic search resulted in 2198 search hits, but only 20 evaluations were found to fulfil the inclusion criteria and are included in the meta-evaluation. The included number of evaluations is low compared to previous similar studies, which mainly can be explained by the more specific inclusion criteria used in the paper.[5] The most common reasons for the exclusion of search hits include that they do not consider policy instruments or the transport sector, that they are not ex-post evaluations, or that the effects on GHG emissions are not analysed. A disadvantage of having few included evaluations is that the findings are not possible to generalise, but an advantage is that the evaluations can be analysed more comprehensively and provide more detailed findings.

Of the included evaluations, the most common types of evaluated policy instruments are different types of EU Directives or programmes (six evaluations) and taxes (six evaluations), followed by biofuel policies (two evaluations), and larger and heavier vehicles (two evaluations). There are also evaluations evaluating several policy instruments in the same study (two evaluations), one evaluation of a voluntary program and one evaluation of a vehicle access restriction.

4.1.2. Classification of evaluation criteria according to the assessment scale

The classification of evaluation criteria according to the three levels on the assessment scale from paper I is summarised in Figure 2. Of the quality criteria, the figure shows that the least frequently analysed/discussed criterion is complexity, where five evaluations have not analysed

[5] This can be compared with 165 evaluations in Auld et al. (2014), 236 evaluations in Fujiwara et al. (2019), 262 evaluations in Haug et al. (2010), and 259 evaluations in Huitema et al. (2011).

any side effects or causality of the policy instrument, and only three evaluations provide a detailed analysis. For the other three quality criteria, internal validity, reliability, and robust methodology, around half of the evaluations are classified as having higher detail and around two evaluations do not include any discussion about the criteria. Among the outcome evaluation criteria, the figure shows that effectiveness is the most frequently analysed criterion, which is expected because it was one of the inclusion criteria. Only six evaluations have analysed this criterion with a higher detail, including whether the observed effects can be linked to the policy instrument, and the rest have analysed it with a lower detail. Efficiency and sustainability are the least frequently analysed criteria in evaluations, and the relevance criterion has the highest number of highly detailed analyses. The coherence and impact criteria have the same number of evaluations for the three levels on the assessment scale, with eight not analysing the criteria and four analysing the criteria in detail.

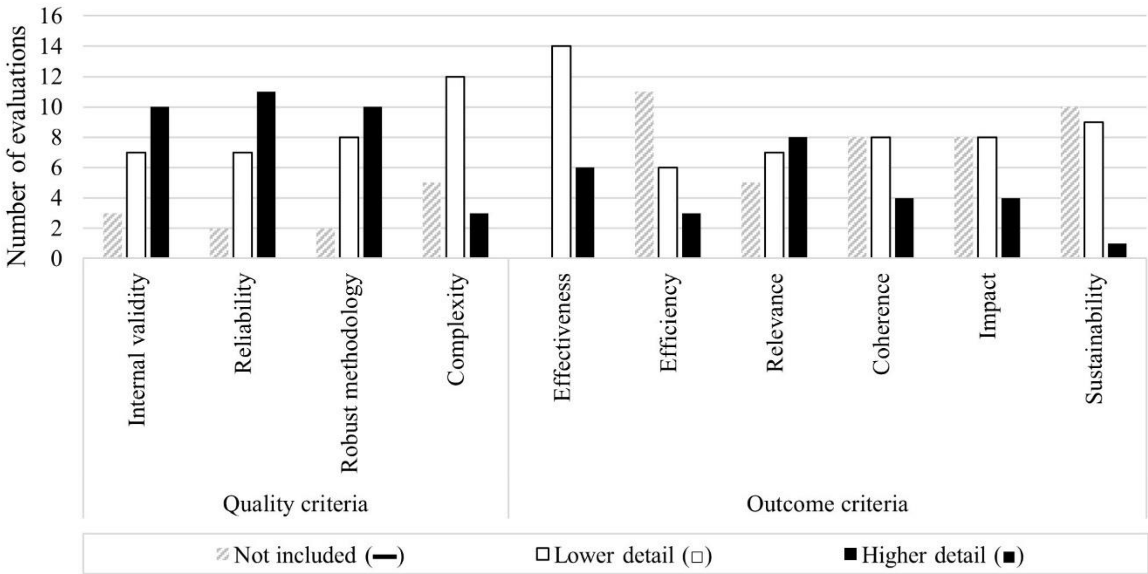

Figure 2. Number of evaluations classified according to the three levels on the assessment scale for each evaluation criteria. Source: copied from Trosvik et al. (2023).

In paper I, the classification of the criteria revealed that some aspects commonly were missing in the included evaluations. For example, for the evaluation criterion of internal validity, inadequate descriptions of surveys or questionnaires used in the evaluations were the most common reason for a classification as lower detail. Similarly, for the evaluation criterion reliability, the most common type of missing information is a description of included variables. The evaluation criterion robust methodology, which addresses the motivation for the choice of method, was classified as high detail if the evaluation both motivates why the specific method is the most appropriate in addition to discussing potential methodological weaknesses. Even though a classification as lower detail does not necessarily imply that the methodology is of low quality, it still implies an uncertainty concerning the quality of the method as it is hard to appreciate its motivation and potential weaknesses.[6] Finally, the evaluation criterion complexity, which addresses whether the evaluation uses a method that allows an analysis of causality and potential side effects of the policy instruments, is found in paper I to be the least frequently classified as highly detailed. When evaluating the effects of policy instruments, it is relevant to analyse whether observed effects are linked to the implementation of the policy instrument, or if there may be alternative explanations (EC, 2017a; OECD, 2021). However, the most common method to analyse effects is found to be the use of statistics to describe or calculate effects, which involves a risk of non-causal interpretations. Drawing conclusions about policy instruments' effects, without discussing alternative explanations, may lead to misleading results and difficulties for policy makers in interpreting results.

