THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Reducing greenhouse gas emissions – Examples from the freight transport sector

Essays on economic growth, public policy instruments, and renewable energy

S. JOHANNA TAKMAN

Department of Architecture and Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2021

Reducing greenhouse gas emissions – Examples from the freight transport sector
Essays on economic growth, public policy instruments, and renewable energy
S. Johanna Takman

Technical report: 2021:7
Lic / Architecture and Civil Engineering / Chalmers University of Technology

Department of Architecture and Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Chalmers Reproservice
Gothenburg, Sweden 2021

Reducing greenhouse gas emissions – Examples from the freight transport sector
Essays on economic growth, public policy instruments, and renewable energy
S. Johanna Takman
Department of Architecture and Engineering
Chalmers University of Technology

ABSTRACT

The overall aim of this thesis is to improve the understanding of if, and how, we can combat climate change and other non-wanted environmental changes alongside economic development and improved quality of life. Paper I address this question by investigating the relationship between CO_2 emissions and GDP per capita. Using panel data analysis, an N-shaped relationship is found for lower-middle- and high-income countries, indicating that CO_2-emissions increase with economic growth beyond a certain income level. However, no significant relationship is found for upper-middle-income countries. The study also shows that increasing the share of renewable energy is crucial for reducing CO_2-emissions.

Paper III investigate the performance of European public policy instruments promoting a modal shift of freight transports from road to rail and/or water. Performing a literature review, 93 public policies are identified, whereof ex-post evaluations are found for 20. The evaluated policies are mainly subsidies/grants at national level, or EU-policies. Variation in evaluation methods and performance indicators complicates comparisons of policy performance. However, policies promoting rail are in general more successful than those promoting waterborne transport. Common factors for underachievement include lack of applications, outreach problems, and complicated application processes. Furthermore, broad and general policy targets complicate evaluation as well as fulfilment of objectives.

Paper II analyse barriers, opportunities, and potential solutions to renewable energy diffusion, focusing on liquefied biogas for heavy trucks. Interviews with experts and stakeholders in Sweden show that main barriers include financial limits, lacking infrastructure, lacking knowledge, and unstable policy instruments. Yet, several policy instruments already target the barriers to LBG diffusion and given current taxes and subsidies, costs of using LBG trucks are only marginally higher than those for using diesel trucks in Sweden. Thus, continuously evaluating policy performance is important.

Keywords: Evaluation; Climate change mitigation; Greenhouse gas emissions; Economic development; Environmental Kuznets curve; Freight transport; Modal shift; Public policy instruments; Renewable energy; Liquefied biogas

List of papers

This thesis includes the following papers, referred to by Roman numerals:

I. Allard, A., Takman, J., Uddin, G.S., Ahmed, A. 2018. The N-shaped environmental Kuznets curve: An empirical evaluation using a panel quantile regression approach. *Environmental Science and Pollution Research* **25,** 5848–5861. https://doi.org/10.1007/s11356-017-0907-0

II. Takman, J., Andersson-Sköld, Y. 2021. A framework for barriers, opportunities, and potential solutions for renewable energy diffusion: Exemplified by liquefied biogas for heavy trucks. *Transport Policy* **110**, 150-160. https://doi.org/10.1016/j.tranpol.2021.05.021

III. Takman, J., Gonzalez-Aregall M. 2021. A review of policy instruments to promote freight modal shift in Europe: Evidence from evaluations. *VTI Working Paper* 2021:6.

Contribution statement:

In paper I, Allard, A and Takman, J. are the main authors of the paper, referred to in alphabetical order. Takman, J. contributed with Conceptualisation, Methodology, Formal analysis, Writing – Original Draft, Writing – Review and Editing, & Visualization.

In paper II, Takman, J. is the main author of the paper and contributed with Conceptualisation, Methodology, Investigation, Writing – Original Draft, Writing – Review and Editing, & Visualization.

In Paper III, Takman, J. is the main author of the paper and contributed with Conceptualisation, Methodology, Investigation, Writing – Original Draft, Writing – Review and Editing, & Visualization.

Other work and publications not appended:

The author has contributed significantly to the following publications and presentations, which are not appended to the thesis:

- 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.
- Takman, J., Trosvik, L., Vierth, I., 2020. *Triple F etableringsprojekt – Omvärldsanalys Policy.* Triple F leverans 2020.2.13.
- Takman, J., Trosvik, L., Vierth, I., Klintbom, P., Huffmeier, J., 2019. *Triple F Systemövergripande uppföljning 2019 – Uppföljning av hur godstransporter närmar sig det svenska klimatmålet 2030 Delrapport.* Triple F leverans 2019.1.16.

- Takman, J., 2020. *Fossil Free Freight (Triple F) – Uppnås klimatmålet för godstransporter?* (abstract). Oral presentation at the 2020 Transportforum Conference, Linköping, January 8-9.
- Takman, J., 2019. *A taxonomy of modal shift policy in Europe* (abstract). Oral presentation at the 2019 European Transport Conference, Dublin, October 9-11.
- Takman, J., 2019. *A taxonomy of modal shift policy in Europe* (abstract). Oral presentation at the 2019 International Transportation Economics Association Conference, Paris, June 12-14.

Acknowledgements

There are several people who have made this licentiate thesis possible and to whom I would like to express my sincerest gratitude.

Firstly, I would like to give my warmest thanks to my supervisors. To my main supervisor Yvonne Andersson-Sköld, for encouraging me when I need it the most and for all insightful discussions and inputs that has helped shape this thesis. To Inge Vierth for your guidance, support and for sharing your knowledge and expertise within the research field. Last but not least, thank you Mattias Haraldsson for encouraging me to start this PhD and for arranging my doctorship together with Yvonne.

I am also grateful for the opportunity to study as an industrial PhD student at Chalmers University of Technology at the department for Architecture and Civil Engineering. A special thanks to Lars Rosén for welcoming me to the research group of Engineering Geology and for your guidance.

During the writing of this thesis, there are a few people who I have worked closely together with. My co-authors Alexandra, Gazi, Ali, Yvonne, and Marta, thank you for your contributions to the papers, your valuable insights, and all discussions we have had. I would also like to thank Lina, Kristina, Lisa, Elisabeth, Axel, Cecilia, and Stefan from whom I have learned a lot during collaborations in different projects. I have enjoyed working with you all.

At VTI I am fortunate to have plenty of wonderful colleagues who I want to thank as they contribute to a great working environment with lots of laughter and interesting discussions during lunch and coffee breaks. A special thanks to Noor, Lisa, Ajsuna and Nina for all the lunch walks in the forest.

My warmest thanks to my family and friends who have supported me throughout the process of writing this thesis. All the moments I share with you outside of work makes all the difference. Thank you, Mom and Dad, for always being there for me and always being supportive no matter what. Susana, thank you for all the mornings at the gym, which gets me ready for the upcoming workday. Your friendship means a lot to me. A special thanks to my cousins in Gothenburg who have invited me to stay with them during my trips to Chalmers. You have made my trips a lot of fun and your hospitality has been very cherished.

Finally, to Marcus. Without you, I would never have reached this far. Working from home during the pandemic would have been much tougher without your company. Thank you for your love, encouragement, and patience. You have been my number one motivation and greatest support during this process. Love you!

Stockholm, September 2021

Johanna

TABLE OF CONTENTS

1. INTRODUCTION

At the overarching level, the papers in this thesis all attempts to contribute with knowledge regarding if, and how, we can mitigate climate change along with economic development[1] (improved standard of living and quality of life for the individuals in a community). Paper I address this question from a wider perspective by investigating the relationship between GDP per capita and CO_2-emissions in 74 middle- and high-income countries. Paper II and III focus on how to reduce greenhouse gas (GHG) emissions and other negative externalities[2] from the freight transport sector. More specifically, Paper III investigate the effectiveness and efficiency of European public policy instruments targeting a modal shift of freight from road to rail and/or waterborne transports. Paper II analyse barriers, opportunities, and potential solutions for switching to renewable energy sources, by investigating the case of liquefied biogas (LBG) for heavy trucks in Sweden. Thus, the overall question of mitigating climate change alongside economic development is addressed from a wider perspective, as well as from specific case studies. In the following chapters, I will attempt to put these papers in a context and convince the reader of why the research theme is important.

1.1. Background

1.1.1. Climate change and economic growth

Global warming is considered one of the most serious problems that the world is facing today (Zhu et al., 2016). Negative consequences caused by climate change and environmental degradation has already begun to affect humanity in the form of extreme weather events such as floods, droughts, heatwaves, and tropical cyclones (IPCC, 2021). These weather and climate extremes in their turn result in devastating consequences for society that will only become more severe along with increased GHG emissions, such as damage to eco systems, negative health impacts, negative economic impacts, and reduced living standards. Simultaneously, human influence is very likely the main driving force behind climate change and environmental degradation (IPCC, 2021).

The urgency of combating climate change has resulted in agreements, goals, and public policy instruments at the global, national, and local levels. In December 2015, the Paris Agreement was adopted at COP21 with a target of limiting global warming to well below 2, but preferably below 1.5, degrees Celsius. Furthermore, 17 sustainable development goals were set up by the UN in 2015, addressing diverse issues such as ending poverty and hunger, good health and wellbeing, affordable and clean energy, decent work and economic growth, responsible consumption, as well as climate action (United Nations, 2020). Reaching all the sustainability goals is not simple, as some of them may adversely affect each other. While some of the targets

---

[1] In this thesis, the term economic development is used to describe the standard of living and quality of life for the individuals in a community (Greenwood and Holt, 2014). Instead, the term economic growth refers to market productivity and measures such as GDP per capita. While economic growth can be an important component of economic development, an increased GDP per capita do not necessarily equal to increased standard of living for the individuals in a community if for example inequality and crime rise.

[2] See section 2.2.1 for an explanation of the term externalities.

positively influence each other, the targets addressing for example climate change and renewable energy have been found to be less consistent with the other sustainable development goals (Weitz et al., 2018). For example, as lifestyles improve, the demand for energy tend to increase (Dincer, 2000). In order to develop and apply policy instruments, as we work towards mitigating climate change while simultaneously improving living standards and quality of life for the individuals in our society, it is important to improve the understanding of the complex relationship between climate change and the economic activities that we engage in.

In the environmental economics literature, the hypothesis of an inverted u-shaped relationship between economic growth and environmental degradation is well known as the environmental Kuznets curve (EKC). The original EKC hypothesis suggests that environmental degradation initially rises with an increased per capita income. However, as per capita income continues to grow, demand for environmental quality rises, which results in decreased environmental deterioration (Hussen, 2005). The EKC hypothesis has been investigated by multiple researchers and has both been confirmed and rejected in previous literature. However, it has been argued that the original EKC will not hold in the long run, and studies have observed that the relationship instead might be N-shaped, suggesting that environmental degradation will once again start to rise as per capita income continue to grow (Lorente and Álvarez-Herranz, 2016; Poudel et al., 2009). Literature regarding this possibly N-shaped relationship is scarce. Even though it has been empirically documented in previous studies, few researchers have investigated why the relationship would be N-shaped. Thus, further research is necessary to improve the understanding of the pollution-income relationship. This N-shaped relationship is investigated in Paper I of this thesis.

1.1.2. Climate and freight transports

The freight transport sector contributes to economic development in several ways (North, 1958). It is one of the major economic contributors and it provides people and businesses with important support by moving commodities to locations where they are needed. Nevertheless, freight transports also come with several negative externalities such as GHG emissions, road congestion, air emissions, noise pollution, and accidents (Ambra et al., 2019; Lin, 2019; Nocera et al., 2018). Today, the transport sector accounts for approximately 16.2 % of the global GHG emissions (Ritchie and Roser, 2020) and is one of the major sectors where GHG emissions are still increasing (Zhang and Fujimori, 2020). Road transports represent the largest share of the emissions, where freight transports constitute about 40% (Ritchie and Roser, 2020). The current growth of freight transportation, stemming from among other things the development of trade, has enlarged volumes of freight tonnage and intensified freight's negative externalities (Ambra et al., 2019; Lin, 2019; Nocera et al., 2018). Over the coming decades, freight transport is expected to continue rising, increasing the importance of finding sustainable freight transport solutions (IPCC, 2014).

Several different challenges need to be tackled to decrease the freight transport sectors GHG emissions and negative externalities. The Swedish research program Triple F (Fossil Free Freight) classifies the challenges into three main categories (Triple F, 2020):

1. A transition to energy efficient and fossil-free vehicles and ships.

2. An increased share of renewable energy.
3. A society with more efficient transport.

The first challenge, a transition to energy efficient and fossil-free vehicles and ships, includes both a modal shift to more energy efficient transport modes as well as a shift towards more energy efficient vehicles within a specific transport mode. For example, a modal shift from road to rail and/or waterborne transport could help reduce negative externalities from freight transports (Bickford et al., 2014; Nealer et al., 2012) as these transport modes generally consumes less energy per ton and emits fewer GHG emissions than road transports (Breathen, 2011). The second challenge, an increased share of renewable energy, includes the replacement of fossil energy with renewable energy in the freight transport sector, for example by using renewable fuels or by electrifying the vehicles. This is important for all transport modes. Finally, the third challenge, a society with more efficient transport, includes for example improved logistics such as coordination and consolidation of transports or improved routes. In this thesis, the focus lies on the first challenge (Paper III) and the second challenge (Paper II).

To address the above-mentioned challenges, public policy instruments play an important role (IPCC, 2014). Several public actors at the global, national, and local levels have already set up targets and adopted policy instruments with the purpose of reducing GHG emissions and other negative externalities from freight (Pinchasik et al., 2020). Yet, the transition towards a more sustainable freight transport sector is progressing slowly. For example, when it comes to achieving a modal shift from road to rail and inland waterways transport, no modal shift has been achieved at the aggregate level in the European Union (Eurostat, 2020), despite several policy instruments and efforts. Furthermore, several European countries are far from meeting their modal shift objectives (Pinchasik et al., 2020). This indicates that the current policy landscape has not yet been very successful in achieving the desired modal shift. It is therefore important to evaluate the performance of past and present public policy instruments to identify, develop, and apply effective and efficient policy instruments that can contribute to a modal shift and reduced GHG emissions. Paper III address this problem by investigating the evaluated effectiveness and efficiency of European public policy instruments in terms of achieving modal shift and reducing negative externalities.

There are currently several barriers which slows down the transition towards more sustainable freight transports. For example, a modal shift of freight transports and a switch to renewable energy may result in higher costs for both the supply and demand side actors of transport services. Other factors such as a lack of infrastructure (eg. railways, ports, or fuel infrastructure) might also complicate the transition to more energy efficient transports or renewable energy. Identifying these challenges, but also identifying opportunities, is of great importance to find solutions and to develop policy instruments that can speed up the transition towards more sustainable freight transports. Paper II, address this question by performing interviews, estimating cost examples, and applying a framework to identify and classify barriers, opportunities, and potential solutions for renewable energy diffusion, specifically focusing on the case of liquefied biogas (LBG) for heavy trucks in Sweden.

1.2. Aim and objectives

The overall aim of this thesis is to improve the understanding of if, and how, we can combat climate change alongside economic development (improved standard of living and quality of life for the individuals in a community). To contribute to the overarching research question, three more specific research questions (RQ:s) are addressed within the thesis, as expressed below.

- **RQ1** (Paper I): How can the relationship between economic growth and GHG emissions be described?
- **RQ2** (Paper III): How does European public policy instruments contribute to the modal shift of freight from road to rail and waterborne transports?
- **RQ3** (Paper II): What are the barriers, opportunities, and potential solutions to the diffusion of renewable energy in general, and liquefied biogas for heavy trucks in particular?

1.3. Thesis outline

The remainder of this thesis is structured as follows: The second chapter presents a theoretical background and central concepts explored in this thesis. Primarily, theories and central concepts regarding climate change and economic growth are presented. Furthermore, the role of public policy in mitigating climate change is discussed, as well as central concepts regarding technology diffusion. The third chapter present and discuss data and methodologies applied for answering the research questions. Chapter four presents and discuss the results and the contribution to the research field. Chapter five concludes.

2. THEORETICAL FRAMEWORK

In this chapter, I discuss some concepts and theories related to the research performed within this thesis. These theories and concepts have been essential in both formulating research questions, as well as in the attempts to answer them. First, I discuss central theories related to climate change and economic growth. Thereafter, I discuss concepts and theories related to public policy instruments and renewable energy diffusion.

2.1. Climate change and economic growth

Scarcity is the very central factor of economics. It forces trade-offs that require us to make choices and prioritize. Yet, climate and environmental sustainability has only recently become a relevant topic in economic theories (Alvarez and Lorente, 2015; Hussen, 2005). Historically, other economic concerns have been given priority in policy instruments, while climate and the environment has been treated as something separate from human activity (Giddings et al., 2002). Yet, as climate and the environment are interconnected with the economy, a change in one can have significant effects on the other (Giddings et al., 2002).

One of the most discussed theories within the field of environmental economics is the environmental Kuznets curve (EKC). The EKC was first proposed by Grossman and Krueger (1991) and suggests that environmental degradation and pollution is an inverted U-shaped function of economic growth. According to the EKC, economic growth is prioritized over the environment during the early stages of industrialization, leading to increased material output and increased pollution. However, during the later stages of industrialization, increased income is expected to lead to an increased demand for environmental quality. This results in decreased pollution levels due to more effective environmental regulations and a willingness to pay for a cleaner environment (Kijima et al., 2010). This inverted U-shaped relationship between environmental degradation and economic development is illustrated in Figure 1.

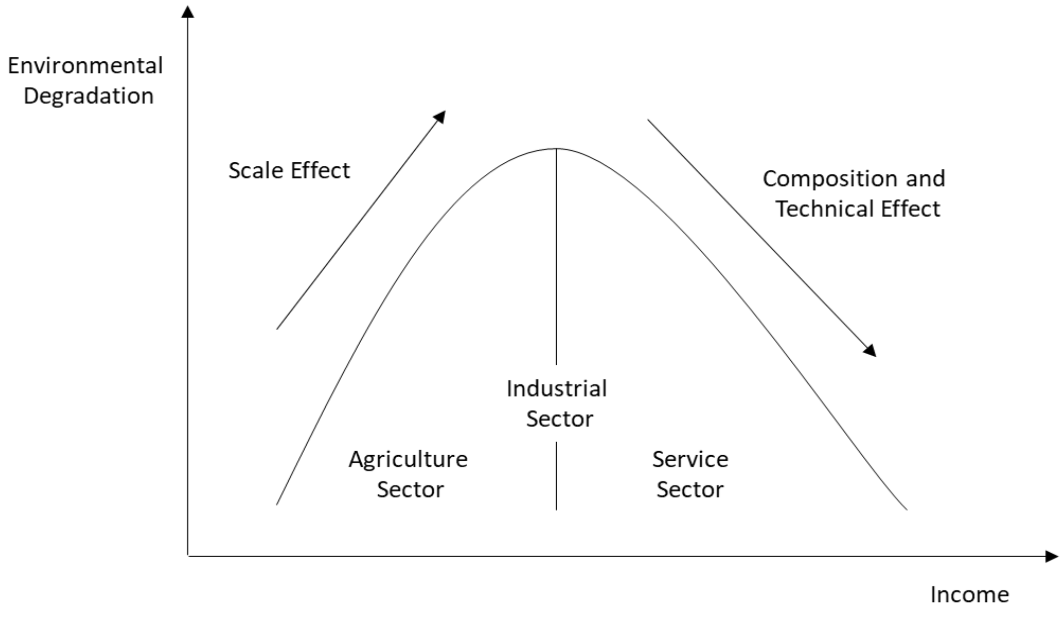

Figure 1 - Environmental degradation as a function of income - The inverted U-shaped EKC.

According to Grossman and Krueger (1991), economic growth affects the environment through three mechanisms: scale effect, composition effect, and technical effect. Given that the nature of an activity is unchanged, an increased demand for the activity (e.g. due to increased income) will lead to increased pollution in accordance with the *scale effect* (Grossman and Krueger, 1991). As the economic structure of a country goes from polluting industries towards specialization in the service sector, environmental degradation will decrease through the *composition effect*. However, during the primary stages of economic growth, pollution will likely increase as the economic structure change from agriculture to industrial production (Balsalobre et al., 2015). Finally, with increased income comes increased possibilities to invest in environmental research, development, and demonstration, which encourage the development of cleaner technologies (Balsalobre et al., 2015). Thus, the *technical effect* will lead to decreased environmental degradation due to productivity improvements and adoption of cleaner technologies.

The pollution haven hypothesis (PHH) could be another possible explanation for the downward slope of the EKC (Kaika and Zervas, 2013). The PHH suggest that as environmental degradation increases along with economic growth, more stringent environmental regulations will be applied and the cost of meeting these environmental regulations rise (Cole, 2004). This might lead to trade patterns where the developed countries specialize in cleaner production and/or services, while outsourcing the pollution intensive production to developing countries with less strict regulations (Arrow et al., 1995; Cole, 2004; Kaika and Zervas, 2013; Stern, 2004).

Several studies have empirically documented an N-shaped EKC, suggesting that the original EKC hypothesis will not hold in the long run. Instead, the N-shaped EKC suggests that environmental degradation will once again start to rise along with economic growth beyond a certain income level (de Bruyn et al., 1998). Potential explanations for the N-shaped relationship could be that decreased possibilities to further improve distribution of industries result in the scale effect overcoming the composition effect, or that diminishing returns on technological changes decrease the technical effect (Balsalobre et al., 2015; Lorente and Álvarez-Herranz, 2016; Torras and Boyce, 1998). In paper I, this N-shaped EKC is further investigated.

2.2. Public intervention

Public policy instruments are political tools employed to correct for *market failures* and to reach one or several societal objectives, such as reducing GHG emissions. By implementing policy instruments, public authorities (eg. national or local governments) can steer private or public actors towards certain actions or measures that are in line with the societal goals. Below, some central concepts related to public policy instruments are discussed.

2.2.1. Market failures

Market failures refer to situations where the optimal use of the society's resources is not achieved through market mechanisms. There exist several different examples of market failures, which are briefly discussed below.

Externalities are often described as nonmonetary effects that are not taken into account in the decision-making process (Baumol and Oates, 1988). The externalities are either costs or benefits which comes from an economic transaction and accrues to a third party which did not participate in the transaction (Sterner and Coria, 2012). The emissions of greenhouse gases and other pollutants are typical examples of *negative* externalities. For example, if a company buys a transport service, the firm does not compensate for the costs that are borne by other individuals in society, such as the costs resulting from GHG emissions, air pollution, noise, accidents, and congestion. Neither the producer, nor the user of the transport service pays for all these extra costs, and the total cost to society from the transport service is thereby larger than the price paid by the polluting company. Therefore, the actual cost to society of the commodity/service is not represented by the market price. Consequently, compared to the social optimum, negative externalities result in an excess consumption of goods and services when the price paid by the consumers are lower than the social price.

Public goods are commodities or services which are non-excludable and non-rivalrous (Sterner and Coria, 2012). Anyone in society can use the public goods, even if they do not pay for them, and the use by one person do not hinder another person from using it (e.g., air, public roads, streetlights etc.). As it is not possible to hinder non-paying actors from using the public goods, free-rider problems often occur, resulting in a lower than optimal level of public goods provided at the free market. Public intervention might therefore be necessary to finance the public goods, for example through taxes.

Monopolies and oligopolies are common examples of **imperfect competition**. In general, imperfect competition results in a sub optimal supply of goods and services at the market, as well as higher than optimal prices (Sterner and Coria, 2012).

Information failure occurs due to lacking information and can lead to a sub optimal functioning of the market (Sterner and Coria, 2012). If information is asymmetrically distributed among actors, this can lead to actors withholding important information regarding for example GHG emissions and environmental risks in order to continue producing the good/service. Lack of information can also lead to difficulties in designing effective and efficient policy instruments.

2.2.2. Different types of policy instruments

There exist several different types of public policy instruments, which can be used to correct for the market failures presented above, as well as to steer towards societal goals. In paper III of this thesis, different types of policy instruments commonly used in transport policy are categorized into three main categories: economic (e.g., taxes and subsidies), administrative (e.g., legislations, technical requirements, environmental classifications) and information (e.g., eco-labelling, advising, education, training, research, and development) (Swedish Environmental Protection Agency, 2021, 2012). For example, to correct for negative externalities such as GHG emissions, public authorities can implement economic policy instruments such as carbon taxes, resulting in polluting actors having to pay for the emissions that they cause.

2.2.3. Effectiveness and efficiency

In order to ensure that public policy instruments function in an optimal way, it is important to evaluate performance of the policy instruments. According to OECD/DAC Network on Development Evaluation (2019), policy evaluations should consider the following criteria when evaluating policy instruments: relevance (is the policy instrument doing the right things?), coherence (how well does the policy instrument fit into the policy landscape?), effectiveness (is the policy instrument achieving its objectives?), efficiency (are resources being used in an optimal way?), impact (what difference does the policy instrument make?), and sustainability (will the benefits from the policy instrument last?). In this thesis, the focus lies on effectiveness and efficiency.

Effectiveness and efficiency are important concepts when discussing public policy. While effectiveness measure whether a policy instrument achieves its objectives or not, efficiency also consider how economically the resources are converted into results. In the context of climate policy, effectiveness measure if we reach a specific climate target, while efficiency measure if the target is reached at the lowest possible cost to society. In policy evaluation, *effectiveness* should analyse progress towards policy objectives (European Commission, 2017; OECD/DAC Network on Development Evaluation, 2019). This includes examining quantitative and qualitative effects, as well as investigating why, whether and how the observed changes are linked to the policy instrument (European Commission, 2017). The performance criteria *efficiency* should instead measure how economically resources are converted to results (OECD/DAC Network on Development Evaluation, 2019). This includes looking at the costs and benefits of the policy instrument, and how they accrue to different stakeholders (European Commission, 2017).

2.2.4. Theory versus practice

While it may seem simple in theory to address market failures with policy instruments, the reality is often more complicated. In theory, a global CO_2-tax representing the external costs of CO_2-emissions is often mentioned as the most efficient policy instrument for addressing the increasing GHG emissions (Pigou, 1920). However, policies considered optimal in theory are not always possible to implement in practice due to various reasons, such as political factors and acceptance of policy instruments. For example, the distributional effects of a policy instrument might affect the acceptance of it (Criqui et al., 2019). Therefore, while the first best policy instrument is desirable from a theoretical perspective, the theoretical second-best policy instrument might be best in reality if it is the alternative possible to implement in practice.

In economics, the so-called Tinbergen Rule states that for each and every policy target there must also be at least one policy tool (Tinbergen, 1952). However, it is common that policy instruments affect more than one target, both in positive and negative ways (Knudson, 2009). Therefore, selectivity is mentioned as a positive attribute for policy instruments as it leads to better matching between policy instrument and target. Knudson (2009) argue that there are no “magic bullets” that can fix all climate and environmental problems, and that a series of policy tools need to be developed to match policy instruments and targets.

To improve the understanding of how policy instruments function and perform in practice, policy evaluations are important tools (European Commission, 2017). Based on policy evaluations, the decision making regarding current and future policy instruments can be improved and based on lessons learned from previous experiences. Paper III of this thesis analyses and compares different policy evaluations in order to draw conclusions regarding the effectiveness and efficiency of previous and current policy instruments.

2.3. Diffusion of innovations

While adopting policy instruments can help to correct for market failures and steer towards different societal objectives, understanding the market situation is of great importance to identify what market failures that exist and where public intervention is needed. Switching from fossil energy to renewable energy in the transport sector requires adoption of new technologies. Improving the knowledge of how, why, and how fast new technologies spread is therefore of great importance to understand how to speed up the process of renewable energy diffusion, and to identify if any policy instruments can help this process.

Diffusion of innovations is widely discussed in the literature. In 1962, Everett Rogers described a theory of technology diffusion in the book “diffusion of innovations” (Rogers, 2010). According to Rogers (2010) diffusion is the process by which a specific innovation is communicated over time in a social system. Some main elements affect the diffusion of the innovation, mainly the innovation itself, different communication channels, time, and the social system. The diffusion process is described to follow an S curve (see Figure 2). The curve corresponds to different stages of the consumers adoption to the new technology, where the innovators are the first ones to adopt the technology, followed by early adopters, early majority, late majority and finally laggards (see Figure 3). The diffusion is seen as a process, starting with awareness, interest, evaluation, trial, and finally adoption.

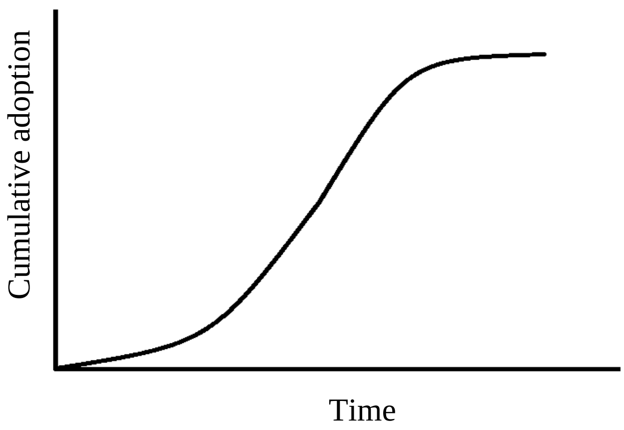

Figure 2 - Cumulative innovation adoption as a function of time

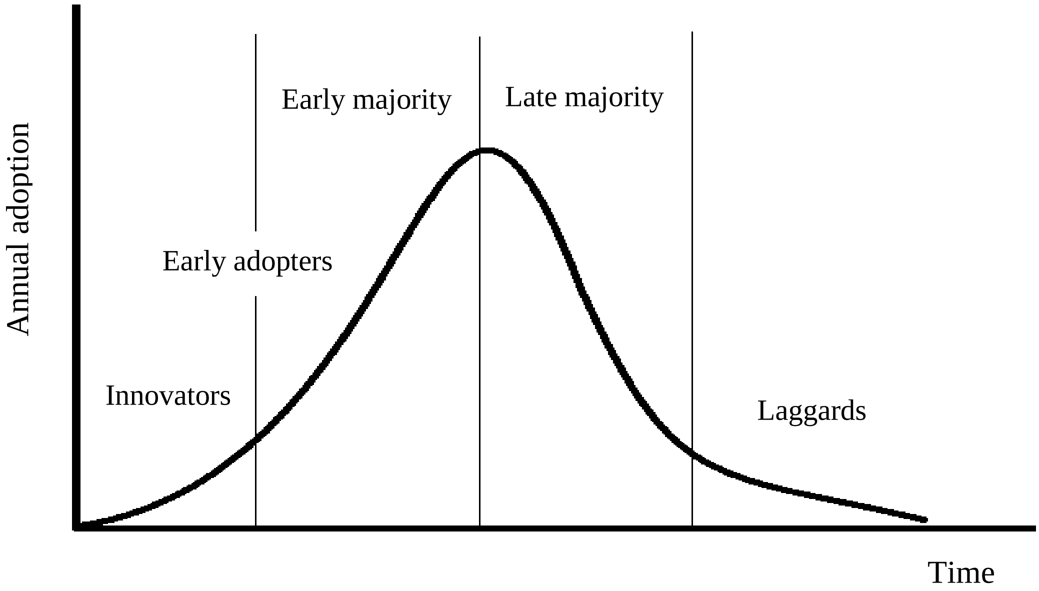

Figure 3 - Annual adoption of new technology by different actors as a function of time.

Diffusion of renewable energy specifically has also been investigated in previous literature (e.g. Browne et al., 2012; Kanda et al., 2015; Mignon and Bergek, 2016; Romm, 2006). Several models and theoretical frameworks have been applied and take on several different approaches, such as focusing on technology suppliers (Kanda et al., 2015), technology adoption (Montalvo, 2008), and sociotechnical systems seen from multilevel perspectives (Geels, 2012). Some studies investigate renewable energy diffusion by analysing the challenges for the diffusion process. For example, Banister (2005) suggests a framework for classifying barriers to sustainable transport, sorting the barriers into 7 main categories: financial barriers, technical and commercial barriers, institutional and administrative barriers, public acceptability, legal and regulatory barriers, policy failures and unintended outcomes, and finally physical barriers. Another framework is proposed by Mignon and Bergek (2016) for analysing challenges in the later-stage diffusion of renewable electricity. They distinguish between system- and actor-level challenges in their framework. The system-level challenges are sorted into six categories: market structure challenges, infrastructure challenges, financial challenges, institutional challenges, interaction challenges, and technology supply challenges. The actor-level challenges are sorted into two categories: adopter resources, and behavioural factors. Paper II of this thesis further investigate the barriers, opportunities, and potential solutions to the diffusion of renewable energy by specifically focusing on the case of liquefied biogas for heavy trucks in Sweden.

3. DATA AND METHODS

Different types of data and methodologies have been applied to answer the research questions in this thesis. In paper I, panel data analysis was used to address RQ1. Paper III applied a literature review approach to address RQ2. Finally, to answer RQ3, interviews and a total cost of ownership analysis was performed in Paper II. In this chapter I describe these data and methodologies.

3.1. Panel data analysis

Paper I applied a quantitative approach to address RQ1: How can the relationship between economic growth and GHG emissions be described? More specifically, panel data analysis was applied, with a focus on panel quantile regressions. Below, the selection of data and variables, as well as the methodological approach is described and discussed.

3.1.1. Data

To test the EKC-hypothesis, an empirical model was estimated consisting of a relationship between the dependent variable environmental degradation and the explanatory variables economic growth, renewable energy consumption, technological development, trade, and institutional quality. As several of these variables are immeasurable, proxy variables had to be used to stand in for the variables that cannot be directly measured. CO_2-emissions per capita were used as a proxy for environmental degradation, as is common in previous literature investigating the EKC (Balsalobre et al., 2015; Lorente and Álvarez-Herranz, 2016). Real GDP per capita was used as a proxy for economic growth. Renewable energy consumption was measured as the share of total energy consumption. To measure technological development, patent applications was used as a proxy. However, as there is generally some delay before innovations are implemented in society, we chose to lag the patents variable by one year, to both reflect the innovative activity level and the innovative output. The sum of exports and imports as the share of GDP was used to measure the effects of trade on CO_2-emissions. Finally, to measure institutional quality, the Freedom House political rights index and civil liberties index were used as a proxy.

All above-mentioned data were obtained from the World Development Indicators (WDI) except for the institutional quality variable which was obtained from the Freedom House. The total sample includes annual data for the dependent and explanatory variables for 74 middle- and high-income countries over the period of 1994-2012. This was the longest and most up to date time series available without reducing the sample, due to missing data. All variables except for institutional quality are expressed in natural logarithms to minimize issues with heteroskedasticity and to improve comparability with previous studies on the EKC.

3.1.2. Panel quantile regressions

Based on the theoretical relationship between environmental degradation and income described in previous EKC-literature (see for example Grossman and Krueger, 1991; Stern, 2004), we estimated an empirical model expressed as follows:

$$CO_{2it} = \alpha + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 GDP_{it}^3 + \beta_4 REN_{it} + \beta_5 R\&D_{i(t-1)} + \beta_6 TRD_{it} + \beta_7 INS_{it} + \varepsilon_{it}$$

Where CO_2 refers to CO_2 emissions, GDP is income per capita, REN is renewable energy consumption, R&D refers to technological development, TRD is trade, and INS refers to institutional quality. The coefficient α measures the average pressure on CO_2 emissions when GDP has no effect, β refers to the direction and importance of the explanatory variables, ε is the error term, and *i* and *t* are indexes for country and time. If $\beta1>0$, $\beta2<0$, and $\beta3>0$, there will be a cubic polynomial or N-shaped relationship between CO_2 emissions and GDP per capita, while the relationship will be shaped as an inverted U (the original EKC-hypothesis) if β3 instead is equal to 0. However, there are also several other possible combinations of signs for the β-parameters, and thereby several other possible shapes of the relationship between CO_2 emissions and GDP per capita.

To analyse the dataset and test the empirical model, we applied panel data analysis. Panel data analysis is a common method in economics. It was chosen as method as it allows for more complicated and realistic models than a single cross section analysis, and as a time series analysis was not an appropriate method in this case as the sample of countries was extensive and the time period too short for drawing inferences. Furthermore, panel data is the most commonly used methodology in previous EKC literature and is a useful method when looking for generalizable results (Lieb, 2003).

As a first approach in the regression analysis, we used a pooled ordinary least square (OLS) estimator and a fixed effects model (FEM). However, it is common that the statistical distribution of data has an unequal variation and that the relationship between the variables differ between the locations on the dependent variable's conditional distribution (Cade and Noon, 2003). Therefore, estimations based on mean values, such as pooled OLS and FEM, might generate incorrect results. Instead, in quantile regressions, the conditional distribution of the dependent variable is divided into different quantiles, making them more robust to outliers (Hübler, 2017). Quantile regressions can therefore provide a more complete picture of the relationship between the variables as they evaluate the different points on the conditional distribution of the dependent variable (Cade and Noon, 2003). Thus, we chose to mainly focus on a panel quantile approach when testing the empirical model. This methodology was chosen as it provides a more comprehensive picture of the relationship between the variables, and because it can capture the heterogeneous structure of the different income groups and different market conditions. We estimated regression models for both the total sample of 74 countries, and for lower middle-income countries, upper middle-income countries, and high-income countries separately.

3.2. Literature review

In Paper III, a literature review approach was applied to address RQ2: How does European public policy instruments contribute to the modal shift of freight from road to rail and waterborne transports?