Among the outcome criteria, paper I finds that the efficiency criterion is one of the least commonly evaluated criteria of the included evaluations in the study. The efficiency criterion is relevant to analyse to be able to compare the effects of policy instruments. For example, a policy instrument could be found to lead to substantial reductions of GHG emissions but be very expensive in terms of costs for society, and the same reductions could potentially be achieved more efficiently. To understand how GHG emissions can be reduced to the lowest cost for society, an analysis of policy instruments' efficiency is highly relevant.

4.1.3. Affiliation of authors and methodological choices

The classification of evaluation criteria is also connected to the affiliation of authors. Figure 3 and Figure 4 show the share of evaluations classified at the three levels of the assessment scale for each evaluation criterion sorted by affiliation by authors. The affiliation of authors is divided into university, consultants, and other, where other includes research institutes, government agencies, the EC, and evaluations having authors with different affiliations (e.g., one university-affiliated author and one consultant). Figure 3 presents the results for the quality criteria and shows that, for the evaluation criterion internal validity, 50% of the evaluations were classified as highly detailed, where 30% are written by authors affiliated to universities, 15% by consultants, and 5% by others. The criteria reliability and robust methodology have about the same distribution of classifications. For the complexity criterion, 60% of the evaluations are classified as lower detail, where 35% are written by university-affiliated authors. Figure 4 presents the corresponding results for the outcome criteria. Of the effectiveness analyses that have a higher detail, it is the same share of evaluations with authors having university affiliation as being consultants. For the criteria efficiency, relevance, coherence, and impact, consultants provided a detailed analysis for about 15-20% of the evaluations, whereas university-affiliated authors commonly did not present an analysis of these.

[6] Regarding the criteria of robust methodology and reliability, it was beyond the scope of paper I to analyse the quality of evaluations' methods and whether relevant and complete data sources have been used. Such analyses would require that all included evaluations have well-described methodologies and that the authors of the paper have good knowledge of all methodologies used in the included evaluations as well as research areas. Thus, to avoid misleading or biased analyses of these criteria, the paper reviews the description and motivation for the chosen method and the presentation of data sources and references.

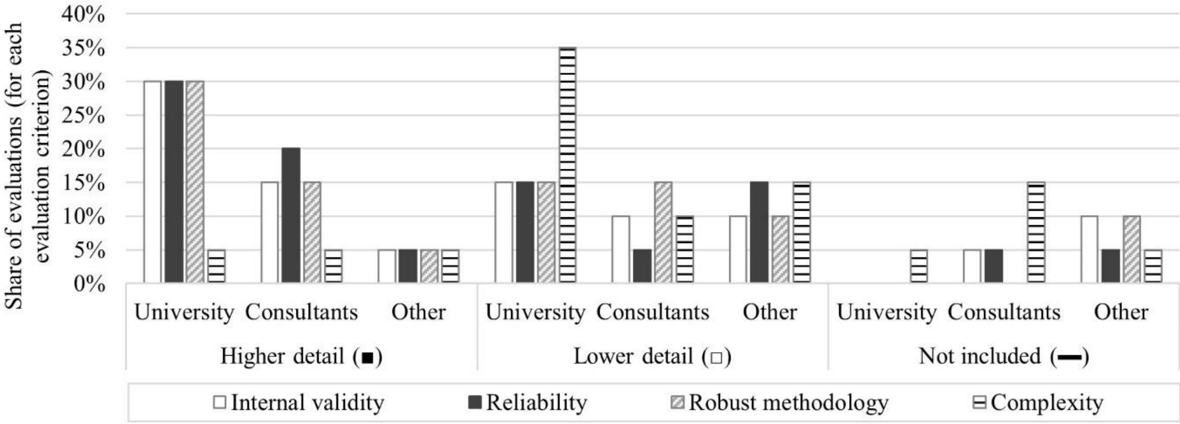

Figure 3. The share of evaluations for each quality criterion classified according to the three levels on the assessment scale, sorted by author affiliation. Source: copied from Trosvik et al. (2023).