The purpose of the literature review performed in Paper III was to identify as many modal shift public policy instruments as possible in Europe, and to identify policy evaluations regarding their effectiveness and efficiency. To identify the policy instruments and their evaluations, we had to include grey literature as this is mainly where such information can be found. The term grey literature refers to unpublished research and publicly available open-source information which is usually only available through certain channels and which may not enter the normal systems and channels of publication, distribution and bibliographic control (Benzies et al., 2006). Grey literature can for example include government reports, newsletters, government information websites, committee reports, PowerPoint presentations, working papers etc. Most grey literature is not peer-reviewed and has limited referencing of information (Benzies et al., 2006). Given the nature of grey literature, it is often difficult to access through databases such as Scopus and Web of Science. When it comes to information about policy instruments, there is no database, webpage or other source that already includes information regarding all implemented modal shift policy instruments in Europe. Therefore, it has not been possible to apply the same type of search techniques in this literature review as when conducting systematic literature reviews which only include white literature. Instead, several different search techniques were applied in Paper III. Information was gathered from a variety of different sources to identify as many modal shift policy instruments as possible, including their ex-post evaluations (if any).

As a first step of the literature review, we searched for modal shift *public policy instruments* in already existing databases, such as the European Commissions (2021) database for state aid cases and the OECD (2021) database on policy for the environment. This search strategy was complemented with searches for grey and white literature in Google and Google Scholar. Search words included for example “policy instrument”, “freight”, “modal shift”, “multimodal transport”, “intermodal” etc. More detailed searches were also conducted, including search word combinations such as “subsidy”, “rail”, and “Italy”. Following this search process, information regarding existing policy instruments were identified from various sources including academic studies, websites of governmental institutions, reports published by public organizations, etc. Snowball techniques were then applied to identify additional policy instruments, for example by following the reference lists in academic studies and reports.

For a policy instrument to be selected, it had to fulfil some requirements:

- Being implemented by a public actor in Europe.
- Targeting a freight modal shift from road to rail and/or waterborne transports or having a clear focus on reducing freight transports by truck.
- Being implemented, or active at any time after 2000.

All selected policy instruments were included in a database constructed within the project. In the database, the policy instruments were sorted based on several categories, including the geographical level of the policy instrument (regional, national, or local), which transport mode the policy instrument promotes (rail, water, or road discourage), and what policy group (economic, administrative, or information) the policy instrument belongs to.

As a second step of the literature review, we searched for *ex-post evaluations* of each policy instrument that had been included in the database to achieve information regarding policy performance. The searches were conducted in Google and Google Scholar and included the name of the policy instrument in combination with the search words “evaluation”, “impact”, and “assessment”. Some evaluations had already been identified during the first step of the literature review and were therefore found using different search words and snowball techniques. For each evaluation that was found during the search process, information regarding both evaluation characteristics (actor performing evaluation, purpose, methodology, and performance criteria considered) and policy performance (effectiveness and efficiency) was included in the database.

3.3. Group interviews and individual interviews

Paper II primarily applied a qualitative approach, including group interviews and individual interviews, to address RQ3: What are the barriers, opportunities, and potential solutions to the diffusion of renewable energy in general, and liquefied biogas for heavy trucks in particular? Furthermore, a cost example comparing the total cost of ownership for liquefied biogas trucks and conventional diesel trucks was also estimated within the study, which is further described in section 3.4. Below, the interview approach is discussed.

To answer RQ3, we performed group- and individual interviews with experts and stakeholders in four Swedish regions: Blekinge Län, Region Jönköping Län, Region Örebro Län, and Västra Götalandsregionen. To capture the perspectives of actors from the full biogas chain, the group- and individual interviews included actors representing biowaste, biogas, and vehicle producers, as well as fuel distributors, haulers, transporters, and transport buyers. Furthermore, local and regional planners as well as a politician participated in the group interviews. Actors responsible for awareness-building activities in the regions also contributed to the study by participating in the interviews and by supplying stakeholder and expert contacts.

Group interviews were selected as primary methodology as they provide data via replies to questions, in contrast to focus group discussions, where the aim is to foster discussion among group members (Parker and Tritter, 2006). The group interviews were then complemented with individual interviews with actors who had been invited but unable to attend any of the group interviews. Both the group interviews and the individual interviews were semi-structured. Representatives from a total of 30 organisations participated in the study. Seven of these actors participated in the individual interviews.

At least two researchers took notes in every group interview. The sessions were recorded and transcribed. The individual interviews were conducted by phone. All respondents were promised confidentiality in relation to their specific replies. In both types of interviews, the same main questions and sub-questions were asked. The two main questions were:

- What incentives and barriers for LBG use exist?
- What would be required for LBG to gain a larger market share in heavy road freight transport?

During the group interviews, each person answered the same questions. Therefore, the respondents’ answers often complemented previous respondents’ answers. In some cases, the questions also led to discussions. Given how the group interviews were organised, we did not attempt to quantify the answers.

The answers from the group- and individual interviews were sorted according to several categories, in accordance with a framework applied in the study. The framework is based on several previous studies of how to classify barriers to technology diffusion, but mainly the studies by Browne et al. (2012) and Mignon and Bergek (2016).

While quantitative data for example can bring us generalized results from randomized groups, it has the shortcoming that it cannot provide us specific feedback details. In the case of renewable energy, quantitative data can for example show us how much renewable energy that is used, but it cannot tell us why actors choose to use it or not, and what would be required to further increase the use. Qualitative data, such as interviews, has the advantage that it can provide us with these type of feedback details, and it can provide us with a deeper understanding of the choices that different actors make. However, one shortcoming of interviews is that it only captures the perspective of the interviewees. Therefore, perspectives from other actors are omitted.

In Paper II of this thesis, most actors attending the group interviews represented biogas producers and distributors, even though representatives from the entire biogas chain were invited to participate. Only one transport buyer, except for buyers such as municipalities, participated in the group interviews, leading to an underrepresentation of demand side actors. This highlights the importance of having one's interests at stake or gaining something from spending time on activities outside one's daily business, such as the group interviews held in Paper II. This is a dilemma when seeking information from relevant actors in stakeholder-driven research. As several of the demand side representatives declined their invitations due to a lack of time, we solved this underrepresentation by holding complementary individual interviews with transporters and transport buyers to save their time while still soliciting their views and opinions. Most of the interviewed actors were already active in addressing biogas questions, which might bias the results. However, because the actors are active, they also have considerable knowledge and understanding of biogas systems that other actors lack. A few transport buyers who were not active biogas users were also included in this study to ensure that their perspectives were also considered.

3.4. Total cost of ownership

As a further approach to address RQ3, a relative total cost of ownership (TCO) analysis was performed. Costs have previously been shown to be an important factor when choosing vehicle type and energy source (Ammenberg et al., 2018; Lantz et al., 2007; Steenberghen and López, 2008). To complement the interviews and analysis of barriers, opportunities, and potential solutions, we estimated costs of using LBG vehicles compared to conventional diesel vehicles. TCO is a common measure to estimate the costs of different vehicle alternatives (see for example Engholm et al., 2020; Lee et al., 2013; Vora et al., 2017). However, as we are primarily interested in the cost savings (or additional costs) of LBG compared to conventional diesel vehicles, rather than in the total cost of ownership per se, we chose to estimate a *relative* TCO. By doing this, we measure the annualized cost savings (or additional costs) per vehicle kilometre but exclude some cost components that will likely not differ between an LBG-truck and a conventional diesel truck but that would normally be included in a TCO (for example driver costs, loading and unloading costs etc.).

4. RESULTS AND DISCUSSION

In this chapter, I summarise and discuss the main findings regarding each research question, as well as the contribution to the research field. The chapter ends with a discussion of how the results regarding RQ1 to RQ3 contribute to the overall aim of the thesis.

4.1. Relationship between economic growth and GHG emissions

Paper I contribute with knowledge regarding RQ1: How can the relationship between economic development and GHG emissions be described? The research distinguish itself from previous literature by focusing on different income groups, using quantile regressions, studying the possibility of an N-shaped EKC, as well as by including other factors than income in the analysis, namely the variables renewable energy, technological development, trade, and institutional quality. Below, results regarding RQ1 are presented and discussed.

The results regarding the shape of the relationship between CO_2-emissions and GDP per capita are inconclusive, both between income groups, methodologies, and quantiles. Most of the statistically significant results show an N-shaped EKC. However, due to the heterogenous results, no strong conclusions can be drawn regarding the CO_2-GDP relationship.

When using a pooled OLS estimator, evidence for an N-shaped EKC is found for lower-middle-income countries, high-income countries, and the total sample of 74 countries. However, for upper-middle-income countries, no significant relationship is found. The results from the quantile regressions are also inconclusive. An N-shaped EKC is found in some quantiles for lower-middle-income countries, high-income countries, and the total sample. However, an N-shaped EKC is not found in any quantile for the upper-middle-income countries, and most quantiles do not show any significant relationship at all. Interestingly, a few quantiles show an opposite N-shaped EKC for upper-middle-income countries. This finding is complicated to explain. It could potentially be caused by an inflow of technology from more developed countries due to a growing amount of foreign direct investment and multinational companies operating in upper-middle-income countries. Thus, improvements in the countries' technological frontiers could outpace the scale effect and lead to a negative effect of GDP per capita on CO_2-emissions. The opposite N-shaped relationship could also be a consequence of the studied time period omitting important observations for these income groups.

The inconclusive results might depend on heterogeneity between and within the investigated income groups. Therefore, a further breakdown of the included countries and their specific characteristics, could improve the understanding of why the N-shaped EKC is only apparent in some quantiles. The inconclusive results indicate that the relationship between CO_2-emissions and GDP per capita should be studied with carefulness. It is common in the research field to only use mean regressions as method, which might generate non-representative results for many of the countries included in the sample. When using quantile regressions, we see that the relationship between CO_2-emissions and per capita GDP widely differs between quantiles.

A large part of previous literature investigating the EKC do not include a cubic relationship in their estimations and can thereby not capture the possibility of an N-shaped EKC. Yet, the inverted U-shaped EKC, which has been confirmed in several previous studies, is only found in one single quantile in this study. This indicates that studies omitting the cubic relationship might mistakenly support the hypothesis of an inverted U-shaped EKC. However, it is also possible that the inconclusive results are a consequence of the CO_2-GDP relationship being more complex than our methodology (and previous EKC methodologies) allows us to examine. The relationship might have a functional form that is not possible to capture by the model applied in this thesis. Thus, future estimation methods need to be further developed to consider the possibilities of other or more complicated relationships.

Paper I also investigated the effect on CO_2 emissions of several additional explanatory variables. All estimations, for all income classifications, show that increasing the share of renewable energy is an important factor for reducing CO_2 emissions. Thus, policy instruments encouraging the substitution to greener energy is of high importance to combat climate change.

Furthermore, the results suggests that technological development leads to increased CO_2 emissions, which could possibly be explained by the RD&D variable measuring all types of advances in technology and not only advances related to "cleaner" technologies. For the high-income countries, the quantile regressions generate inconclusive results regarding the effect of RD&D on CO_2-emissions. This could potentially be explained by some countries having a higher share of energy related RD&D, which reduces CO_2 emissions.

The results show that trade causes increased CO_2 emissions for all income classifications and estimators but is not significant for high-income countries. Increased transportation could potentially explain this positive correlation. The insignificant effect for the high-income countries could indicate that trade both positively and negatively affects CO_2-emissions in these countries. Even though the results do not support the pollution haven hypothesis, they neither reject it.

According to the results, institutional quality only leads to reduced CO_2 emissions for lower-middle-income countries in the lower quantiles. Yet, the results are not consistent with the findings of the sensitivity analysis. It is possible that the indexes used in Paper I do not fully reflect the impact of change in institutional quality. Some further investigation, with the use of other indexes for institutional quality, could help improve the understanding of its effect on CO_2-emissions.

4.2. Modal shift public policy instruments

Paper III contributes with knowledge regarding RQ2: How does European public policy instruments contribute to the modal shift of freight from road to rail and waterborne transports? By performing a literature review, the Paper contributes to the research field by constructing a database over European modal shift public policy instruments and their policy evaluations. Furthermore, observations regarding effectiveness and efficiency from the evaluations are summarized and discussed.

The search process applied to identify policy instruments resulted in the identification of 93 public policy instruments targeting a modal shift in Europe. The majority of the identified policy instruments are economic policies implemented at the national level, most commonly in the form of subsidies or grants provided to rail or waterborne transports. Most commonly, the policy instruments only target one specific transport mode, most often rail.

The search process applied to identify evaluations for the 93 policy instruments only resulted in the identification of ex-post evaluations for 20 policy instruments. Most evaluations concern subsidies and grants or policy instruments at the EU-level. Due to the low number of evaluations, and the homogeneity of the evaluated policy instruments, comparisons of policy performance over different policy categories is complicated.

A wide range of evaluators have performed the evaluations, including among others consultant firms, public authorities, the European Court of Auditors, expert groups, and independent researchers. As the sample of evaluations is small, it has not been possible to draw any conclusions regarding possible relationships between evaluators and evaluation methods or results. Positive, as well as negative policy performance is found in evaluations by all type of evaluators. Further research, with larger samples, is needed to improve the understanding of the relationship between policy evaluations and how the evaluating actors may influence the evaluation outcomes.

About half of the policy instruments with evaluations are subsidies or grants at national level, while the other half represent policy instruments governed at EU-level. Knowing the purpose of an evaluation is important to understand how it may affect the evaluation outcomes. The large share of evaluated EU policy instruments could be a consequence of the commitment to evaluation formulated in Article 318 of the Treaty on the Functioning of the European Union and on other evaluation guidelines and frameworks within the EU. The large share of evaluated subsidies/grants at national level could be explained by them being classified as state aid that needs permission by the European Commission to be implemented or prolonged. Most of the evaluations for subsidies/grants have been performed when applying for prolongation by the European Commission and show an overall positive policy performance. The positive evaluation outcomes may have several explanations. It could for example reflect that subsidies/grant are effective in achieving a modal shift, but it could also reflect that EU member states only apply for prolongation if the policy instrument is considered effective.

There is a variation between evaluations regarding how policy performance is evaluated, both in terms of methodologies used, performance criteria considered, and how the performance criteria are interpreted. Several of the identified evaluations show that there is a gap between evaluation theory and how evaluations are performed in practice, making comparisons between evaluation results difficult.

Several evaluations describe methodological limitations such as difficulties in finding relevant and reliable data, as well as difficulties to measure causality between the policy instrument and observed changes. One way to overcome this problem, would be to design policy instruments in a way that facilitate evaluation, for example by requiring firms receiving funding to collect and present data.

For each evaluated policy instrument, we summarised targets, effectiveness, and efficiency. The results show that policy objectives are often broad and general. A lack of well-defined targets and specified performance indicators is mentioned as a problem by several evaluations as it complicates meeting all policy objectives, as well as to evaluate the policy instruments effectiveness and efficiency. Therefore, it is important that targets and objectives for policy instruments are formulated in such way that they can be evaluated. For several policy instruments, modal shift is considered as an objective itself, rather than a means to achieve reduced external costs from freight transports. As modal shift do not automatically result in reduced externalities, this is problematic. Consequently, it is important that modal shift is treated as a means to reach the ultimate objective of reduced external costs when formulating policy targets.

Several evaluations of EU-policy instruments describe a poor or a mixed performance. However, the performance of subsidies and grants at national level are often described positively in the evaluations. In general, policy instruments promoting a modal shift to rail are described as more successful than those promoting waterborne transports. Commonly mentioned factors for underachievement of the policy instruments include problems related to outreach of the policy, lack of applications, long and complicated application processes and a high administrative burden for the companies applying for financial support. Thus, focusing on better outreach and simpler application processes could improve policy performance.

Despite several interesting findings from Paper III, there are some limitations of the study. The sample of evaluations is limited, making it difficult to draw any general conclusions regarding policy performance. Furthermore, language barriers might have biased the results towards identified policy instruments and evaluations with information available in English. Thus, there is still a need for improved knowledge regarding what types of policy instruments that can effectively and efficiently contribute to a modal shift and reduced external costs from the European freight transport sector.

4.3. Barriers, opportunities, and potential solutions to renewable energy diffusion.

Paper II contributes with knowledge regarding RQ3: What are the barriers, opportunities, and potential solutions to the diffusion of renewable energy in general, and liquefied biogas for heavy trucks in particular? The paper attempts to answer the research question by performing interviews and by estimating a relative TCO. The paper contributes with new knowledge to the research field by specifically studying the case of LBG for heavy trucks in Sweden, but also by developing and applying a framework which categorises barriers, opportunities, and solutions to renewable energy diffusion. The framework consists of five categories: financial barriers; technical, commercial, and physical barriers; policy related barriers; public acceptability; and market structure and interaction barriers. In each category, system- and actor-level opportunities and challenges are distinguished from each other.

The responses from the group and individual interviews fit well into the categories of the framework. Even though the interviews specifically concentrate on LBG for use in heavy trucks, the results largely confirm barriers and opportunities identified in previous literature regarding renewable energy diffusion of other energy sources and technologies.

At the system-level, several opportunities were identified, such as ambitious climate- and environmental targets, striving to create a circular economy, and recently adopted policy instruments in Sweden. Furthermore, increased energy security due to local production and new LBG trucks on the market were mentioned as other opportunities. Several actor-level opportunities were also mentioned, such as potential profitability, an increased demand for renewable products, and climate objectives within organisations.

Commonly cited barriers at the system level concerned an unstable policy context, lack of physical infrastructure, and financial risks such as high investment costs, unknown maintenance costs, and resale values. At the actor level, barriers such as small profit margins of transport companies were noted, along with insufficient knowledge, awareness, and experience.

Discussing solutions within the present framework is an important step in understanding how the diffusion of LBG can accelerate. Therefore, the respondents were also asked how the barriers could be overcome. Financial support and a more stable policy context were called for by the interviewed actors. Furthermore, information campaigns and demonstration activities were suggested in order to raise awareness of LBG vehicle capacity, climate performance, and financial benefits. Good examples on the roads, for example through public procurements or demonstration projects, highlighting vehicle functionality and potential market benefits were also mentioned as potential solutions. Furthermore, the respondents were aware of the need to bring together the entire value chain as such cooperation may accelerate sustainable diffusion.

The results from the interviews indicate that it is important to understand both the perspective of the potential innovation adopters and the system in which they are embedded, to explain the factors affecting the diffusion of LBG. Furthermore, the results indicate that there is a need to also consider a third level in the framework that highlights the networks linking the system and actor levels among various actors. Considering a network level in addition to the system and actor levels could advance our understanding of renewable energy diffusion. Increased knowledge and the encouragement of network formation between the system and actor levels would be useful to improve interactions favouring the diffusion of alternative energy sources.

The results bring some interesting policy implications. Several of the mentioned barriers were already targeted by policy instruments at the time of the interviews. For example, financial aspects were mentioned as a main barrier, despite several existing economic policy instruments, such as tax-exemption from CO_2- and energy tax, vehicle purchase grant, and production support to biogas produced from certain raw materials. The respondents also request solutions such as better demands at public procurements and more LBG fuel stations. These are also barriers which are already targeted by policy instruments in Sweden and at the EU-level. Furthermore, the relative TCO performed within the study show that costs of using LBG trucks is only marginally higher than those for diesel trucks, given the current policy landscape in Sweden (in April 2021). Nevertheless, without current policy instruments, the costs of using LBG-vehicles are higher than the costs of using diesel-trucks, which strengthens the respondents request for a stable policy context. The fact that several of the mentioned barriers already are targeted by policy instruments stress the importance of continuously evaluating existing policy instruments to understand if they are effective and efficient, or if changes or new policies are required.

4.4. Discussion regarding overall research question

The overall research question of this thesis is if, and how, we can mitigate climate change alongside economic development[3] (improved standard of living and quality of life for the individuals in a community). The results from the different papers have all contributed with knowledge to this research theme. First, results from Paper I have shown that the relationship between CO_2-emissions and GDP per capita has the shape of an N for lower-middle-income countries, high-income countries, and the total sample of 74 countries. This N shaped relationship shows that even if CO_2-emissions can decrease along with economic growth at certain income levels, the CO_2-emissions increase with economic growth at lower and higher levels of GDP per capita. This indicate that there might exist goal conflicts between several of the sustainable development goals. However, the results are inconclusive and there might be other potential shapes of the CO_2-GDP relationship.

The findings from Paper I raises several important questions. First, the results raise questions regarding the possibilities to implement policy instruments which can turn the N-shaped relationship between CO_2-emissions and income per capita into an inverted U (which is the original EKC hypothesis). If such policy instruments exist, it could be possible to mitigate climate change along with economic growth. However, the results also raise questions regarding the appropriateness of using GDP per capita as a proxy for *economic development*. While GDP per capita is a suitable measure of the marketable output of an economy, the variable omits several important factors such as the distribution of income or cost of living in a particular country. Furthermore, GDP per capita ignores several important factors related to the standard of living in a society such as education, health, equality, life expectancy, income security, personal safety, destruction of the environment, happiness, social relations, the use of time etc. (Aitken, 2019; Fleurbaey, 2009). Thus, while the results from Paper I indicate that economic *growth* might be harmful for the climate at certain income levels, the results do not tell us how other factors related to economic *development* and quality of living correlate with the emissions of greenhouse gases. It is therefore important that future research on the theme also consider other factors related to quality of living to improve the understanding of the relationship between CO_2-emissions and economic *development*. For example, the use of other types of indices for economic development, such as the Human Development Index (HDI)[4], could provide additional knowledge to the research theme.

Both the question regarding if policy instruments can turn an N-shaped EKC into an inverted U, as well as the discussion regarding what factors to consider when discussing economic development brings us to paper III, where we examined European modal shift policy instruments and their ex-post evaluations. Even though there exist several policy instruments

[3] In this thesis, the term economic development is used to describe the standard of living and quality of life for the individuals in a community (Greenwood and Holt, 2014). Instead, the term economic growth refers to market productivity and measures such as GDP per capita. While economic growth can be an important component of economic development, an increased GDP per capita do not necessarily equal to increased standard of living for the individuals in a community if for example inequality and crime rise.

[4] The Human Development Index is a summary measure compounded of a gross national income (GNI) index, an education index, and a life expectancy index.

in Europe aiming for a modal shift, road transports still dominate the freight transport sector and there is no indication of a modal shift at the aggregate level, indicating that the policy instruments have not yet been very effective in achieving a modal shift. Furthermore, several policy instruments at the EU-level describe a poor or mixed performance. However, most of the evaluations regarding subsidies and grants to rail and water at the national and local levels describe a positive performance of the policy instruments. When determining the performance of a policy instrument, factors such as costs and benefits of the policy instrument, as well as how they accrue to different stakeholders should be considered (European Commission, 2017; OECD/DAC Network on Development Evaluation, 2019). Estimating costs and benefits do not only include the measurements of financial effects, but also intangible benefits and costs such as effects on health, climate, environment, and other factors related to the standard of living in a society. Including these aspects when performing policy evaluations help us understand if a policy instrument achieves its objectives at a minimum cost for society and if the benefits outweigh the costs. Yet, the findings from Paper III show that evaluations of European modal shift policies are few and of varying quality. Despite several guidelines for evaluations, they do not always include estimations or discussions regarding the costs and benefits of the policy instrument. Different methodologies and performance criteria are used in the evaluations, making comparisons between policy performance difficult. Thus, further research and discussions regarding how policy evaluations can be performed in a more harmonized and systematic way, considering several aspects related to economic development, is needed to facilitate comparisons of policy instruments and to improve evidence-based policy and decision-making which can help mitigate climate and environmental change.

The findings in Paper II, regarding barriers, opportunities, and solutions to renewable energy diffusion, also emphasize the importance of public policy instruments and evaluating their performance. The main barriers to LBG diffusion mentioned by the interviewed experts and stakeholders include financial limits, lacking infrastructure, lacking knowledge, and unstable policy instruments. Yet, several policy instruments already target these types of barriers and the costs of using LBG trucks are only marginally higher than those of using diesel trucks in Sweden given current taxes and subsidies. The fact that several of the mentioned barriers are already targeted by policy instruments stress the importance of continuously evaluating the performance of existing policy instruments to understand if they are effective and efficient, or if changes or new policy instruments are needed to increase diffusion of renewable energy.

Mitigating climate change alongside economic development is a complex question. The three different papers in this thesis all contribute with knowledge to this research theme from the global level, European level, and Swedish national level including various stakeholder’s perspectives. All these levels are important to further the understanding of how to combat climate change alongside economic development and it is important that future research continue to study the question from all these levels.

5. CONCLUDING REMARKS AND FURTHER RESEARCH

The overall aim of this thesis was to improve the understanding of if, and how, we can combat climate change along with economic development (improved standard of living and quality of life for the individuals in a community). The three papers in this thesis have all contributed to the research theme. Paper I contributes with knowledge at an overarching level regarding the relationship between CO_2-emissions and economic growth, applying a global perspective and including all sectors. Paper II and III specifically investigate the freight transport sector and are focused on identifying solutions for how to reduce GHG emissions and other negative externalities from transports. Paper III contributes with knowledge regarding the effectiveness and efficiency of public policy instruments in Europe aiming for a modal shift to more energy efficient transport modes. Paper II contributes with knowledge regarding barriers, opportunities, and potential solutions for renewable energy diffusion, specifically investigating the case of liquefied biogas for heavy trucks in Sweden. Thus, the overall question of mitigating climate change alongside economic development is addressed from several different perspectives at the global level, European level, and Swedish national level including various stakeholder's perspectives.

Regarding the relationship between economic growth and GHG emissions, an N-shaped relationship is found for lower-middle- and high-income countries, indicating that CO_2-emissions increase with economic growth beyond a certain income level. This indicate that there might exist goal conflicts between several of the sustainable development goals. However, no significant relationship is found for upper-middle-income countries and the results are inconclusive. Yet, all estimations show that increasing the share of renewable energy is crucial for reducing CO_2-emissions. If the relationship in fact is N-shaped, forceful policy instruments are likely required to turn the N-shaped relationship into an inverted U-shaped relationship.

On the question of how European public policy instruments contribute to a freight modal shift, ex-post evaluations are found for 20 out of the 93 identified policy instruments. The evaluated policy instruments are mainly subsidies and grants at the national level, or different types of policy instruments implemented at the EU-level. The ex-post evaluations show a large variation in both evaluation methods and performance criteria considered, which complicates comparisons of the policy instruments performance. It is therefore important to harmonize and improve the guidelines for policy evaluations within and between countries to improve evidence-based policy-and decision making. That being said, the evaluations that do exist show that the policy instruments promoting rail in general are more successful than those promoting waterborne transport. Common factors for underachievement include lack of applications, outreach problems, and complicated application processes. Furthermore, broad, and general policy targets complicate evaluation as well as fulfilment of policy objectives.

Regarding the barriers, opportunities, and potential solutions to the diffusion of liquefied biogas (LBG) for heavy trucks, interviews with experts and stakeholders in Sweden show that main barriers include financial limits, lacking infrastructure, lacking knowledge, and unstable policy instruments. Yet, several policy instruments already target the barriers to LBG diffusion and given current taxes and subsidies, costs of using LBG trucks are only marginally higher than those for using diesel trucks in Sweden. Thus, it is important that existing policy instruments are evaluated in order to identify if changes or new policy instruments are needed to address the stated barriers.

5.1. Further research

The results from the different papers in this thesis indicate that reducing GHG emissions alongside economic development is complicated. Several questions remain and there is a need to study the question from an aggregated level as well as from detailed levels to entangle the complicated relationship and to find solutions.

Even though Paper I bring several interesting findings, it does not mark the end of the road for studies regarding the EKC. The results are inconclusive and vary between income groups and quantiles. Furthermore, it is possible that the shape of the CO_2-GDP relationship is more complex than the model applied can capture. Further breakdowns of countries according to income groups and other characteristics, as well as a further development of models for estimating the EKC might improve the understanding of the relationship. It is also important with further reflections regarding what we want to measure with the EKC. In this study, as well as in most previous studies on the EKC, GDP per capita is used as a proxy for economic *growth*. However, this variable does not tell us about distribution of income or cost of living in a certain country. Furthermore, economic *growth* is only one component of economic *development*. Therefore, it is important that future studies acknowledge that an increased GDP per capita do not necessarily equal to improved living standards and quality of life. Further research with other indices, such as the Human Development Index (HDI), could improve our understanding of how GHG emissions are affected by economic *development* rather than by economic *growth*.

To learn from previous experience and improve or implement new policy instruments, it is important with further research regarding how policy instruments are designed, how they are evaluated, how they perform, and how previous experiences are used in the decision-making process. The results from Paper III show that there are few ex-post evaluations of policy instruments aiming for a modal shift in Europe. Furthermore, according to the results there is a gap between evaluation theory and how evaluations are performed in practice, making comparisons between evaluation results difficult. Further research is needed both to improve the understanding of how climate policy instruments perform in practice, as well as how ex-post evaluations measure this performance. For example, further research could expand the scope by not only looking at modal shift policy instruments and evaluations in Europe, but also in other regions. Furthermore, by covering other challenges than modal shift, such as promotion of renewable energy, a larger sample of evaluations can be covered. With a larger sample it could be possible to improve the understanding of how different evaluation characteristics (eg. methods, performance criteria considered, purpose, evaluator etc.) influence the results of the evaluation. Paper III only analysed ex-post evaluations. By also considering ex-ante evaluations and comparing these with ex-post evaluations, further research can improve the understanding of how policy instruments actual performance differ from the expected performance.

To complement the research in Paper II, further studies need to gather perspectives from other actors, countries, transport modes, and renewable energy sources regarding barriers, opportunities, and solutions to renewable energy diffusion. The fact that several of the mentioned barriers already are targeted by policy instruments stress the importance of continuously evaluating existing policy instruments to understand if they are effective and efficient, or if changes or new policies are needed. There are currently several renewable options on the market, which all face barriers and opportunities for further diffusion. Studies comparing these different options, for example by analysing their climate and environmental impacts, costs and benefits, and different types of risks would be valuable to improve the understanding of how to increase the share of renewable energy in the freight transport sector.

The papers in this thesis mainly focus on how to reduce greenhouse gas emissions but other types of environmental effects and negative externalities are also discussed briefly. However, no deeper analysis regarding potential goal conflicts is included in this thesis. As some of the discussed solutions for reducing GHG emissions might for example negatively affect the environment, it is important that these types of goal conflicts are further analysed and discussed in future research.

The research also has some practical implications. The results indicate that there is a need for a public database, gathering information from national and local authorities over the world regarding implemented climate policy instruments as well as ex-ante and ex-post evaluations of these. There is also a need for common evaluation guidelines specifying how policy instruments should be evaluated (methods, evaluations criteria etc) to simplify comparisons of policy performance. Furthermore, several evaluations describe methodological limitations such as difficulties in finding relevant and reliable data, as well as difficulties to measure causality between the policy instrument and observed changes. One way to overcome this problem, would be to design policy instruments in a way that facilitate evaluation, for example by requiring firms receiving funding to collect and present data.

REFERENCES

Aitken, A., 2019. Measuring Welfare Beyond GDP. National Institute Economic Review 249, R3–R16. https://doi.org/10.1177/002795011924900110

Alvarez, A., Lorente, D., 2015. Energy Regulation in the EKC Model with a Dampening Effect. Journal of Environmental Analytical Chemistry 02. https://doi.org/10.4172/2380-2391.1000137

Ambra, T., Caris, A., Macharis, C., 2019. Towards freight transport system unification: reviewing and combining the advancements in the physical internet and synchromodal transport research. International Journal of Production Research 57, 1606–1623. https://doi.org/10.1080/00207543.2018.1494392

Ammenberg, J., Anderberg, S., Lönnqvist, T., Grönkvist, S., Sandberg, T., 2018. Biogas in the transport sector—actor and policy analysis focusing on the demand side in the Stockholm region. Resources, Conservation and Recycling 129, 70–80. https://doi.org/10.1016/j.resconrec.2017.10.010

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C.S., Jansson, B.-O., Levin, S., Mäler, K.-G., Perrings, C., Pimentel, D., 1995. Economic growth, carrying capacity, and the environment. Ecological Economics 15, 91–95. https://doi.org/10.1016/0921-8009(95)00059-3

Balsalobre, D., Álvarez, A., Cantos, J.M., 2015. Public budgets for energy RD&D and the effects on energy intensity and pollution levels. Environ Sci Pollut Res 22, 4881–4892. https://doi.org/10.1007/s11356-014-3121-3

Banister, D., 2005. Overcoming barriers to the implementation of sustainable transport., in: Rietveld, P., Stough, R.R. (Eds.), Barriers to Sustainable Transport: Institutions, Regulation and Sustainability.

Baumol, W.J., Oates, W.E., 1988. The Theory of Environmental Policy, 2nd ed. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781139173513

Benzies, K.M., Premji, S., Hayden, K.A., Serrett, K., 2006. State-of-the-Evidence Reviews: Advantages and Challenges of Including Grey Literature. Worldviews on Evidence-Based Nursing 3, 55–61. https://doi.org/10.1111/j.1741-6787.2006.00051.x

Bickford, E., Holloway, T., Karambelas, A., Johnston, M., Adams, T., Janssen, M., Moberg, C., 2014. Emissions and Air Quality Impacts of Truck-to-Rail Freight Modal Shifts in the Midwestern United States. Environ. Sci. Technol. 48, 446–454. https://doi.org/10.1021/es4016102

Breathen, N. (ed.), 2011. Environmental Impacts of International Shipping: The Role of Ports. OECD, Paris.

Browne, D., O'Mahony, M., Caulfield, B., 2012. How should barriers to alternative fuels and vehicles be classified and potential policies to promote innovative technologies be evaluated? Journal of Cleaner Production 35, 140–151. https://doi.org/10.1016/j.jclepro.2012.05.019

Cade, B.S., Noon, B.R., 2003. A gentle introduction to quantile regression for ecologists. Frontiers in Ecology and the Environment 1, 412–420. https://doi.org/10.1890/1540-9295(2003)001[0412:AGITQR]2.0.CO;2

Cole, M.A., 2004. Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages. Ecological Economics 48, 71–81. https://doi.org/10.1016/j.ecolecon.2003.09.007

Criqui, P., Jaccard, M., Sterner, T., 2019. Carbon Taxation: A Tale of Three Countries. Sustainability 11, 6280. https://doi.org/10.3390/su11226280

de Bruyn, S.M., van den Bergh, J.C.J.M., Opschoor, J.B., 1998. Economic growth and emissions: reconsidering the empirical basis of environmental Kuznets curves. Ecological Economics 25, 161–175. https://doi.org/10.1016/S0921-8009(97)00178-X

Dincer, I., 2000. Renewable energy and sustainable development: a crucial review. Renewable and Sustainable Energy Reviews 4, 157–175. https://doi.org/10.1016/S1364-0321(99)00011-8

Engholm, A., Pernestål, A., Kristoffersson, I., 2020. Cost Analysis of Driverless Truck Operations. Transportation Research Record 2674, 511–524. https://doi.org/10.1177/0361198120930228

European Commission, 2021. Case search - Competition - European Commission [WWW Document]. European Commission - Competition. URL https://ec.europa.eu/competition/elojade/isef/index.cfm?clear=1&policy_area_id=3 (accessed 4.28.21).

European Commission, 2017. Better Regulation Guidelines (Commission Staff Working Document No. SWD (2017) 350). European Commission, Brussels.

Eurostat, 2020. Freight transport statistics - modal split [WWW Document]. Eurostat - Statistics Explained. URL https://ec.europa.eu/eurostat/statistics-explained/index.php/Freight_transport_statistics_-_modal_split#Modal_split_in_the_EU (accessed 4.26.21).

Fleurbaey, M., 2009. Beyond GDP: The Quest for a Measure of Social Welfare. Journal of Economic Literature 47, 1029–1075. https://doi.org/10.1257/jel.47.4.1029

Geels, F.W., 2012. A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. Journal of Transport Geography 24, 471–482. https://doi.org/doi:10.1016/j.jtrangeo.2012.01.021

Giddings, B., Hopwood, B., O'Brien, G., 2002. Environment, economy and society: fitting them together into sustainable development. Sustainable Development 10, 187–196. https://doi.org/10.1002/sd.199

Greenwood, D.T., Holt, R.P.F., 2014. Local Economic Development in the 21st Century: Quality of Life and Sustainability. Routledge.

Grossman, G.M., Krueger, A.B., 1991. Environmental Impacts of a North American Free Trade Agreement (Working Paper No. 3914), Working Paper Series. National Bureau of Economic Research. https://doi.org/10.3386/w3914

Hübler, M., 2017. The inequality-emissions nexus in the context of trade and development: A quantile regression approach. Ecological Economics 134, 174–185. https://doi.org/10.1016/j.ecolecon.2016.12.015

Hussen, A.M., 2005. Principles of Environmental Economics: Economics, Ecology and Public Policy.

IPCC, 2021. Summary for Policymakers, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

IPCC (Ed.), 2014. Climate change 2014: mitigation of climate change: Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Kaika, D., Zervas, E., 2013. The Environmental Kuznets Curve (EKC) theory—Part A: Concept, causes and the CO2 emissions case. Energy Policy 62, 1392–1402. https://doi.org/10.1016/j.enpol.2013.07.131

Kanda, W., Sakao, T., Hjelm, O., 2015. Components of Business Concepts for the Diffusion of Large Scaled Environmental Technology Systems. Journal of Cleaner Production. https://doi.org/doi:10.1016/j.jclepro.2015.10.040.