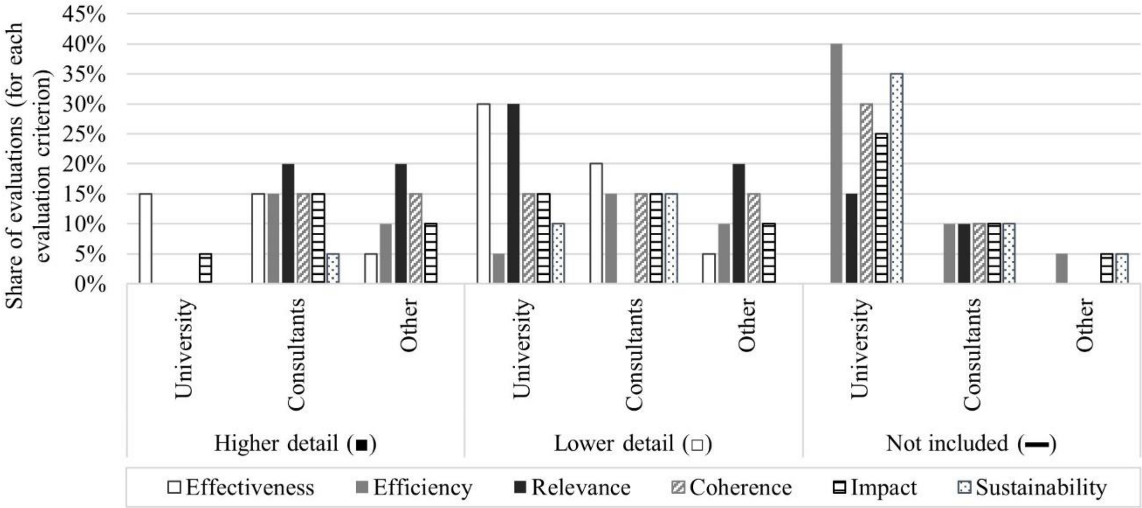

Figure 4. The share of evaluations for each outcome criterion classified according to the three levels on the assessment scale, sorted by author affiliation. Source: copied from Trosvik et al. (2023).

Paper I finds that authors with university affiliations include a higher level of detail about the quality criteria and fewer outcome evaluation criteria compared to authors affiliated as consultants. An explanation for these results may be that consultants more often present their results in reports (grey literature) with a broader scope compared to university-affiliated authors who more often write articles with a narrower scope to be published in peer-reviewed journals (white literature).

The meta-evaluation in paper I also comprises information about the evaluations' methodological choice and whether evaluations classify evaluated policy instruments as successful.[7] The most common type of method is to use statistics to make calculations or descriptive analyses to examine the effects of policy instruments. Other methods include

[7] Policy instruments are classified as successful (not successful) if the evaluation finds that the policy instrument has (not) been effective in reducing GHG emissions and recommends that the policy instrument should be continued (terminated or substantially improved). Evaluations are classified as "mixed results" if the evaluation finds that the policy instrument has reduced GHG emissions, but that it is not enough to reach targets and that improvements need to be made.

econometric approaches (six evaluations), literature reviews (eight evaluations), and surveys/interviews (seven evaluations). Nine evaluations conclude that the evaluated policy instrument has been effective in reducing GHG emissions and an additional nine of the evaluations present mixed results about the effectiveness of their evaluated policy instruments and argue that the policy instrument has achieved GHG emission reductions, although these are not enough to reach targets. Two evaluations find that the policy instrument has not been effective in reducing GHG emissions and argue that the policy instrument should be terminated or substantially improved. Of the nine evaluations that have concluded the evaluated policy instrument(s) to be successful, four have a higher detail level on the criteria internal validity, reliability, and robust methodology, only two have a higher detail on the effectiveness criterion, and only one has a higher detail level on the complexity criterion. Due to uncertainties related to the methodological quality and weaknesses in terms of lacking causality analyses, paper I finds that the conclusions about successfulness from these evaluations should be interpreted with caution.

4.2. The SETS model and scenario analyses of policy instruments

4.2.1. Scenario analyses of policy instruments

The scenario analyses in the SETS model provide estimations of the total discounted costs for all investment options per ship. Shipowners are assumed to choose the investment option with the lowest discounted cost, with the restriction that the investment year must be before the ship has reached its assumed end of lifetime. The policy scenarios are mainly used to test the model mechanisms and to analyse tendencies of how different policy instruments can affect shipowners' decisions. Hence, they are not aimed to provide realistic scenarios of the future development.

Figure 5 presents a summary of the estimated fuel consumption for the main scenarios in the years 2030 and 2045, as well as the fuel consumption in the base year. In the base year, it is assumed that all ships used conventional fuels, except for the public traffic that has some other fuel types. The use of hydrogen and LBG are not shown to be the lowest cost option for any ship in any of the scenarios and are included in the result as a result of plans for the public maritime transport. Therefore, these fuels are not analysed in detail below.

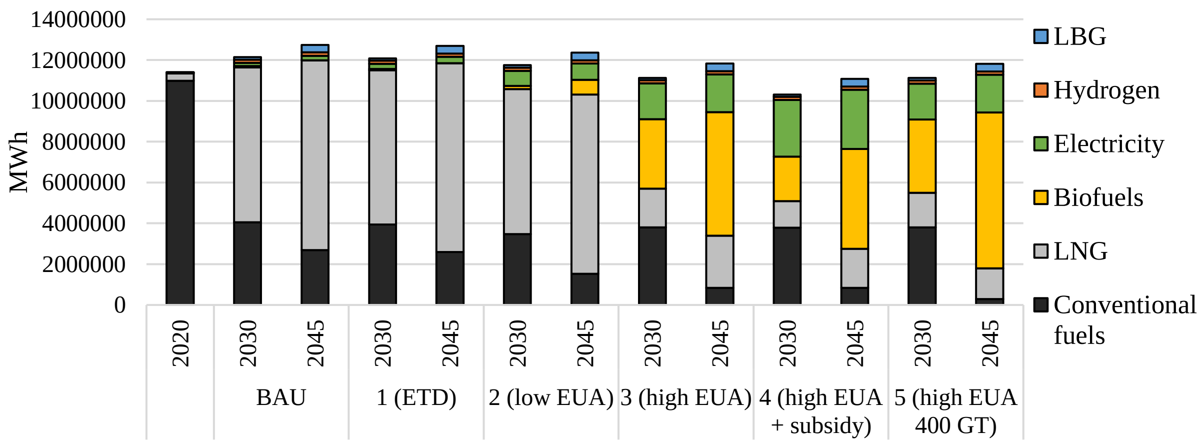

Figure 5. Estimated fuel consumption in scenarios BAU and 1-5 for the years 2030 and 2045. Source: copied from paper II.