Kijima, M., Nishide, K., Ohyama, A., 2010. Economic models for the environmental Kuznets curve: A survey. Journal of Economic Dynamics and Control 34, 1187–1201. https://doi.org/10.1016/j.jedc.2010.03.010

Knudson, W.A., 2009. The Environment, Energy, and the Tinbergen Rule. Bulletin of Science, Technology & Society 29, 308–312. https://doi.org/10.1177/0270467608325375

Lantz, M., Svensson, M., Björnsson, L., Börjesson, P., 2007. The prospects for an expansion of biogas systems in sweden - Incentives, barriers and potentials. Energy Policy 35, 1830–1843. https://doi.org/10.1016/j.enpol.2006.05.017

Lee, D.-Y., Thomas, V.M., Brown, M.A., 2013. Electric Urban Delivery Trucks: Energy Use, Greenhouse Gas Emissions, and Cost-Effectiveness. Environ. Sci. Technol. 47, 8022–8030. https://doi.org/10.1021/es400179w

Lieb, C.M., 2003. The environmental Kuznets curve: A survey of the empirical evidence and of possible causes (Working Paper No. 391). Discussion Paper Series.

Lin, N., 2019. CO2 emissions mitigation potential of buyer consolidation and rail-based intermodal transport in the China-Europe container supply chains. Journal of Cleaner Production 240, 118121. https://doi.org/10.1016/j.jclepro.2019.118121

Lorente, D.B., Álvarez-Herranz, A., 2016. Economic growth and energy regulation in the environmental Kuznets curve. Environ Sci Pollut Res 23, 16478–16494. https://doi.org/10.1007/s11356-016-6773-3

Mahood, Q., Eerd, D.V., Irvin, E., 2014. Searching for grey literature for systematic reviews: challenges and benefits. Research Synthesis Methods 5, 221–234. https://doi.org/10.1002/jrsm.1106

Mignon, I., Bergek, A., 2016. System- and actor-level challenges for diffusion of renewable. Journal of Cleaner Production 128, 105–115. https://doi.org/10.1016/j.jclepro.2015.09.048

Montalvo, C., 2008. General wisdom concerning the factors affecting the adoption of cleaner technologies: a survey 1990–2007. Journal of Cleaner Production 16, 7–13. https://doi.org/10.1016/j.jclepro.2007.10.002

Nealer, R., Matthews, H.S., Hendrickson, C., 2012. Assessing the energy and greenhouse gas emissions mitigation effectiveness of potential US modal freight policies. Transportation Research Part A 46, 588–601. https://doi.org/10.1016/j.tra.2011.11.010

Nocera, S., Cavallaro, F., Irranca Galati, O., 2018. Options for reducing external costs from freight transport along the Brenner corridor. European Transport Research Review 10, 53. https://doi.org/10.1186/s12544-018-0323-7

North, D., 1958. Ocean Freight Rates and Economic Development 1730-1913. The Journal of Economic History 18, 537–555. https://doi.org/10.1017/S0022050700107739

OECD, 2021. Database on Policy for the Environment [WWW Document]. OECD. URL https://pinedatabase.oecd.org/Default.aspx?isid=07ff0e7c-96fe-43f6-8deb-85dfc6f97035 (accessed 4.28.21).

OECD/DAC Network on Development Evaluation, 2019. Better Criteria for Better Evaluation Revised Evaluation Criteria Definitions and Principles for Use.

Parker, A., Tritter, J., 2006. Focus group method and methodology: current practice and recent debate. International Journal of Research & Method in Education 29, 23–37. https://doi.org/10.12691/ajap-1-2-2

Pigou, A., 1920. The Economics of Welfare. Macmillan, London.

Pinchasik, D.R., Hovi, I.B., Mjøsund, C.S., Grønland, S.E., Fridell, E., Jerksjö, M., 2020. Crossing Borders and Expanding Modal Shift Measures: Effects on Mode Choice and Emissions from Freight Transport in the Nordics. Sustainability 12, 894. https://doi.org/10.3390/su12030894

Poudel, B.N., Paudel, K.P., Bhattarai, K., 2009. Searching for an Environmental Kuznets Curve in Carbon Dioxide Pollutant in Latin American Countries. Journal of Agricultural and Applied Economics 41, 13–27. https://doi.org/10.1017/S1074070800002522

Ritchie, H., Roser, M., 2020. CO_2 and Greenhouse Gas Emissions [WWW Document]. Our World in Data. URL https://ourworldindata.org/emissions-by-sector (accessed 8.6.21).

Rogers, E.M., 2010. Diffusion of Innovations, 4th Edition. Simon and Schuster.

Romm, J., 2006. The car and fuel of the future. Energy Policy 34, 2609–2614. https://doi.org/10.1016/j.enpol.2005.06.025

Steenberghen, T., López, E., 2008. Overcoming barriers to the implementation of alternative fuels for road transport in Europe. Journal of Cleaner Production 16, 577–590. https://doi.org/10.1016/j.jclepro.2006.12.001

Stern, D.I., 2004. The Rise and Fall of the Environmental Kuznets Curve. World Development 32, 1419–1439. https://doi.org/10.1016/j.worlddev.2004.03.004

Sterner, T., Coria, J., 2012. Policy Instruments for Environmental and Natural Resource Management, 2nd edition. ed. RFF Press, New York.

Swedish Environmental Protection Agency, 2021. Styrmedel för att förändra val och beslut som orsakar miljöproblem [WWW Document]. Naturvårdsverket. URL https://www.naturvardsverket.se/Stod-i-miljoarbetet/Vagledningar/Samhallsekonomisk-konsekvensanalys/Hur-losa-miljoproblem/Utforligare-stod/Styrmedel/ (accessed 4.7.21).

Swedish Environmental Protection Agency, 2012. Styrmedel för att nå miljökvalitetsmålen: en kartläggning. Naturvårdsverket, Stockholm.

Tinbergen, J., 1952. On the Theory of Economic Policy. North-Holland Publishing Company, Amsterdam.

Torras, M., Boyce, J.K., 1998. Income, inequality, and pollution: a reassessment of the environmental Kuznets Curve. Ecological Economics 25, 147–160. https://doi.org/10.1016/S0921-8009(97)00177-8

Triple F, 2020. Indikatorer övergripande utmaningarna [WWW Document]. Triple F. URL https://triplef.lindholmen.se/node/80021/indikatorer-de-overgripande-utmaningarna (accessed 9.9.21).

United Nations, 2020. The Sustainable Development Goals Report 2020. United Nations.

Vora, A.P., Jin, X., Hoshing, V., Saha, T., Shaver, G., Varigonda, S., Wasynczuk, O., Tyner, W.E., 2017. Design-space exploration of series plug-in hybrid electric vehicles for medium-duty truck applications in a total cost-of-ownership framework. Applied Energy 202, 662–672. https://doi.org/10.1016/j.apenergy.2017.05.090

Weitz, N., Carlsen, H., Nilsson, M., Skånberg, K., 2018. Towards systemic and contextual priority setting for implementing the 2030 Agenda. Sustain Sci 13, 531–548. https://doi.org/10.1007/s11625-017-0470-0

Zhang, R., Fujimori, S., 2020. The role of transport electrification in global climate change mitigation scenarios. Environ. Res. Lett. 15, 034019. https://doi.org/10.1088/1748-9326/ab6658

Zhu, H., Duan, L., Guo, Y., Yu, K., 2016. The effects of FDI, economic growth and energy consumption on carbon emissions in ASEAN-5: Evidence from panel quantile regression. Economic Modelling 58, 237–248. https://doi.org/10.1016/j.econmod.2016.05.003

Environmental Science and Pollution Research (2018) 25:5848–5861
https://doi.org/10.1007/s11356-017-0907-0

RESEARCH ARTICLE

The N-shaped environmental Kuznets curve: an empirical evaluation using a panel quantile regression approach

Alexandra Allard[1] · Johanna Takman[2] · Gazi Salah Uddin[1] · Ali Ahmed[1]

Received: 2 October 2017 / Accepted: 1 December 2017 / Published online: 12 December 2017

Abstract

We evaluate the N-shaped environmental Kuznets curve (EKC) using panel quantile regression analysis. We investigate the relationship between CO_2 emissions and GDP per capita for 74 countries over the period of 1994–2012. We include additional explanatory variables, such as renewable energy consumption, technological development, trade, and institutional quality. We find evidence for the N-shaped EKC in all income groups, except for the upper-middle-income countries. Heterogeneous characteristics are, however, observed over the N-shaped EKC. Finally, we find a negative relationship between renewable energy consumption and CO_2 emissions, which highlights the importance of promoting greener energy in order to combat global warming.

Keywords CO_2 emissions · Renewable energy · Trade · Institutions · Quantile regressions

Introduction

Global warming has become one of the most serious world problems today (Duan et al. 2016). During the Paris Climate Conference in 2015, officially known as the 21st Conference of the Parties (COP21), several goals for keeping the rise in global temperature well below 2° were set up (United Nations 2017). In order to combat climate change issues alongside economic prosperity and to reach the COP21 goals, it is important to understand the effect of economic growth on the environment. Environmental degradation can have devastating consequences for humanity, such as health impacts, floods, droughts, damage to ecosystems, and adversely affected economic growth (IPCC 2014). At the same time, human activity is the main driving force behind climate change (Steffen et al. 2011).

In the environmental economics literature, the relationship between environmental degradation and economic growth is well known as the environmental Kuznets curve (EKC). The EKC suggests that environmental degradation initially rises with per capita income. However, with economic growth comes an increased demand for environmental quality, leading to a decreasing environmental deterioration (Hussen 2005). If there is an inverted U-shaped EKC, environmental improvements would eventually occur as economies grow. Consequently, humanity could, without significant deviations, go back to business as usual and still achieve environmental sustainability (Stern 2004). However, studies have observed that the relationship might be N-shaped (e.g., Bhattarai et al. 2009; Álvarez-Herranz and Balsalobre Lorente 2016), which suggests that environmental degradation will start to rise again beyond a certain income level. Yet, to our knowledge, no previous study has examined the N-shaped relationship between CO_2 emissions and GDP per capita using panel quantile analysis while including additional explanatory variables, such as renewable energy consumption, technological development, trade, and institutional quality.

Responsible editor: Philippe Garrigues

✉ Gazi Salah Uddin
gazi.salah.uddin@liu.se

Alexandra Allard
alexandra@allard.se

Johanna Takman
johanna.takman@vti.se

Ali Ahmed
ali.ahmed@liu.se

[1] Department of Management and Engineering, Linköping University, 581 83 Linköping, Sweden

[2] Swedish National Road and Transport Research Institute, Teknikringen 10, 114 28 Stockholm, Sweden

The aim of this study is to evaluate the N-shaped EKC. To this end, we analyze how different countries' environmental degradation is affected by their economic development. Further, we compare three different groups of countries: lower-middle-income countries, upper-middle-income countries, and high-income countries. There are several economic reasons for categorizing countries into different income groups. For example, it is important to study middle-income countries separately, since these countries are home to 73% of the world's poorest people and five billion out of the world's seven billion people live there. Further, middle-income countries are the major drivers of the global growth (World Bank 2017a). Middle-income countries are a diverse group of countries ranging from small nations to major engines in global growth. We therefore break down middle-income economies in two groups, divided by their income, to control for their diverse nature and the different challenges they might face. Since middle-income countries are not as developed as high-income countries, they do not extend as far on the EKC. In order to analyze a wider range of the EKC, we therefore include high-income countries as a benchmark.

Since environmental degradation is not only affected by economic development, we also include variables to control for the effects of renewable energy consumption, technological development, trade, and institutional quality on environmental degradation. We aim to answer the following research questions: What does the relationship between environmental degradation and economic development look like for lower-middle-income countries, upper-middle-income countries, and high-income countries? How can environmental degradation be explained by renewable energy use, technological development, trade, and institutional quality?

We utilized panel quantile analysis in order to address our research questions. We chose to mainly focus on the quantile panel regressions as it provides a more comprehensive picture of the relationship between the variables in comparison with pooled OLS and fixed effects models. Annual data were obtained from the World Development Indicators (WDI) and from the Freedom House database, covering 74 countries over the period of 1994–2012. This was the longest and most up-to-date time series available without reducing our sample, due to missing data. We estimated regression models both for the total sample and the three income groups separately.

This paper contributes to the existing literature by improving our knowledge of the possible N-shaped relationship between income and environmental degradation. The existing literature has mainly focused on different regions, on OECD countries, or on larger samples of countries. Although a small number of studies have focused on different income groups, none of them have to our knowledge used panel quantile regressions. Therefore, there is a gap in the existing EKC literature, which we intend to fill by combining the use of quantile regressions with income classifications.

Literature review

According to the EKC, first proposed by Grossman and Krueger (1991), the relationship between economic growth and environmental degradation has the shape of an inverted U. The N-shaped EKC suggests that the original EKC hypothesis will not hold in the long run. Instead, beyond a certain income level, increased income might once again lead to a positive relationship between economic growth and environmental degradation (de Bruyn et al. 1998). Torras and Boyce (1998) suggest that the N-shaped relationship occurs when the scale effect overcomes the composition and technical effects. This might be the consequence of reduced possibilities to further improve distribution of industries or because of diminishing returns on technological changes (Torras and Boyce 1998; Álvarez-Herranz and Balsalobre Lorente 2015, 2016).

There are several reviews that covers the existing literature on the EKC (Dinda 2004; Stern 2004; Culas 2012; Kaika and Zervas 2013). The inverted U-shaped relationship between income and environmental degradation has been confirmed by several researchers. For example, when using a fixed effects model (FEM), Leitão (2010) finds it for 94 countries with different development levels and Culas (2012) finds it for 23 African countries. Culas (2012) also finds the inverted U-shaped EKC for 9 Latin American countries when using a random effects model (REM). This shape has also been found for 29 OECD countries when using a stochastic impacts by regression on population, affluence, and technology model (Shafiei and Salim 2014) and for 24 European countries when using a pooled mean group approach (Ahmed et al. 2016). Further, Al-Mulali et al. (2016) find the inverted U-shaped relationship for Europe, East Asia and the Pacific, South Asia, and the Americas when using dynamic OLS. It is also found for various countries, when using quantile regressions with fixed effects (You et al. 2015). When using quantile regressions, the inverted U-shaped EKC is found for ASEAN-5 (Duan et al. 2016) and for 19 APEC countries.[1] However, some of the studies finding an inverted U-shaped EKC have not included the cubic form of income. These studies are thereby ignoring the possibility of an N-shaped EKC (e.g., Culas 2012; Duan et al. 2016; Zhang et al. 2016). Lee et al. (2009) demonstrate this by finding an inverted U-shaped EKC when using a quadratic model and an N-shaped EKC when using a cubic model.

Even though the N-shaped EKC is considered to be a new phenomenon, it was found as early as in the 1990s. Grossman and Krueger (1995) and Panayotou (1997) find an N-shaped relationship between economic development and sulfur

[1] ASEAN-5 includes Indonesia, Malaysia, the Philippines, Singapore, and Thailand (Duan et al. 2016) and APEC stands for Asia-Pacific Economic Cooperation (Zhang et al. 2016).

dioxide (SO_2). In both cases, few observations existed after the second turning point, as it was in the extreme end of the data set, and the N-shape was therefore dismissed. Moomaw and Unruh (1997) find the N-shaped EKC when using FEM and cross-sectional OLS. However, the authors also used a structural transition model which indicated that the shift to declining CO_2 emissions most likely was a result of the 1973 oil crisis. The N-shaped EKC is also found for Austria when using pooled OLS (Friedl and Getzner 2003) and for 28 OECD countries when using generalized least squares (Álvarez et al. 2015). When using FEM, the N-shaped relationship is found for 15 Latin American countries (Bhattarai et al. 2009), 28 OECD countries (Álvarez-Herranz and Balsalobre Lorente 2015), and 17 OECD countries (Álvarez-Herranz and Balsalobre Lorente 2016).

The inverted U-shaped EKC and the N-shaped EKC has also been found by the same researchers but for different regions or environmental degradation measures. For example, when using REM Grossman and Krueger (1995) find the N-shaped EKC for SO_2, but the inverted U-shaped relationship for other environmental indicators. Further, López-Menéndez et al. (2014) find the inverted U-shaped EKC for EU27 countries where at least 20% of the country's electricity is generated from renewable energy sources. However, an N-shaped relationship is found for the EU27 countries where less than 20% of the country's electricity is generated from renewable energy sources.

In recent years, the impact of renewable energy on environmental degradation has been widely studied. Various studies indicate that greenhouse gas (GHG) emissions can be reduced as fossil fuels are replaced with renewable energy (López-Menéndez et al. 2014; Shafiei and Salim 2014; Álvarez-Herranz and Balsalobre Lorente 2015, 2016; Al-Mulali et al. 2016). Thereby, renewable energy consumption should have a negative impact on environmental degradation.

Recently, Shahbaz et al. (2017) showed that utilization of energy efficiency is important for sustainable economic development in the long run, for 25 developed economies during the period of 1970–2014. Attiaoui et al. (2017) found a unidirectional causality from renewable energy consumption to output for 22 African countries during the period of 1990–2011. Lu (2017) finds that a long run equilibrium exists among renewable energy consumption, carbon emission, and GDP using panel data for 24 Asian countries during the period of 1990–2012. Paramati et al. (2017) analysis on Next 11 countries suggests that renewable energy production and various economic activities are required for sustainable economic development.

We consider the several control variables in our empirical investigation. In line with the previous literature, we identify particularly three important variables: technology and innovation, trade or openness, and institutional quality. All, strongly connected with environmental policies. For instance, several studies use research and development and patent to measure countries' technology and innovation (Álvarez et al. 2015; Álvarez-Herranz and Balsalobre Lorente 2015, 2016; Ahmed et al. 2016). They found that technological innovation has a negative effect on environmental degradation. Further, the empirical evidence on the relationship between trade and environmental degradation is inconclusive.[2] Moreover, some studies have suggested that institutional variables such as corruption and level of democracy might be important determinants of environmental policies (Zhang et al. 2016; Leitão 2010; Panayotou 1997; Torras and Boyce 1998).

Data and preliminary analysis

We include three groups of countries in the sample: high-income countries, upper-middle-income countries, and lower-middle-income countries. These classifications are defined in accordance with the World Bank (2017b). We choose not to include low-income economies in the study, because these countries' contribution to the global share of GDP as well as to CO_2 emissions is minimal. It would also be problematic to find balanced data for the low-income countries. In contrast, middle-income countries have had a rising importance for the global economy with an increasing industrial output and, hence, rising emissions. Since middle-income economies are expected to grow even more, it is important to investigate how this will affect the global environment. By using high-income economies as a benchmark, we can compare these groups of countries to get a better understanding of what we need to do in order to achieve sustainable development.

This study is based on annual data for CO_2 emissions per capita, real GDP per capita, renewable energy, technological development, trade, and institutional quality. Data for institutional quality are obtained from the Freedom House (2017a) database and remaining series are downloaded from the WDI, obtained from the World Bank (2017c). The dataset covers an unbalanced panel of 74 countries or a balanced panel of 55 countries over the time period 1994 to 2012. Since we use lags of 1 year for technological development, the corresponding time period for this variable is 1993 to 2011. We include all lower-middle-income countries, upper-middle-income countries, and high-income countries with available data for the selected variables over the time period. The included countries are shown in Table 11 (see Appendix 1).

We use CO_2 emissions (CO_2) as a proxy for environmental degradation, as is common in this field of research (Álvarez

[2] See, e.g., Lee et al. (2009), Al-Mulali and Ozturk (2015), You et al. (2015), Al-Mulali et al. (2016), Friedl and Getzner (2003), Duan et al. (2016), Nguyen et al. (2017), and Sohag et al. (2017).

et al. 2015; Álvarez-Herranz and Balsalobre Lorente 2016). Further, CO_2 emissions represent more than 80% of the total global GHG emissions (World Bank 2014). The variable does not measure CO_2 emissions from imported goods and do not subtract emissions from exported goods. Thus, using this variable leads to a production-based approach of the EKC. The CO_2 series is measured in metric tons per capita which enables us to adjust for the effect of population growth on the pollution level. To measure the effect of economic growth on environmental degradation, we use real GDP per capita (*GDP*). Substitution to greener energy sources might decrease environmental degradation. As a measure for this substitution effect, we use renewable energy consumption as the share of total energy consumption (*REN*). To measure the technological development of a country, we use patent applications (*R&D*) as a proxy. We combine two different series, one for patents applied by residents and one for those applied by non-residents. We use an aggregate measure of patents in order to capture the total effect of a country's technological development on the environment. Another possible variable for measuring technological development would be research and development expenditure as a share of GDP. According to Popp (2012), the collection of data for expenditures in research and development can differ between countries and this data is therefore noisy. The available data is also limited for this variable and patent applications is a commonly used proxy for technology (Ahmed et al. 2016). To measure the effects of trade on environmental degradation, we use trade as share of GDP (*TRD)* as a proxy. The variable is constructed as the sum of exports and imports of goods and services measured as the share of GDP. All data are extracted from the World Development Indicator, WDI (World Bank 2017c). As a proxy for the institutional quality in a country, we use the Freedom House (2017a) political rights index and the civil liberties index (*INS*).[3]

Descriptive statistics

Table 1 presents the descriptive statistics of the dependent and the explanatory variables for the total sample of 74 countries over a period of 19 years. In order to minimize the issue of heteroscedasticity and to improve the comparability with previous studies, all variables except for *INS* are expressed in natural logarithms, since *INS* is an index ranging from 1 to 13. Also, when using the natural logarithm on *INS*, it gets further away from a normal distribution with skewness close to − 2 and a high value for the kurtosis.

As we can see in Table 1, we have some excessive skewness to the left for *REN* and CO_2, however a range of ± 2 from a normal distribution with skewness of 0 can be seen as acceptable. Further, we see some excessive kurtosis of 7.07 for *REN* in comparison to a normal distribution with a kurtosis of 3. However, the other variables do not express any excessive deviations from a normal distribution.

The correlations between all variables are shown in Table 2. The value of all correlations between the explanatory variables are way below 0.7, which we use as a rule of thumb for stronger correlation. However, the correlation between *GDP* and *INS* is 0.69, which might lead to problems with multicollinearity when the variables are estimated in the same model. Nevertheless, excluding one of the variables might lead to omitted variable bias. Regarding the rest of the variables, we do not consider their correlations to be of any concern.

Methodology and hypotheses

Model

The theoretical relationship between environmental degradation and economic growth is usually described as follows (Grossman and Krueger 1991; Stern 2004):

$$\mathrm{GHG}_{it} = \alpha_{it} + \beta_1 GDPpc_{it} + \beta_2 GDPpc_{it}^2 + \beta_3 GDPpc_{it}^3 + \beta_4 Z_{it} + \varepsilon_{it}, \tag{1}$$

where GHG refers to the greenhouse gas emissions, that is, environmental degradation, GDPpc stands for income per capita, and *Z* contains all other variables that might affect environmental quality. The coefficient α_{it} measures the average environmental pressure when income has no influence, β refers to the direction and importance of the exogenous variables, and ε_{it} is the error term. Depending on the sign of the different β parameters related to income, the EKC will adopt different shapes (Álvarez-Herranz and Balsalobre Lorente 2016):

(i) If $\beta_1 = \beta_2 = \beta_3 = 0$, there will be either a flat pattern or no relationship between environmental degradation and income.
(ii) If $\beta_1 > 0$ and $\beta_2 = \beta_3 = 0$, there will be a monotonic increasing relationship such that environmental degradation increases along with economic growth.
(iii) If $\beta_1 < 0$ and $\beta_2 = \beta_3 = 0$, there will be a monotonic decreasing relationship between environmental deterioration and income.

[3] In the political rights index, the functioning of the government, electoral process, and political pluralism and participation are included. Associational and organizational rights, personal autonomy and individual rights, freedom of expression and belief, and the rule of law are included in the civil liberties index. As the ideas about civil liberties and political rights constantly evolve changes in the methodology are sometimes made. However, when changes are made, they are introduced gradually, so the comparability between the years remain possible (Freedom House 2017b). We add up these indexes so that 13 is the highest level of institutional quality.

Table 1 Descriptive statistics for total sample

Variable	Mean	Median	Max	Min	Std. dev.	Skewness	Kurtosis	*N*
CO_2	1.42	1.74	3.23	− 1.97	1.08	− 1.00	3.42	1406
GDP	9.08	9.09	11.61	5.90	1.36	− 0.22	2.05	1406
REN	2.38	2.67	4.53	− 4.80	1.51	− 1.53	7.07	1406
R&D	7.48	7.43	13.17	1.61	2.04	0.39	3.17	1406
TRD	4.26	4.24	6.09	2.75	0.54	0.24	3.75	1406
INS	9.43	11.00	13.00	1.00	3.72	− 0.78	2.32	1406

All variables except for *INS* are expressed in natural logarithms in this table, and the following tables. All variables expect *INS* are obtained from WDI (World Bank 2017c). The indexes used in *INS* are obtained from Freedom House (2017a)

CO_2 CO_2 emissions measured in metric tons per capita, *GDP* GDP per capita measured in constant 2010 US dollar, *REN* renewable energy consumption as a share of total energy consumption, *R&D* patent application from residents and nonresidents, *TRD* the sum of exports and imports as share of GDP, *INS* the sum of a political rights index and a civil liberties index minus 15

(iv) If $\beta_1 > 0$ and $\beta_2 < 0$ and $\beta_3 = 0$, we will see the classical inverted U-shaped EKC.

(v) If $\beta_1 < 0$ and $\beta_2 > 0$ and $\beta_3 = 0$, there will be a U-shaped relationship between environmental degradation and income.

(vi) If $\beta_1 > 0$ and $\beta_2 < 0$ and $\beta_3 > 0$, there will be a cubic polynomial or N-shaped relationship between environmental deterioration and income.

(vii) If $\beta_1 < 0$ and $\beta_2 > 0$ and $\beta_3 < 0$, there will be an inverted, or opposite, N-shaped relationship between environmental degradation and economic growth.

We estimated an empirical model consisting of a relationship between CO_2 emissions (*CO_2*) and the following explanatory variables: income (*GDP*), renewable energy consumption (*REN*), technological development (*R&D*), trade (*TRD*), and institutional quality (*INS*). The model is given by

$$\mathrm{CO}_{2it} = \alpha + \beta_1 \mathrm{GDP}_{it} + \beta_2 \mathrm{GDP}^2{}_{it} + \beta_3 \mathrm{GDP}^3{}_{it} + \beta_4 \mathrm{REN}_{it} + \beta_5 R\&D_{i(t-1)} + \beta_6 \mathrm{TRD}_{it} + \beta_7 \mathrm{INS}_{it} + \varepsilon_{it} \quad (2)$$

where i and t are indexes for country and time. All variables except for *INS* are expressed in natural logarithms. We assume that there is some delay before innovations are implemented in a society. In accordance with previous literature (e.g., Álvarez et al. 2015; Álvarez-Herranz and Balsalobre Lorente 2015) we, therefore, choose to lag *R&D*. Popp (2012) argues that patents not only measure the coming years' innovative output, but also measure the level of innovative activity in the country today. As we want *R&D* to reflect both the innovative activity level and innovative output in a country, we choose to lag *R&D* by 1 year. Further, increasing the lag length would not be possible without reducing our sample or imputing a lot of units, due to missing data for the variable for years earlier than 1993.

Table 2 Pearson correlations

	CO_2	GDP	REN	R&D	TRD	INS
CO_2	1.00	–	–	–	–	–
GDP	0.80	1.00	–	–	–	–
REN	− 0.56	− 0.26	1.00	–	–	–
R&D	0.46	0.38	− 0.22	1.00	–	–
TRD	0.25	0.18	− 0.21	− 0.32	1.00	–
INS	0.43	0.69	0.19	0.18	0.05	1.00

Quantile regression

The statistical distribution of data often has an unequal variation and the relationship between the variables can therefore change between the locations on the dependent variable's conditional distribution. Estimations based on the mean values, such as pooled OLS, FEM, and REM, can therefore give incorrect results (Cade and Noon 2003). Quantile regressions evaluate the different points on the conditional distribution of the dependent variable and can thereby provide a more complete picture of the relationship between the variables (Cade and Noon 2003). The motivation for panel quantile approach is to capture the heterogeneous structure of the different income groups and different market condition, as the pooled OLS only consider the mean. We therefore chose to complement the pooled OLS and FEM with a quantile regression analysis.

In quantile regressions, the conditional distribution of the dependent variable is divided into different quantiles, where the 50th quantile represent the median (Hübler 2017). Therefore, quantile regressions are more robust to outliers than estimation techniques referring to the mean. Hübler (2017) also states that the differences between the median and the mean can be large for variables such as CO_2 and GDP. Thus, quantile regression is an interesting approach to the N-shaped EKC hypothesis, because of the possibilities to

Table 3 Hypotheses

Explanatory variable	Effect on CO_2 emissions per capita
GDP	+
GDP^2	−
GDP^3	+
REN	−
R&D	−
TRD	+ for middle-income countries, − for high-income countries
INS	−

estimate different slopes for different quantiles. Given x_i, the conditional quantile of y_i is expressed as

$$Q_{y_{it}}(\tau|x_{it}) = x_{it}^{\tau}\beta_{\tau} \quad (7)$$

where $Q_{y_{it}}(\tau|x_{it})$ means the τth quantile of the dependent variable, x_{it}^{τ} is the vector of explanatory variables for each country i at year t for quantile τ, and β_{τ} symbolizes the slopes of the explanatory variable for quantile τ (Duan et al. 2016). To test the robustness of our variables, we estimated regressions on a balanced dataset and regressions where we excluded renewable energy consumption. We decided to estimate a model which only included balanced data to control for our imputed units. Further, we chose to estimate a model where we excluded renewable energy consumption, since the variable indirectly could measure technological development in the field of renewable energy.

Hypotheses

In accordance with the economic theories and empirical evidence presented earlier in the paper, we formulated hypotheses regarding the directions of the β-parameters. Table 3 shows the expected effect of each explanatory variable on CO_2.

In accordance with the theory of the N-shaped EKC, we hypothesized *GDP* to have a positive effect on CO_2 emissions, reflecting the increasing emissions in the early stages of growth. GDP^2 should show a negative effect indicating decreasing emissions beyond the first turning point, while GDP^3 should show a positive sign, as emissions once again increase with income. We hypothesized that a higher share of renewable energy sources will reduce CO_2 emissions, indicating a negative sign of renewable energy. More efficient technology or emission specific changes in processes should reduce emissions and therefore we hypothesized technological development to have a negative effect on CO_2 emissions. In accordance with the pollution haven hypothesis, we hypothesized that trade will lead to increasing emissions for the middle-income countries, especially for the lower-middle-income countries, and decreasing emissions for high-income countries. Finally, we hypothesized institutional quality to have a negative effect on CO_2 emissions, as institutions should be important components for reducing emissions.

Results and discussions

Preliminary checkups

According to the VIF test, presented in Table 14 (see Appendix 2), no multicollinearity exists in our model. All VIF values are below 5, with the highest value of 3.123, indicating that there is no problem with multicollinearity. The results from the panel data unit root tests are presented in Table 4. The table shows the results from the Fisher PP-statistics (Maddala and Wu 1999) and the LLC-statistics (Levin et al. 2002). All tests were estimated both with a constant and a trend. Rejection of the null hypothesis indicates that the series are stationary.

The tests show that all series are I(0) stationary. However, as can be seen in the table, only the PP-statistics rejects the null hypothesis for the CO_2 series, while only the LLC-statistics rejects the null hypothesis for the *GDP* series. Since we perform these tests to check the statistical properties of the series, rather than deciding between using the variables in level or first difference, the different results between the PP- and LLC-statistics for CO_2 and *GDP* are of less importance. We proceeded by estimating the pooled OLS, FEM, and the quantile regressions in level.

Table 4 Panel data unit root tests

Variable	Level Fisher PP-statistic	LLC-statistic
CO_2	177.621**	−0.718
GDP	77.757	−17.182***
REN	231.783***	−4.684***
R&D	258.250***	−9.618***
TRD	197.093***	−7.029***
INS	177.976***	−4.942***

***, **, and * indicate significant p values at the 1, 5, and 10% level, respectively. Both a constant and a trend were used in the tests

Pooled OLS, fixed effects model, and quantile model

The results from the pooled OLS estimations and the FEM estimations for the unbalanced panels are presented in Table 5. The FEM estimations are fixed both over the individuals and the time period. We also present the p values from the Hausman tests in the table. Estimations (1) and (5) show the results for the total sample, estimations (2) and (6) cover the lower-middle-income countries, estimations (3) and (7) show the results for the upper-middle-income countries, and estimations (4) and (8) cover the high-income countries. The results from the quantile regressions for the total sample and for the different classifications are presented in Tables 6, 7, 8, and 9. Table 10 summarizes the results from all quantile regressions. Table 10 shows that the quantile regression results regarding the relationship between income and environmental degradation are inconclusive. The N-shaped EKC is found in half of the regressions, but some results also indicate that the relationship might have the shape of an inverted N.

Discussion

According to our hypothesis and the theoretical framework, an N-shaped relationship between income and environmental degradation should be expected in the estimations. However, as seen in Tables 5, 6, 7, 8, 9, and 10, the results are inconclusive both between classifications and between the different methods used. The pooled OLS estimations confirm our hypothesis of an N-shaped EKC for the total sample, lower-middle-income countries, and high-income countries. However, when estimating the regressions with FEM, no N-shaped relationship is found for any of the classifications. Instead, the high-income countries show an inverted N-shaped relationship. This is in contrast to the results of Álvarez-Herranz and Balsalobre Lorente (2015, 2016) where estimations with FEM generates the expected N-shaped EKC. Even though the pooled OLS is chosen as the main method in this paper according to the Hausman tests, the results from estimations with FEM should still be consistent and need to be analyzed. Since the N-shaped curve is found when using the pooled OLS estimator, but not when using FEM, it is possible that the heterogeneity eliminates the N-shaped EKC. Observable individual specific effects that are constant over time cannot be separated from non-observable individual specific effects when using FEM. Some effects of *GDP* might therefore be captured in the individual intercept, eliminating the N-shaped EKC. For example, being a rich and highly educated country, which should be correlated to *GDP*, might be included in the individual intercept if this is a factor that is constant over time.

Table 5 Results from pooled OLS and FEM estimations

	Pooled OLS estimator				Fixed effects model			
Explanatory variables	(1) Total sample	(2) LMIC	(3) UMIC	(4) HIC	(5) Total sample	(6) LMIC	(7) UMIC	(8) HIC
GDP	4.319*** (1.159)	31.136*** (11.025)	− 15.357 (21.846)	17.924* (10.162)	− 0.014 (1.116)	9.872 (16.649)	1.903 (10.655)	− 15.913** (7.720)
GDP^2	− 0.361*** (0.134)	− 4.457*** (1.551)	2.005 (2.664)	− 1.737* (1.008)	0.109 (0.131)	− 1.394 (2.360)	− 0.149 (1.270)	1.666** (0.780)
GDP^3	0.011** (0,005)	0.214*** (0.072)	− 0.085 (0.108)	0.057* (0.033)	− 0.006 (0.005)	0.069 (0.111)	0.005 (0.050)	− 0.057** (0.026)
REN	− 0.230*** (0.011)	− 0.533*** (0.014)	− 0.278*** (0.023)	− 0.172*** (0.014)	− 0.257*** (0.013)	− 0.529*** (0.074)	− 0.229*** (0.022)	− 0.185*** (0.016)
R&D	0.102*** (0.008)	0.186*** (0.010)	0.143*** (0.016)	0.027*** (0.009)	0.068*** (0.009)	0.120*** (0.037)	0.082*** (0.012)	0.004 (0.013)
TRD	0.284*** (0.027)	0.236*** (0.041)	0.522*** (0.044)	0.046 (0.032)	0.116*** (0.022)	0.135 (0.091)	0.123*** (0.036)	0.084** (0.039)
INS	0.019*** (0.006)	− 0.010* (0.006)	0.023** (0.010)	0.042*** (0.009)	0.005 (0.004)	0.002 (0.013)	0.008** (0.004)	0.000 (0.009)
Intercept	− 17.444	− 73.461	36.260	− 61.033	− 3.101	− 24.385	− 7.956	51.741
Hausman	–	–	–	–	0.342	0.827	0.617	0.372
Observations	1406	323	380	703	1406	323	380	703
Countries	74	17	20	37	74	17	20	37
R^2	0.816	0.920	0.617	0.504	0.989	0.987	0.980	0.960
Adjusted R^2	0.815	0.919	0.610	0.499	0.988	0.985	0.978	0.956

LMIC lower-middle-income countries, *UMIC* upper-middle-income countries, *HIC* high-income countries

***, **, and * indicate significant p values at the 1, 5, and 10 % level, respectively. Standard errors are presented in the parentheses

Table 6 Results from quantile regression for the total sample

Explanatory variables	10th	20th	30th	40th	50^{th}	60th	70th	80^{th}	90th	95th
GDP	−1.790	−6.581***	−4.043***	1.052	5.545***	4.945***	4.109***	6.470***	4.223	0.158
	(1.667)	(1.614)	(1.400)	(1.743)	(1.148)	(1.478)	(1.114)	(1.551)	(3.485)	(0.486)
GDP^2	0.385**	0.940***	0.641***	0.047	−0.500***	−0.461***	−0.373***	−0.623***	−0.356	0.067
	(0.185)	(0.179)	(0.163)	(0.205)	(0.135)	(0.167)	(0.130)	(0.173)	(0.374)	(0.056)
GDP^3	−0.019***	−0.040***	−0.028***	−0.006	0.016***	0.015**	0.012**	0.021***	0.011	−0.004**
	(0.007)	(0.007)	(0.006)	(0.008)	(0.005)	(0.006)	(0.005)	(0.006)	(0.013)	(0.002)
REN	−0.206***	−0.158***	−0.148***	−0.154***	−0.185***	−0.270***	−0.297***	−0.293***	−0.256***	−0.253***
	(0.009)	(0.012)	(0.010)	(0.011)	(0.017)	(0.017)	(0.018)	(0.009)	(0.015)	(0.006)
R&D	0.068***	0.073***	0.087***	0.089***	0.099***	0.116***	0.110***	0.107***	0.081***	0.069***
	(0.006)	(0.009)	(0.007)	(0.008)	(0.009)	(0.008)	(0.010)	(0.008)	(0.013)	(0.006)
TRD	0.302***	0.368***	0.355***	0.314***	0.345***	0.308***	0.242***	0.233***	0.219***	0.269***
	(0.022)	(0.035)	(0.017)	(0.024)	(0.023)	(0.030)	(0.038)	(0.030)	(0.040)	(0.016)
INS	0.022***	−0.005	−0.011**	−0.004	0.006	0.027***	0.029***	0.017***	0.021*	0.043***
	(0.007)	(0.008)	(0.005)	(0.006)	(0.004)	(0.005)	(0.008)	(0.006)	(0.012)	(0.003)
Intercept	−1.931	11.565	4.615	−9.356	−21.387	−18.532	−15.423	−22.427	−15.802	−2.775

***, **, and * indicate significant p values at the 1, 5, and 10% level, respectively. The standard errors, presented in the parentheses, are obtained with a bootstrap of 500

The results from the quantile regressions are also inconclusive. None of Tables 6, 7, 8, 9, and 10 show uniform results for any of the classifications regarding the relationship between income and environmental degradation. Even though the pooled OLS showed an N-shaped EKC for the total sample, lower-middle-income countries, and high-income countries, only some of the quantiles confirm these results. These inconclusive results might depend on heterogeneity between and within these income groups. A further breakdown of the included countries and their specific characteristics, such as environmental laws and composition of industries, might therefore be needed to fully understand why the N-shaped EKC is only apparent in some of the quantiles.