In the BAU scenario, the estimations indicate that, if no action is taken, conventional marine fuels will continue to dominate until about 2030. After 2030, an increasing share of LNG can be seen, which by 2045 would be the dominant fuel choice in the Swedish maritime transport sector given the assumptions in the model, while investments in other fuel types are found to be negligible. In paper II, the explanation is found to be that LNG is the lowest cost option for several ship types, especially in those segments with relatively high energy use per year. Although there are a higher number of ships having conventional fuels as their lowest cost option, the total estimated energy use of LNG is higher by the end of the model period because ships with relatively high energy use per year more commonly have LNG as their lowest cost option. The total energy use is expected to increase by about 12% in this scenario over the model period, which can be explained by the assumed transport demand.

Scenario 1 (ETD) differs only marginally from the BAU scenario in terms of energy use and lowest cost investment options of fuels and propulsion systems for ships. The total energy use is expected to increase by about 11% over the time period 2020-2045, which is slightly less than in the BAU scenario. This can be explained by some ships choosing to invest in battery electric propulsion. Scenario 2 (low EUA) is found to result in increased investments in battery electric propulsion and biofuels, but LNG still has the highest share of the total energy use. The total energy use is expected to increase by about eight percent in this scenario over the time period 2020-2045, which is less than in the BAU scenario.

In scenario 3 (high EUA), the estimations indicate that, if the maritime transport sector is included in the EU ETS with a high EUA price, the resulting fuel costs would make biofuels, LNG, and electricity the lowest cost options for some shipowners, where biofuels would be choice of fuel type with highest total energy use. In paper II, the most common lowest cost option is found to still be conventional fuels in terms of the number of ships. However, those ships are found to have relatively low energy use per year compared to the ships having biofuels as their lowest cost option, which is why the total energy use of biofuels is higher than that for conventional fuels by the end of the model period. This indicates that the increased fuel costs for conventional fuels affect ships with relatively high energy use more than ships with relatively low energy use. The investments are estimated to happen gradually as the sector is included in the EU ETS. The scenario is indicated to lead to an increase of the total energy use by about four percent over the model time period.

Scenarios 4-5 also model a high EUA price, but scenario 4 (high EUA + subsidy) also models the infrastructure subsidy and scenario 5 (high EUA 400 GT) include ships from 400 GT and above. Scenarios 4 and 5 indicate a reduction of three percent and an increase of four percent, respectively. In paper II, the energy use reduction in scenario 4 (high EUA + subsidy) is found to be explained by an increase of the use of electricity by 61% (which corresponds to 81 more ships choosing battery electric propulsion) compared to scenario 3. In scenario 5 (high EUA 400GT), the use of conventional marine fuels is almost zero, and biofuels are dominating the fuel mix, which explains why the total energy use is the same as in scenario 3, although a higher transition to alternative fuels is found.

Since the SETS model can estimate the lowest cost option for each ship, it is possible to examine how the lowest cost options differ across different ship segments and ship types. Figure 6 shows the share of ships for each ship type (excluding public ships) that have chosen different fuels in the scenarios BAU and 3 (high EUA), in total over the time period 2020–2045. The figure does not include information about the volume of the fuel consumption, only the share of ships in each segment that have chosen different options during the model period. In the BAU scenario, Figure 6 shows that electric propulsion is chosen by between 2-24% of the ships in the segments fishing vessels, passenger ferries, ropax ships, service ships, and other ships. Within these segments, it is found in paper II that it is mainly smaller ships, under 5000 GT, that are expected to switch to electric propulsion. Figure 6 also shows that shipowners of all ship types choose to switch to LNG, where the share varies between 3–50%. Within the ship types bulk carriers, passenger ferries, service ships, tanker ships, and other ships, over 90% choose to continue using conventional fuels. In scenario 3 (high EUA), the main difference is that all ship types, except fishing vessels, other ships, and passenger ferries, have biofuels as their lowest cost option, where the share varies between 3-95%. The share of ships choosing electricity is only increased for the ropax ship type, which increases from 24% to 35%.

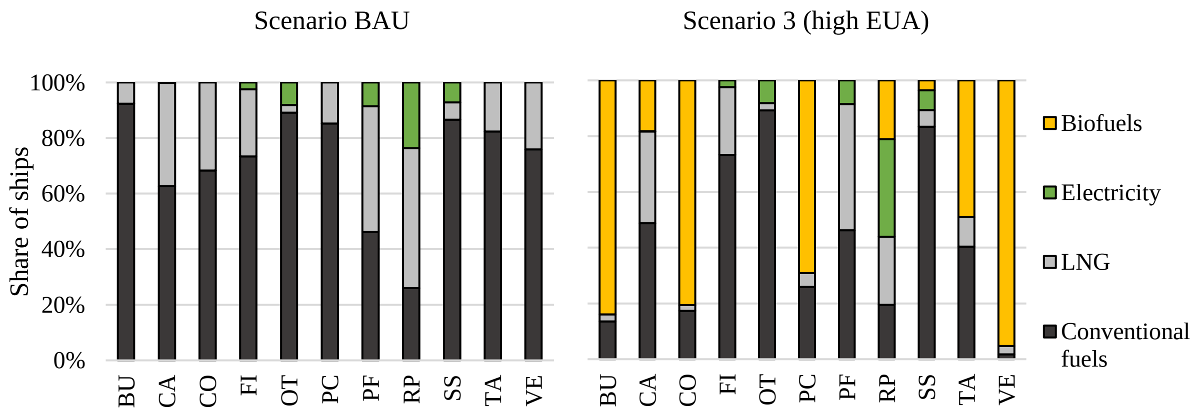

Figure 6. The total share of ships choosing different investment options for each ship type ship type (i.e., their lowest cost option) in the scenarios BAU (left) and 3 (right), excluding public ships. Source: copied from paper II.