One interesting finding is that upper-middle-income countries differ from the other classifications regarding the relationship between income and CO_2 emissions. In contrast to the other groups of countries, none of the methods generated an N-shaped EKC in any estimation for the upper-middle-income countries. In fact, some of the quantiles instead show an opposite N-shaped EKC. This indicates that economic growth initially will improve environmental quality up to a certain income level where the relationship instead will be

Table 7 Results from quantile regression for lower-middle-income countries

Explanatory variables	10th	20th	30th	40th	50th	60th	70th	80th	90th	95th
GDP	40.733*	37.528**	33.957**	31.983***	31.701**	9.085	15.229	11.520	25.203	17.236
	(22.708)	(18.940)	(14.890)	(12.110)	(13.582)	(19.349)	(17.187)	(13.825)	(18.766)	(21.340)
GDP^2	−5.796*	−5.305**	−4.796**	−4.498***	−4.485**	−1.451	−2.109	−1.585	−3.553	−2.512
	(3.124)	(2.611)	(2.063)	(1.692)	(1.906)	(2.737)	(2.392)	(1.923)	(2.668)	(3.052)
GDP^3	0.276*	0.251**	0.227**	0.212***	0.213**	0.078	0.099	0.074	0.168	0.123
	(0.143)	(0.119)	(0.095)	(0.078)	(0.089)	(0.129)	(0.111)	(0.089)	(0.126)	(0.145)
REN	−0.524***	−0.505***	−0.481***	−0.484***	−0.493***	−0.481***	−0.514***	−0.533***	−0.525***	−0.608***
	(0.025)	(0.029)	(0.022)	(0.015)	(0.015)	(0.018)	(0.022)	(0.019)	(0.019)	(0.092)
R&D	0.201***	0.209***	0.236***	0.229***	0.225***	0.217***	0.162***	0.159***	0.159***	0.157***
	(0.021)	(0.022)	(0.012)	(0.013)	(0.014)	(0.018)	(0.017)	(0.017)	(0.020)	(0.018)
TRD	0.256***	0.273***	0.241***	0.234***	0.199***	0.069	0.149**	0.197***	0.227***	0.194***
	(0.071)	(0.068)	(0.061)	(0.058)	(0.063)	(0.064)	(0.062)	(0.040)	(0.038)	(0.072)
INS	−0.042***	−0.038***	−0.036***	−0.042***	−0.045***	−0.039***	−0.005	0.011*	0.019***	0.015
	(0.007)	(0.007)	(0.007)	(0.007)	(0.008)	(0.012)	(0.014)	(0.007)	(0.006)	(0.016)
Intercept	−96.551	−89.853	−81.654	−77.106	−75.730	−19.260	−37.220	−28.480	−60.130	−39.387

***, **, and * indicate significant p values at the 1, 5, and 10% level, respectively. The standard errors, presented in the parentheses, are obtained with a bootstrap of 500

Table 8 Results from quantile regression for upper-middle-income countries

Explanatory variables	10th	20th	30th	40th	50th	60th	70th	80th	90th	95th
GDP	43.444* (24.478)	13.616 (24.351)	9.607 (26.289)	− 16.357 (34.620)	− 31.844 (28.634)	− 74.154** (30.883)	− 92.891** (35.934)	− 59.712* (34.981)	33.700 (37.743)	4.165 (44.630)
GDP^2	− 5.101* (2.999)	− 1.531 (2.988)	− 1.035 (3.219)	1.974 (4.202)	3.930 (3.446)	8.987** (3.685)	11.238*** (4.287)	7.137* (4.218)	− 4.201 (4.568)	− 0.395 (5.695)
GDP^3	0.201 (0.122)	0.059 (0.122)	0.039 (0.131)	− 0.077 (0.169)	− 0.159 (0.138)	− 0.360** (0.146)	− 0.451*** (0.170)	− 0.282* (0.169)	0.174 (0.183)	0.013 (0.240)
REN	− 0.158*** (0.028)	− 0.241*** (0.040)	− 0.288*** (0.036)	− 0.345*** (0.035)	− 0.396*** (0.032)	− 0.377*** (0.033)	− 0.386*** (0.035)	− 0.364*** (0.038)	− 0.323*** (0.045)	− 0.315*** (0.099)
R&D	0.151*** (0.052)	0.166*** (0.030)	0.145*** (0.024)	0.133*** (0.044)	0.178*** (0.017)	0.168*** (0.016)	0.177*** (0.015)	0.168*** (0.016)	0.157*** (0.017)	0.078 (0.098)
TRD	0.543*** (0.049)	0.468*** (0.045)	0.468*** (0.039)	0.509*** (0.056)	0.531*** (0.061)	0.560*** (0.060)	0.566*** (0.056)	0.603*** (0.062)	0.689*** (0.112)	0.222 (0.725)
INS	− 0.022 (0.024)	− 0.013 0.019)	− 0.022 (0.016)	− 0.003 (0.018)	0.015 (0.012)	0.027*** (0.009)	0.038*** (0.008)	0.045*** (0.011)	0.083*** (0.013)	0.052 (0.053)
Intercept	− 126.169	− 42.745	− 31.635	42.640	83.154	200.904	252.829	163.612	− 91.701	− 13.728

***, **, and * indicate significant *p* values at the 1, 5, and 10% level, respectively. The standard errors, presented in the parentheses, are obtained with a bootstrap of 500

positive before it ones again becomes negative. This is an interesting finding that is difficult to explain. Possibly, it could be a consequence of a high-energy efficiency, compensating for the increased emissions caused by the scale effect. Further, it could also be a consequence of a growing amount of foreign direct investment and multinational companies operating in these countries, leading to an inflow of technology from more developed countries. Improvements in the countries' technological frontiers could thereby outpace the scale effect, causing a negative effect of *GDP* on CO_2. However, in most quantiles for the upper-middle-income countries, no significant relationship is found.

The inconclusive results suggest that the EKC relationship should be studied with carefulness. It is common in the research field to only use mean regressions as method, which might generate non-representative results for many of the countries included in the sample. When using quantile regressions, we see that the relationship between income and environment widely differs between quantiles. These results are in line with those of Duan et al. (2016), You et al. (2015), and

Table 9 Results from quantile regression for high-income countries

Explanatory variables	10th	20th	30th	40th	50th	60th	70th	80th	90th	95th
GDP	99.187** (44.082)	− 7.424 (47.173)	38.070* (19.701)	31.216* (16.572)	15.636 (15.596)	32.518** (14.150)	46.389*** (8.835)	7.975 (35.73-5)	1.845 (40.72-4)	− 0.776 (50.320)
GDP^2	− 9.337** (4.360)	0.956 (4.775)	− 3.698* (1.935)	− 3.022* (1.624)	-1.486 (1.538)	− 3.206** (1.413)	− 4.692*** (0.883)	− 0.863 (3.585)	− 0.222 (4.090)	0.095 (4.848)
GDP^3	0.293** (0.143)	− 0.038 (0.161)	0.121* (0.063)	0.098* (0.053)	0.048 (0.050)	0.106** (0.047)	0.159*** (0.029)	0.032 (0.119)	0.010 (0.136)	− 0.003 (0.155)
REN	− 0.220*** (0.021)	− 0.187*** (0.025)	− 0.166*** (0.020)	− 0.151*** (0.014)	− 0.136*** (0.014)	− 0.123*** (0.016)	− 0.121*** (0.021)	− 0.168** (0.073)	− 0.152** (0.076)	− 0.186*** (0.049)
R&D	− 0.030 (0.019)	0.004 (0.016)	0.011 (0.011)	0.010 (0.008)	0.014* (0.008)	0.007 (0.008)	0.036** (0.019)	0.064*** (0.017)	0.075*** (0.016)	0.059** (0.026)
TRD	0.029 (0.031)	0.040 (0.079)	0.016 (0.046)	0.027 (0.035)	0.020 (0.037)	0.020 (0.035)	− 0.041 (0.063)	0.023 (0.070)	0.135 (0.083)	0.193* (0.101)
INS	0.068*** (0.011)	0.046** (0.021)	0.019 (0.013)	0.014 (0.009)	0.009 (0.009)	0.008 (0.010)	0.007 (0.013)	0.039 (0.045)	0.046 (0.046)	0.087 (0.033)
Intercept	− 349.324	17.970	− 129.645	− 106.494	− 53.791	− 108.620	− 151.146	− 23.937	− 4.682	2.350

***, **, and * indicate significant *p* values at the 1, 5, and 10% level, respectively. The standard errors, presented in the parentheses, are obtained with a bootstrap of 500

Table 10 Summary of the quantile regression estimations

	Total sample			LMIC			UMIC			HIC		
Quantile	L	M	H	L	M	H	L	M	H	L	M	H
GDP	−	+	+	+	+	/	/	/	−	+	+	/
GDP^2	+	−	−	−	−	/	/	/	+	−	−	/
GDP^3	−	+	+	+	+	/	/	/	−	+	+	/
REN	−	−	−	−	−	−	−	−	−	−	−	−
R&D	+	+	+	+	+	+	+	+	+	/	/	+
TRD	+	+	+	+	+	+	+	+	+	/	/	/
INS	/	/	+	−	−	+	/	/	+	+	/	/

+ means that the variable has a significant positive effect on CO_2 emission for at least two out of three quantiles, − means that that the variable has a significant negative effect on CO_2 emission for at least two out of three quantiles, and / means that no significant or uniform effect could be found

L lower quantiles, the 10th, 20th, and 30th quantile; *M* middle quantiles, 40th, 50th, and 60th quantiles; *H* for higher quantiles, 70th, 80th, 90th, and 95th quantiles

Zhang et al. (2016) where the shape of the EKC also is inconclusive when using quantile regressions. Policy implications which are only based on results from mean regressions might therefore be ineffective. Further, a large part of the existing literature on the EKC omit the cubic relationship in their estimations and thereby ignore the possibility of an N-shaped EKC. In this paper, the inverted U-shaped relationship, confirmed in several previous studies, is only found in the 10th quantile for upper-middle-income countries. Thus, this is the only regression in our study that supports the original EKC hypothesis. Omitting the cubic relationship might therefore lead us to erroneously support the inverted U-shaped EKC hypothesis.

Another possible explanation for the inconclusive results might be that the relationship between income and environmental degradation is more complex than our methodology allows us to examine. The relationship might have a functional form other than those that are possible to capture by the model applied in this paper. Therefore, the estimation methods need to be further developed to test for other more complicated relationships. For example, we do not test for a non-monotonic increasing or decreasing relationship, like a cubic function with saddle point, which could be a possible shape of the relationship.

According to the theoretical framework and our hypotheses, the share of renewable energy in total energy consumption should have a negative effect on CO_2 emissions. This hypothesis is supported by all estimations, both with the pooled OLS estimator, FEM, and quantile regressions. The results are also robust to the sensitivity analysis and are highly significant in all income groups. The robustness of this variable shows that the substitution to renewable energy is an important aspect in reducing the environmental degradation. These results are also in line with the findings in the previous literature (López-Menéndez et al. 2014; Shafiei and Salim 2014; Álvarez-Herranz and Balsalobre Lorente 2015, 2016; Al-Mulali et al. 2016). When we excluded renewable energy in the sensitivity analysis, the N-shaped EKC was no longer apparent for the total sample and lower-middle-income countries. This suggests that increasing the share of renewable energy is crucial in order to achieve a negative relationship between income and environmental degradation in the first place. However, the share of renewable energy cannot exceed 100%, which might be the reason for the second turning point of the EKC. Environmental deterioration does not only come from the use of energy, but also from other factors such as the destruction of natural resources, for example, deforestation, as well as the industrial process. When the share of renewable energy is already filled, further increases in income might therefore lead to increased pollution levels along with the scale effect.

It was hypothesized that technological development would have a negative effect on CO_2 emissions because of greener and more efficient technologies. However, in contrast to our hypothesis, the results show a positive effect of technological development on environmental degradation. Yet, the relationship is insignificant in most estimations for the high-income-countries. The results are inconsistent with those of Álvarez et al. (2015), Ahmed et al. (2016), and Álvarez-Herranz and Balsalobre Lorente (2015, 2016), where the effect was negative. However, their studies were conducted on OCED countries and European countries, which are more developed than parts of our sample. Further, Álvarez et al. (2015) and Álvarez-Herranz and Balsalobre Lorente (2015, 2016) used energy RD&D as a proxy instead of patents. A possible reason behind the positive effect of technological development is that our proxy includes all patents and not only patents linked to cleaner technologies. Therefore, we include technological development with all characteristics, where some lead to less pollution and some lead to more.

As stated above, the effect of technological development on CO_2 emissions is inconclusive for the high-income countries. The insignificant results shown in several quantiles and in the pooled OLS might depend on the share of environmentally related patents in these countries. It is possible that technological development might have a negative effect on CO_2 emissions in some of the countries if these invest more in developing greener technologies than others. This heterogeneity could be a reason behind the insignificant effect in some of the estimations. It should also be noted that the positive effect of technological development decreases as we move from the lower income groups to the higher. This can indicate that as a country develops, their share of green patents will rise and thereby decrease the positive effect on CO_2 emissions. In the sensitivity analysis, where renewable energy was excluded, technological development still has a positive effect on CO_2 emissions, even if the impact of the variable is slightly changed. This implies that even if renewable energy captures some of the effect of technological development on CO_2 emissions, the change in technological development is not crucial.

According to our hypotheses trade would be positive for middle-income countries but negative for high-income countries. However, previous literature is quite inconsistent for this variable. For example, Lee et al. (2009) find evidence for the PHH, while You et al. (2015) do not find any significant results for the variable. In contrast to these studies, our results show a positive effect of trade on environmental degradation for all classifications when using pooled OLS, FEM, and quantile regressions. However, the variable is not significant for the high-income countries when using pooled OLS or in any of the quantiles. The insignificant effect indicates that trade might have both positive and negative effects on CO_2 emissions in the high-income countries. We argue that increasing transportation, as a consequence of trade, might be one reason for the positive relationship. However, in the high-income countries, this positive effect on CO_2 emissions might be in conflict with a negative effect. When countries engage in trade, the distribution of industries change as richer countries can move their production to countries with lower costs and thereby shift their production to the service sector. This will result in a reduction in CO_2 emissions in high-income countries. The reduction might be large enough to compensate for the increased CO_2 emissions coming from transportation and the scale effect. Therefore, our results neither confirm nor reject the PHH.

The results for our last variable, institutional quality, is inconclusive. Most regressions show a positive effect of institutional quality on CO_2 emissions, in contrast to our hypothesis. However, this might be a consequence of the correlation between institutional quality and GDP being 0.69. The expected negative effect on CO_2 emissions is only confirmed in a few estimations: in the 10th to 60th quantile and the pooled OLS for the lower-middle-income countries, and in the 30th quantile for the total sample. Thus, one conclusion that can be drawn from our results is that institutional quality is most important for the lower-middle-income countries, especially for countries with lower pollution levels. A reason might be that less-developed countries often have worse political rights and civil liberties. If a country already has well-developed political rights and civil liberties, an increase in any of these variables might not affect the country as much. Improved institutions in, for example, high-income countries might therefore not have any direct impact on the environment, unless the institution is directly connected to environmental quality. However, these findings are in contrast to the results of Zhang et al. (2016), who observed a negative effect of democracy on CO_2 emissions in the 90th to 95th quantiles and that corruption improves environmental quality in the lower quantiles. Further, our results are also inconsistent with those of Panayotou (1997), Torras and Boyce (1998), Leitão (2010), and Al-Mulali and Ozturk (2015), which all find that institutional quality has a negative effect on environmental degradation. However, when estimating their models, they used other proxies for institutional quality, which might explain the differences in results.

One reason behind the inconclusive results for institutional quality, both within this study and in comparison to previous literature, could be that the methodology for creating the indexes changes with the ideas about political rights and civil liberties. The indexes might therefore not fully reflect the impact of a change in one country's institutions, when the common ideas in the world change in the same direction. Further, for many countries, the index does not change over the time period. This is the case for many high-income countries which have the highest level of institutional quality, according to this index, for all the measured years. It should be added that the results regarding the effect of institutional quality on CO_2 emissions are not robust in the sensitivity analysis. The effect is negative for the total sample and lower-middle-income countries in the estimations on the balanced panels. Further, it is negative in all estimations except for upper-middle-income countries when excluding renewable energy. It is therefore possible that the variable for renewable energy captures some of the effect of environmental connected institutions, which otherwise might be included in institutional quality.

Conclusions and policy implications

Using a pooled OLS estimator, we find evidence for an N-shaped relationship between income per capita and CO_2 emissions for lower-middle-income countries, high-income countries, and the total sample. These results support our hypothesis of an N-shaped EKC. However, no significant relationship is found for the upper-middle-income countries. When using quantile regressions, the N-shaped EKC is only found in some of the quantiles for lower-middle-income countries, high-income countries, and the total sample, but not in any of the quantiles for the upper-middle-income countries. Even though the majority of the statistically significant results show an N-shaped EKC, the results are heterogeneous and no strong conclusions can be drawn regarding the shape of the EKC.