BU: Bulk carrier, CA: Cargo ship, CO: Container ship, FI: Fishing vessel, OT: Other ships, PC: Passenger cruise, PF: Passenger ferry, RP: Ropax ship, SS: Service ships, TA: Tanker ship, VE: Vehicle carrier.

The estimated reductions of CO_2e emissions (TTW) for scenarios BAU and 1-5 are illustrated in Figure 7. Scenario 1 is found to have a similar development of CO_2e emissions as the BAU scenario, where the emissions are indicated to stay at almost the same level as in 2020. Hence, an implementation of the proposed ETD is indicated to only contribute marginally to the achievement of climate targets. Scenario 2 is indicated to reduce CO_2e emissions by about 15%. Scenarios 3, 4, and 5 are estimated to result in a reduction of 71%, 76%, and 85%, respectively, which can be explained by the high adoption of electricity and biofuels, which have emission factors that are equal to zero in the TTW perspective. In paper II, the CO_2e emissions are also estimated for the WTW perspective, where the main finding is that the estimated emissions in scenarios 3, 4, and 5, are found to be about twice as high by 2045 as in the TTW perspective. Even if biofuels and electricity are considered to have zero GHG emissions in the tank-to-wake phase, they are associated with some emissions from well-to-tank (see emission factors in Table 1 in Chapter 2).

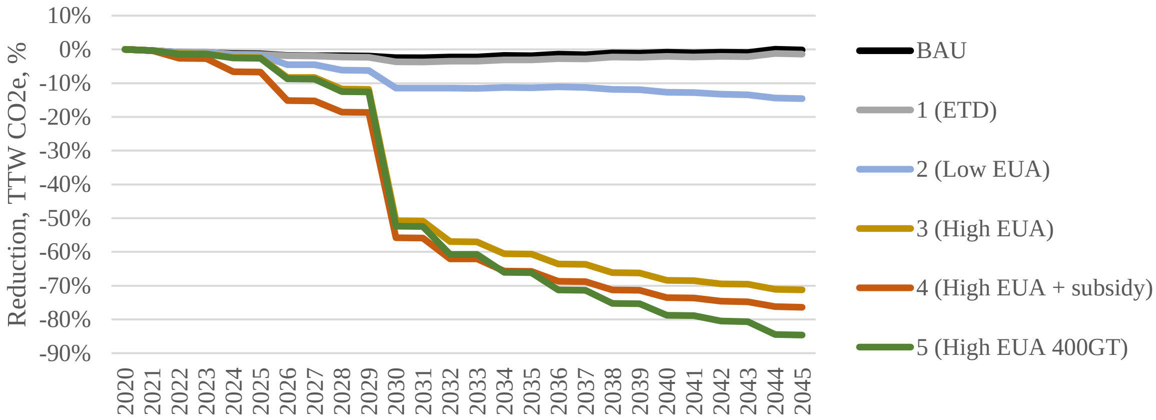

Figure 7. Estimated reductions of CO2e emissions (TTW) in scenarios BAU and 1-5. Source: copied from paper II.

4.2.2. Sensitivity analyses

Paper II also models six sensitivity analyses to investigate how other assumptions affect the model results. For example, the sensitivity analyses include different fuel costs, the inclusion of ships with 400 GT and above with low EUA, higher storage margin of ships, higher and lower discount rates, and an adjustment of the model area. Overall, the sensitivity analyses are in line with what can be expected, for which the results are summarised below.

Two of the sensitivity analyses assume different fuel costs compared to the main scenarios. Both of these scenarios use the same assumptions as in scenario 3 (high EUA) except for an assumption about a lower cost of electricity and a higher cost of biofuels and LNG. The scenario with lower electricity cost is in paper II found to result in lower use of biofuels and higher electricity use compared to scenario 3. The lower electricity cost also affects the fuel costs for e-methanol, which in the sensitivity scenario is found to account for almost 40% of the total energy use. The scenario with a higher cost of biofuels and LNG is found to result in electricity and e-methanol being the only alternative fuels, while biofuels and LNG are not the lowest cost option for any ships in this scenario.

Another sensitivity scenario also uses the same assumptions as in scenario 3 (high EUA) but assumes a larger size of the energy storage tank. A higher storage margin means that the storage tank or electric battery must be larger, which is relevant to model since many ships are traditionally storing fuel for weeks or even months. In comparison with scenario 3 (high EUA), the total energy use is found to increase by about five percent more over the time period 2020-2045, which can be explained by a higher share of shipowners choosing biofuels rather than electricity. Paper II finds that since the investment cost of batteries is relatively high, the total investment cost for battery electric propulsion becomes higher in this scenario, such that the lower energy use from the relatively more energy efficient propulsion system does not outweigh the investment cost.

The choice of discount rate can have a significant impact on the results, where a high discount rate generally implies that investments with costs arising far into the future will be relatively less expensive than investments that have costs arising closer in time. This reduces the present value of return on investment, and therefore more investment will be postponed (Kou & Luo, 2018). Sensitivity scenarios with lower and higher discount rates are therefore included in paper II. In the scenarios with lower discount rates, a higher share of shipowners chooses other fuels than conventional fuels, while in the scenarios with higher discount rates, a lower share of shipowners chooses other fuels than conventional fuels compared to the base case.

As mentioned in section 3.1, the ship route dataset only includes ship movements within the Shipair model area. This means that ships that have called Sweden, but which later travel outside of the model area have lower yearly estimated energy consumption than in reality. Hence, the benefits from switching to more energy efficient options, in terms of reduced energy consumption, are for those ships not included in the model and the investment costs in the propulsion system is unproportionally high in relation to the total costs when including fuel costs. Therefore, sensitivity scenarios model a situation where the investment cost for the propulsion system only includes the share of the total travel time within the model area. Paper II finds that more shipowners have conventional marine fuels as their lowest cost options in this sensitivity scenario, which can be explained by the more expensive investment costs of LNG compared to conventional fuels. In addition, options with high investment costs more often become the lowest cost option for ships with relatively high energy use.

CHAPTER 5

Discussion

This chapter presents a discussion of the results, scope, and limitations related to the research questions in this thesis. Section 5.1. discusses how policy evaluations of climate policy instruments can contribute to reliable conclusions about the performance of policy instruments, while section 5.2. discusses how the developed SETS model can be used to understand how proposed climate policy instruments affect shipowners' investment decisions in renewable fuels.

5.1. Evaluation criteria in policy evaluations

To better understand how different evaluation criteria are approached in evaluations and to assess how the fulfilment of different criteria can be improved in future evaluations, paper I reviews certain criteria and evaluation approaches in more detail, which is summarised below.

Previous studies (Bovens et al., 2008; Mastenbroek et al., 2016; Schoenefeld & Jordan, 2017) have found that there is a risk of selective or biased policy evaluations due to political pressures because policy evaluations may uncover problems of the evaluated policy instrument which may call for legislative repeal. If the evaluator has a governmental connection or if governmental actors commission organisations to conduct evaluations, this risk can be increased (Bovens et al., 2008; Mastenbroek et al., 2016; Schoenefeld & Jordan, 2017). Paper I finds almost no difference between white and grey literature in terms of the results regarding the policy instruments' successfulness, which could indicate that there is no difference in judgements made of policy instruments' successfulness between white and grey literature. However, depending on the interpretation of what a successful policy instrument is, evaluations that are classified as having mixed results about the effectiveness could in many cases instead be classified as not successful. For example, two studies commissioned by the EC are classified as mixed results and argue that the stringency of the policy instruments should increase. Hence, this is in a way equivalent to the policy instrument not being successful in terms of reaching the targets in its current design.

Another risk for selective or biased policy evaluations includes a situation referred to as a confirmation bias, which Schoenefeld and Jordan (2017) argue is a risk in internal evaluations, where only the evidence that supports the policy instrument is presented. There is an example of an evaluation in paper I where the evaluators are affiliated with the same agency that launched the evaluated policy instrument. Although this may involve benefits such as the authors having an inside knowledge of how the policy works, some of the study's analyses raise the question of the risk for a lack of independence and less critical evaluations (Schoenefeld & Jordan, 2017). For example, the study only presents barriers for reducing GHG emissions that are addressed by the evaluated policy instrument, while not mentioning other barriers not addressed by the policy instrument. Furthermore, although the evaluation concludes that the evaluated policy instrument is effective, it states that observed changes cannot be quantified and only provides analyses for certain parts, while not discussing others.

Although these findings cannot be generalised due to the low number of included evaluations in paper I, they are in line with findings of earlier studies. Few of the included evaluations state the motivation or purpose of the evaluation, discuss the extent to which established political targets are appropriate, or whether there are any competing interests involved, which is a finding in line with Turnpenny et al. (2009), who found that few evaluations address or question underlying political motivations or the framing of the evaluations.

The risk for selective or biased policy evaluations is increased if evaluations' analyses of the quality criteria are lacking due to a risk for reduced replicability and verification of evidence. Therefore, the analyses related to the complexity criterion, which addresses whether the evaluation uses a method that allows for an analysis of causality and side effects of the policy instruments, is in paper I compared between three studies. The three studies all conclude that their evaluated policy instruments have been successful, yet the evidence supporting their conclusions differ. For example, one evaluation of how a voluntary policy model contributes to fuel efficiency and reduced environmental impacts from freight transport is classified as not having analysed the complexity criterion. The study reviews literature and provides statistics of CO_2 emission reductions. However, side effects and causality are not analysed, although there are relevant aspects to discuss, such as changes in freight transport supply, rebound effects, or modal shifts. Another study, which assesses the environmental efficiency of the Swedish carbon tax on transport fuels, is instead classified as analysing the complexity criterion at a high detail. To estimate the effects of the carbon tax, the study uses an approach that allows for an analysis of the counterfactual of not implementing the policy instrument and it also discusses alternative explanations and side effects, such as risks for carbon leakage. Conclusions about a policy instrument being successful without consideration of side effects or causality may lead to overestimated or underestimated effects and misleading recommendations for policy makers. Hence, the lack of analyses of causality and side effects in the first study weakens the relatively strong conclusion of the policy instrument being effective.

An example of a difficulty in comparing the results of evaluations is when evaluations come to different conclusions. For example, in paper I, there are two policy evaluations of the Swedish carbon tax, where one finds that the tax is an effective and efficient policy instrument (Andersson, 2019) and the other finds no significant effect and concludes that policy makers should not rely entirely on taxation to achieve environmental targets (Shmelev & Speck, 2018). However, the two policy evaluations have, in paper I, been classified at different levels on the assessment scale. For example, Andersson (2019) has been classified as having higher detail on both robust methodology and complexity because the study describes the method in detail, discusses methodological weaknesses, compares results with earlier studies, and includes a causality analysis as well as an identification of potential side effects. In contrast, Shmelev and Speck (2018) have been classified as the lowest level of detail on the evaluation criteria robust methodology and complexity because they include almost no description of the method, do not discuss potential weaknesses, and do not include any complexity analysis. Hence, based on this information, the findings by Andersson (2019) seem more reliable compared to those by Shmelev and Speck (2018) since the method is explained in more detail, is possible to replicate, and includes an analysis of whether the observed effects can be linked to the policy instrument. This type of finding highlights the importance of comparability between evaluations to ensure evidence-based decision making. It also points to how the criteria can be used to determine how to interpret contradicting results on the same policy.

5.2. Scenario modelling in the SETS model

The main contribution of the developed SETS model is that it can take into account data for individual ships and their operational pattern when estimating the impact of potential policy instruments. Although there are previous maritime modelling studies that analyse effects from potential policy instruments (Gu et al., 2019; Wang et al., 2015; Zhu et al., 2018), they have more limited data and often focus on specific examples of ship types or specific sectors. Paper II finds that the lowest cost option differs across different ship types and ship segments, which highlights the importance of considering ship specific factors when analysing the impact of different policy instruments for maritime transport. This finding is also in line with Wang et al. (2015), who find that an ETS will affect different sectors to different degrees.

The scenario analyses in paper II give a relatively large variation in which fuel types that are the lowest cost option for shipowners in the model. For example, in the scenarios with low price signals to reduce GHG emissions (e.g., in scenarios BAU, 1 (ETD), and 2 (low EUA)), conventional fuels and LNG are found to be the most common lowest cost options for shipowners. When a higher price signal is modelled (e.g., in scenarios 3 (high EUA), 4 (high EUA + subsidy), and 5 (high EUA 400 GT)), a significant transition towards biofuels and electricity is estimated. Other fuel types included as potential options for shipowners in the model, such as hydrogen, LBG, e-methanol, and e-methane, are not found to be the lowest cost option in almost any of the estimated scenarios.

There is a risk that a significant part of the CO_2 emissions will be missed by only including ships with a minimum GT of 5000. To affect these emissions and to prevent a transition towards smaller (and often less energy efficient ships), Vierth et al. (2022) recommend that ships with a lower GT should be included in the long term. The scenario analyses in paper II model the effects from an implementation of the EU ETS for ships above 400 GT, rather than the proposed level of ships above 5000 GT, and find that this could decrease CO_2e emissions (TTW) by 8-14% more compared to the scenarios with allowance prices affecting ships of 5000 GT and above. Furthermore, this would likely improve the potential cost-effectiveness of the policy instrument since the private marginal cost of reducing emissions (i.e., the cost of reducing emissions with an extra unit, e.g., an extra kilo of greenhouse gases) would be the same for all actors. That way, the responsibility is distributed such that actors who can reduce their emissions relatively easily and cheaply reduce their emissions more than actors who find it relatively difficult and expensive to reduce their emissions (Söderholm & Hammar, 2005).

The SETS model results are generally in line with findings of previous studies. Zhu et al. (2018) find that a maritime ETS can motivate ship operators to utilise new technologies and to deploy more energy efficient ships. In addition, Gu et al. (2019) conclude that an ETS with a low price signal will not lead to significant emissions reductions in the short term, but that a more significant CO_2 emission reduction can be expected in the case of low bunker prices and high allowance prices. Moreover, Solakivi et al. (2022) find that blending of biofuels will be the main short-term solution, and that e-fuels will be cost-competitive first beyond 2050, which is in line with the SETS model results for most scenarios.

The SETS model is based on the assumption that shipowners will choose the lowest cost investment option. However, there are some costs that have not been included in the model due to data unavailability, which, if included, could have an effect on the model results. For example, only the costs for the propulsion system are included, and hull costs are not considered. In reality, when a ship reaches its end of lifetime, shipowners can be expected to consider either a retrofit of the propulsion system or investing in a newbuilt ship. A newbuilt ship can be expected to have a more energy efficient hull design and include other technical improvements which can reduce energy consumption per tonne-kilometre. Additionally, newbuilt ships have a trend of becoming larger, which with a higher capacity to transport goods and passengers may have an effect on the potential revenues.

Shipowners' choice of propulsion system and fuel type is also affected by other factors, which can influence the results of the model. For example, expectations about future fuel supply and availability of bunker/charging infrastructure, as well as size requirements of different propulsion systems can have a significant influence on shipowners' choices. One of the sensitivity analyses in paper II models a requirement of a larger energy storage tank, together with the assumptions used in scenario 3 (high EUA). In that scenario, fewer shipowners choose electric propulsion and instead choose biofuels as alternative fuels, which can be explained by the relatively high investment costs for batteries compared to those for biofuels. The assumption of a relatively small storage tank capacity in the main scenarios is made because when transitioning to energy carriers with lower energy density, such as hydrogen and batteries, this will likely have to change in the future to be able to fit the energy onboard the ship. Another limitation that could affect the model results is the choice of included fuel types in the model. In paper II, it is assumed, for simplicity, that conventional marine fuels are used by all ships in the base year (except for public maritime actors). However, HFO with scrubber, which currently is the cheapest investment option for many shipowners (Andersson et al., 2020), is not included. Since HFO generally is cheaper than MGO, its exclusion from the model might have an effect on the model results. If the conventional fuels were cheaper (as is the case for HFO), policy instruments, such as the ETD and the EUA price, may have to be even higher than the assumptions in the model for alternative fuels to be cost competitive and for a transition to occur based on shipowners' lowest cost options.

In the long term, there are also other uncertainties for shipowners to take into account when making investment decisions, such as uncertainties about which infrastructure and fuels that will be easily available. The sensitivity analyses with high (low) discount rates, which could represent investments as being (less) risky for shipowners, indicate that a lower (higher) share of shipowners choose other fuels than conventional fuels compared to the base cases. Without the long-term policy price signal, shipping companies may rather choose to slow down their ships (slow steaming) in order to reduce fuel consumption than make substantial investments (Gu et al., 2019).

Chapter 6

Conclusions and recommendations

This chapter summarises the concluding remarks and recommendations from the two papers in relation to the overall aim of this thesis.

The overall aim of this thesis was to improve the knowledge about how policy instruments can contribute to effective and efficient reductions of GHG emissions in the freight and maritime transport sectors. The two papers in this thesis have contributed to an improved understanding of the research questions within this thesis. Paper I contributes with knowledge about evaluations of implemented climate policy instruments in the freight transport sector, while paper II contributes with a developed scenario modelling tool and an improved understanding of the potential effects from proposed policy instruments on the maritime transport sector. Hence, the overarching aim of this thesis has been analysed both from an ex-post and an ex-ante point of view.

Research question 1 is analysed in paper I by carrying out a meta-evaluation of policy evaluations with the aim to understand how already implemented policy instruments perform and whether they contribute to climate targets in an efficient and effective way. It is concluded that few policy evaluations evaluate the effects on GHG emissions of climate policy instruments in the freight transport sector. Instead, many evaluations analyse effects on other environmental issues, such as air pollution, or the policy instruments' implementation, compliance, or enforcement. This is of high concern given the ambitious political goals with respect to cutting GHG emissions and the numerous climate policy instruments that, at least partly, are designed to address emission reductions.

There is insufficient transparency of methodological choice and data sources among the included policy evaluations, as well as insufficient analyses of the policy instruments' performance. Therefore, many evaluations are not suitable to inform evidence-based decision making or for comparing the performance of different policy instruments. It is recommended that an evaluation obligation of policy instruments should be considered, which could provide more systematic monitoring and evaluation of implemented policy instruments that could help ensure that climate targets are reached efficiently. Moreover, evaluation guidelines for evaluators should be improved to enable more consistency and comparability across evaluation studies. For example, methodological recommendations are currently missing in the guidelines by the OECD (2021) and partly missing in the guidelines by the EC (2017a; 2017b)**.** To be able to compare climate policy instruments in the transport sector and understand whether they contribute to achieving targets to the lowest cost for society, all evaluations must at least include an assessment of their effectiveness and efficiency. Additionally, analyses of the policy instruments' side effects and the causality between the implementation and the effects should be analysed to ensure that the estimated effects of policy instruments are not overestimated or underestimated. Finally, guidelines of policy evaluations should consider including recommendations of well-motivated choice of methodology, comparisons with related studies, and discussions of potential weaknesses.

Research question 2 is analysed in paper II by developing a scenario modelling tool, referred to as the SETS model, that can be used to analyse the effects of proposed policy instruments on shipowners' investment decisions over the time period 2020-2045. The main contribution with the developed model, in comparison with previous modelling studies, is that it can take into account data for individual ships and their operational patterns when estimating the impact of potential policy instruments.

Investment choices are found to vary between ship segments (and individual ships) as well as between different scenarios, which emphasises the need for considering ship specific data when analysing the effects of policy instruments. Furthermore, the scenario analyses indicate that policy instruments have the potential to affect shipowners' investment choices, but that relatively strong policy instruments are required for significant effects to arise. In scenarios with lower price signals, only relatively small CO_2e emission reductions can be seen, whereas in scenarios with higher price signals, more significant CO_2e emission reductions can be expected.

The proposed inclusion of maritime transport in the EU ETS is planned to cover ships above 5000 GT. However, since smaller ships would not be affected, a significant part of the GHG emissions from maritime transport would be missed. The scenario analyses indicate that an implementation of the EU ETS for ships above 400 GT, rather than the proposed level of ships above 5000 GT, could decrease CO_2e emissions (TTW) by 8-14% more. In addition, a coverage for ships of 400 GT and above could help prevent the risk of a transition to smaller (and often less energy efficient) ships, and to increase the cost-effectiveness of the policy instrument.

The findings from the two papers included in this thesis indicate that reducing GHG emissions from the freight transport sector involves many difficulties. For example, the freight transport sector is often referred to as a hard-to-abate sector and GHG emissions are forecasted to increase. In addition, the first study (paper I) concludes that there are too few systematic climate policy evaluations in the freight transport sector to be able to compare results, draw reliable conclusions and support evidence-based policy making. Such information would be useful for policy makers to be able to design new policy instruments as well as improve and adjust already implemented ones. The second study (paper II) highlights that shipowners' investments in renewable fuels and propulsion systems are complex and that the choices likely will be different for different ship segments, which would require a diversity of available infrastructure and fuel types in ports. Hence, several questions remain to achieve GHG emission reductions in the freight transport sector in line with climate targets in a cost-effective and efficient way. Relevant areas for future research are to better understand how climate policy evaluations can become more systematic and of higher quality. This may, for example, include investigating barriers and conditions for the evaluability of climate policy instruments, the connection between ex-ante and ex-post evaluations, and which evaluation methods that are suitable for evaluating different types of policy instruments. Additionally, the SETS model should be developed further to, for example, take into account other factors that can have an impact on shipowners’ choice of propulsion system and fuel type, analyse other emissions than greenhouse gases, and to complement the model with a cost-benefit analysis to better understand potential welfare effects in society from proposed policy instruments.

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