The inconclusive results might be a consequence of heterogeneity across and within the income groups of countries. Further breakdowns of the countries could therefore help explain the relationship between income and environmental degradation and why it differs between the classifications. The results show that the upper-middle-income countries deviate from the other income groups and no single estimation or quantile show an N-shaped EKC. A further investigation of these countries' characteristics would therefore be needed to understand what factors that distinguish this income group from the others.

To increase the share of renewable energy is a determining factor in reducing CO_2 emissions. This is confirmed in all estimations for all classifications and the results are highly significant. These results indicate that it is important to encourage substitution to greener energy in order to combat climate change. In contrast to our hypothesis, the results suggest that technologic development increases CO_2 emissions. However, we argue that this is because our variable measures all advances in technology and not only those related to environmental improvements. The quantile regressions generate inconclusive results for the high-income countries, which could be a consequence of some countries having a higher share of energy related RD&D. This could explain why the effect is statistically insignificant in several quantiles and indicates that increases in energy innovation reduces CO_2 emissions.

According to our results, trade has a positive effect on CO_2 emissions for all classifications and methods used, but is not significant for high-income countries. We argue that this positive effect occurs as a result of increased transportation. The insignificant effect for the high-income countries indicates that trade might both have positive and negative effects in these countries. Even though our results do not support the PHH, they neither reject it. When it comes to institutional quality, our results only show the expected negative effect on CO_2 emissions for lower-middle-income countries in the lower quantiles. This indicates that improvements in institutional quality is most important for these countries. However, these results are not consistent with the results from our sensitivity analysis, indicating that the indexes do not fully reflect the impact of change in institutional quality. It would therefore be interesting to investigate if the results for institutional quality would be the same when using other indexes.

Based on our findings, it is clear that policies need to be designed individually for each country, depending on their income level and intensity of CO_2 emissions. There is no policy that will fit every country, since the relationship of CO_2 emissions with income, renewable energy, technological development, trade, and institutional quality differs with country income classifications and quantiles. Our most important policy suggestion is to implement more policies that promote the substitution to renewable energy. Policies promoting technologies with less-polluting characteristics should also be implemented; this is especially important for middle-income countries. For lower-middle-income countries, it is also important to implement policies that increase the institutional quality, in terms of political rights and civil liberties.

The inconclusive results in this study regarding the shape of the EKC suggest that further research is needed to fully understand the pollution-income relationship. The relationship might have a functional form that cannot be captured by the empirical model applied in this paper. Therefore, further research should apply models which consider other possible shapes than those normally examined in EKC-studies. It is important to further investigate the relationship between income and environmental degradation in order to combat climate change and to reach a sustainable economic development.

Acknowledgements This paper benefited from the discussions we had with seminar participants at the Economics Division, Linköping University, Sweden. Third author is thankful for the financial support provided by the Jan Wallander and Tom Hedelius Foundations.

Appendix 1

Table 11 Country classification

Lower-middle-income countries	Upper-middle-income countries	High-income countries
Armenia	Algeria	Australia
Bangladesh	Argentina	Austria
Egypt, Arab Republic	Belarus	Belgium
Guatemala	Brazil	Canada
India	Bulgaria	Chile
Indonesia	China	Croatia
Kenya	Colombia	Czech Republic
Mongolia	Ecuador	Denmark
Pakistan	Georgia	Estonia
Philippines	Iran, Islamic Republic	Finland
Sri Lanka	Kazakhstan	France
Tajikistan	Macedonia, FYR	Germany
Tunisia	Malaysia	Greece
Ukraine	Mexico	Hungary
Uzbekistan	Peru	Iceland
Vietnam	Romania	Ireland
Zambia	Russian Federation	Israel
	South Africa	Japan
	Thailand	Korea, Republic
	Turkey	Latvia
		Lithuania
		Luxembourg
		Netherlands
		New Zealand
		Norway
		Poland
		Portugal
		Saudi Arabia
		Singapore
		Slovak Republic
		Slovenia
		Spain
		Sweden
		Switzerland
		UK
		USA
		Uruguay

Appendix 2

Table 12 Balanced data pooled OLS

Explanatory variables	Total sample	Lower MIC	Upper MIC	HIC
GDP	5.745*** (1.345)	49.580*** (13.251)	6.677 (19.232)	43.649*** (14.606)
GDP^2	− 0.515*** (0.153)	− 6.752*** (1.821)	− 0.576 (2.344)	− 4.201*** (1.431)
GDP^3	0.016*** (0.006)	0.309*** (0.083)	0.015 (0.095)	0.135*** (0.047)
REN	− 0.258*** (0.012)	− 0.478*** (0.017)	− 0.411*** (0.025)	− 0.142*** (0.016)
R&D	0.077*** (0.008)	0.217*** (0.013)	0.110*** (0.014)	0.057*** (0.010)
TRD	0.262*** (0.030)	− 0.122** (0.053)	0.371*** (0.040)	0.151*** (0.043)
INS	− 0.011* (0.006)	− 0.062*** (0.008)	0.037*** (0.009)	− 0.006 (0.026)
Intercept	− 21.290	− 121.340	52.416	− 150.600
Observations	1045	171	323	551
Countries	55	9	17	29
R^2	0.820	0.956	0.692	0.527
Adjusted R^2	0.819	0.954	0.685	0.521

***, **, and * indicate significant *p* values at the 1, 5, and 10% level, respectively. Standard errors are presented in the parentheses

Table 13 Pooled OLS when excluding REN

Explanatory variables	Total sample	Lower MIC	Upper MIC	HIC
GDP	1.574 (1.333)	28.976 (25.769)	− 17.185 (25.607)	32.389*** (11.145)
GDP^2	0.010 (0.153)	− 4.011 (3.625)	2.413 (3.123)	− 3.109*** (1.106)
GDP^3	− 0.005 (0.006)	0.189 (0.169)	− 0.107 (0.127)	0.100*** (0.036)
R&D	0.128*** (0.009)	0.297*** (0.023)	0.083*** (0.018)	0.069*** (0.009)
TRD	0.414*** (0.030)	0.575*** (0.093)	0.565*** (0.051)	0.157*** (0.034)
INST	− 0.043*** (0.005)	− 0.057*** (0.014)	− 0.054 (0.009)	− 0.044*** (0.007)
Intercept	− 12.274	− 75.068	36.283	− 111.836
Observations	1406	323	380	703
Countries	74	17	20	37
R^2	0.754	0.563	0.472	0.394
Adjusted R^2	0.753	0.555	0.464	0.389

***, **, and * indicate significant *p* values at the 1, 5, and 10% level, respectively. Standard errors are presented in the parentheses

Table 14 VIF test

Variables	VIF
GDP	3.123
REN	1.554
R&D	1.536
TRD	1.368
INS	2.655

References

Ahmed A, Uddin GS, Sohag K (2016) Biomass energy, technological process and the environmental Kuznets curve: evidence from selected European countries. Biomass Bioenergy 90:202–208

Al-Mulali U, Ozturk I (2015) Investigating the validity of the environmental Kuznets curve hypothesis in Cambodia. Ecol Indic 57:324–330

Al-Mulali U, Ozturk I, Solarin SA (2016) Investigating the environmental Kuznets curve hypothesis in seven regions: the role of renewable energy. Ecol Indic 67:267–282

Álvarez A, Balsalobre D, Cantos JM (2015) Public budget for energy RD&D and the effects on energy intensity and pollution levels. Environ Sci Pollut Res 22(7):4881–4892

Álvarez-Herranz A, Balsalobre Lorente D (2015) Energy regulation in the EKC model with a dampening effect. Int J Environ Anal Chem 2(3): 1–10

Álvarez-Herranz A, Balsalobre Lorente D (2016) Economic growth and energy regulation in the environmental Kuznets curve. Environ Sci Pollut Res 23(16):16478–16494

Attiaoui I, Toumi H, Ammouri B, Gargouri I (2017) Causality links among renewable energy consumption, CO2 emissions, and economic growth in Africa: evidence from a panel ARDL-PMG approach. Environ Sci Pollut Res 24(14):13036–13048

Bhattarai K, Paudel KP, Poudel BN (2009) Searching for an environmental Kuznets curve in carbon dioxide pollutant in Latin American countries. J Agric Appl Econ 41(1):13–27

Cade B, Noon B (2003) A gentle introduction to quantile regression for ecologists. Front Ecol Environ 1(8):412–420

Culas RJ (2012) REDD and forest transition: tunneling through the envrionmental Kuznets curve. Ecol Econ 79:44–51

de Bruyn SM, van den Bergh JC, Opschoor JB (1998) Economic growth and emissions: reconsidering the empirical basis of environmental Kuznets curves. Ecol Econ 25(2):161–175

Dinda S (2004) Environmental Kuznets curve hypothesis: a survey. Ecol Econ 49(4):431–455

Duan L, Guo Y, Zhu H, Yu K (2016) The effects of FDI, economic growth and energy consumption on carbon emissions in ASEAN-5: evidence from panel quantile regression. Econ Model 58:237–248

Freedom House (2017a) Freedom in the World. Retrieved from Freedom House: https://freedomhouse.org/report-types/freedom-world (2017, February 08)

Freedom House (2017b) Freedom in the World 2017. Retrieved from Freedom House: https://freedomhouse.org/report/methodology-freedom-world-2017 (2017, February 20)

Friedl B, Getzner M (2003) Determinants of CO2 emissions in a small open economy. Ecol Econ 45:133–148

Grossman GM, Krueger AB (1991) Environmental impacts of a North American Free Trade Agreement. Working Paper No. 3914

Grossman GM, Krueger AB (1995) Economic growth and the environment. Q J Econ 110(2):353–377

Hübler M (2017) The inequality-emissions nexus in the context of trade and development: a quantile regression approach. Ecol Econ 134:174–185

Hussen A (2005) Principles of environmental economics. Routledge, New York

IPCC (2014) Summary for policymakers. In: Climate change 2014: Impacts,Adaptation, and Vulnerability Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press

Kaika D, Zervas E (2013) The environmental Kuznets curve (EKC) theory—part A: concept, causes and the CO2 emissions case. Energ Policy 62: 1392–1402

Lee C-C, Chiu Y-B, Sun C-H (2009) Does one size fit all? A reexamination of the environmental Kuznets curve using the dynamic panel data approach. Appl Econ Perspect Policy 31(4):751–778

Leitão A (2010) Corruption and the environmental Kuznets curve: empirical evidence for sulfur. Ecol Econ 69:2191–2201

Levin A, Lin C-F, Chu C-S (2002) Unit root tests in panel data: asymptotic and finite-sample properties. J Econ 108(1):1–24

López-Menéndez AJ, Moreno B, Pérez R (2014) Environmental costs and renewable energy: re-visiting the environmental Kuznets curve. J Environ Manag 145:368–373

Lu WC (2017) Renewable energy, carbon emissions, and economic growth in 24 Asian countries: evidence from panel cointegration analysis. Environ Sci Pollut Res 24:26006–26615

Maddala GS, Wu S (1999) A comparative study of unit root tests with panel data and a new simple test. Oxf Bull Econ Stat 61(S1):631–652

Moomaw WR, Unruh GC (1997) Are environmental Kuznets curves misleading us? The case of CO2 emissions. Environ Dev Econ 2: 451–463

Nguyen DK, Sévi B, Sjö B, Uddin GS (2017) The role of trade openness and investment in examining the energy-growth-pollution nexus: empirical evidence for China and India. Appl Econ 49:1–16

Panayotou T (1997) Demystifying the environmental Kuznets curve: turning a black box into a policy tool. Environ Dev Econ 2:465–464

Paramati SR, Sinha A, Dogan E (2017) The significance of renewable energy use for economic output and environmental protection: evidence from the Next 11 developing economies. Environ Sci Pollut Res24:13546–13560

Popp D (2012) The role of technological change in green growth. Policy Research Working Paper 6239

Shafiei S, Salim RA (2014) Non-renewable and renewable energy consumption and CO2 emissions in OECD countries: a comparative analysis. Energ Policy 66:547–556

Shahbaz M, Shahzad SJH, Mahalik MK, Sadorsky P (2017) How strong is the causal relationship between globalization and energy consumption in developed economies? A country-specific time-series and panel analysis. Appl Econ. https://doi.org/10.1080/00036846.2017.1366640

Sohag K, Al Mamun M, Uddin GS, Ahmed AM (2017) Sectoral output, energy use, and CO2 emission in middle-income countries. Environ Sci Pollut Res 24(10):9754–9764

Steffen W, Grinewald J, Crutzen P, Mc Neill J (2011) The Anthropocene: conceptual and historical perspectives. Philos Trans R Soc 369:842–867

Stern DI (2004) The rise and fall of the environmental Kuznets curve. World Dev 32(8):1419–1439

Torras M, Boyce JK (1998) Income, inequality, and pollution: a reassessment of the environmental Kuznets curve. Ecol Econ *25*(2):147–160

United Nations (2017) The Paris Agreement. Retrieved from United Nations Framework Convention on Climate Change: http://unfccc.int/paris_agreement/items/9485.php (2017, May 12)

World Bank (2014). Understanding CO2 emissions from the global energy sector. Retrieved from World Bank: http://documents.worldbank.org/curated/en/873091468155720710/pdf/851260BRI0Live00Box382147B00PUBLIC0.pdf

World Bank (2017a) Middle income countries. Retrieved from World Bank: http://www.worldbank.org/en/country/mic/overview (2017, February 14)

World Bank (2017b) World Bank Country and Lending Groups. Retrieved from The World Bank: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups (2017, February 09)

World Bank (2017c) World Development Indicators. Retrieved from World Bank: http://data.worldbank.org/indicator (2017, February 08)

You W-H, Zhu H-M, Yu K, Peng C (2015) Democracy, financial openness, and global carbon dioxide emissions: heterogeneity across existing emission levels. World Dev 66:189–207

Zhang Y-J, Yin Y-L, Chevallier J, Shen B (2016) The effect of corruption on carbon dioxide emissions in APEC countries: a panel quantile regression analysis. Technol Forecast Soc Chang 112:220–227

Transport Policy 110 (2021) 150–160

Contents lists available at ScienceDirect

Transport Policy

journal homepage: www.elsevier.com/locate/tranpol

A framework for barriers, opportunities, and potential solutions for renewable energy diffusion: Exemplified by liquefied biogas for heavy trucks

Johanna Takman [a,b,*], Yvonne Andersson-Sköld [a,b,**]

[a] Swedish National Road and Transport Research Institute (VTI), Box 55685, 102 15, Stockholm, Sweden
[b] Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden

ARTICLE INFO

Keywords:
Renewable energy
Heavy trucks
Framework
Opportunities
Barriers
Liquefied biogas

ABSTRACT

This study has developed and applied a framework to analyse barriers, opportunities, and potential solutions for the diffusion of alternative fuels, here exemplified by liquefied biogas (LBG) for heavy trucks. The study is based on expert and stakeholder interviews in Sweden. Also, the study estimates a cost example of using heavy duty LBG-trucks instead of conventional diesel trucks.

The framework is based on two previously published frameworks to categorise barriers, opportunities, and potential solutions and comprises five categories: financial, technical/commercial/physical, policy, public acceptability, and market structure/interaction barriers. Each category considers both the system and actor levels. The results of this study fit the framework's categories well, and the framework is appropriate for analysing the diffusion of liquefied biogas for heavy trucks, and other technologies with similar characteristics. The results further indicate that a network level, in addition to the system and actor levels, could advance our understanding of renewable energy diffusion.

The most mentioned opportunities were climate/environmental benefits, potential profitability, and newly introduced policies. The cost estimates show that given current taxes and policies in Sweden, the costs of using LBG-trucks are only marginally higher than those of using conventional diesel trucks.

Commonly cited barriers were financial issues, an unstable policy context, lack of infrastructure, and lack of knowledge. Suggested solutions for overcoming barriers were financial incentives, a stable policy context, demonstration projects, and information campaigns. Improved knowledge and working together throughout the biogas value chain, with a palette of renewable energy options, are important for accelerating a sustainable renewable fuel diffusion. Several policy instruments that currently exists in Sweden already target the mentioned barriers. Thus, it is important to continuously evaluate policy instruments to understand if they are effective and efficient, or if anything need to be changed to reach the targets of the policy instrument.

1. Introduction

There is an urgent need to combat climate change. The transport sector is the only major sector in the EU in which greenhouse gas (GHG) emissions are still rising (European Commission, 2019). Meeting the Paris Agreement targets calls for effective climate actions that will help reduce CO_2 emissions in just a few years (Gota et al., 2016). Replacing fossil energy with renewable energy is one of several important actions to reduce CO_2 emissions. The European Union aims to increase the share of renewable energy in the transport sector, with an overall target of 14% for the Member States by 2030, in accordance with the revised Renewable Energy Directive (2018/2001/EU). This will require a shift to alternative fuels in the transport sector, which will require more than one alternative energy source (Ammenberg et al., 2018). Several barriers must be overcome to accelerate the diffusion of renewable energy technologies for transport purposes. Identifying these barriers, as well as opportunities, is of great importance in order to find solutions and design policy instruments.

Both passenger cars and freight transport by road cause significant CO_2 emissions. Policy instruments with the aim to reduce CO_2 emissions

* Corresponding author. Swedish National Road and Transport Research Institute (VTI), Box 55685, 102 15, Stockholm, Sweden.
** Corresponding author. Swedish National Road and Transport Research Institute (VTI), Box 55685, 102 15, Stockholm, Sweden.
E-mail addresses: johanna.takman@vti.se (J. Takman), yvonne.andersson-skold@vti.se (Y. Andersson-Sköld).

https://doi.org/10.1016/j.tranpol.2021.05.021
Received 20 March 2020; Received in revised form 11 May 2021; Accepted 17 May 2021
Available online 29 May 2021

have already started to have an effect for passenger transport but have not yet had the same effect for freight transports (Pinchasik et al., 2018). At the same time, the demand for freight transport is expected to continue to increase in the future, increasing the importance of effective policy instruments with the aim to reduce CO_2 emissions.

Electrification is a frequently discussed solution for reducing transport related CO_2 emissions. When looking at registered vehicles by propulsion system in Sweden, there is a clear increasing trend towards electric vehicles and hybrids in the private vehicle segment, even if compressed biogas and ethanol are also common alternatives (Transport Analysis Sweden, 2020). However, in the long haulage heavy duty truck segment, alternatives such as battery electric vehicles (BEV) and compressed biogas have not yet gathered any larger market shares and there are several other alternatives for replacing fossil fuels that are also being discussed in the long haulage heavy-duty segment.

Some of the discussed renewable alternatives for long haulage heavy duty trucks are compatible with today's vehicles and fuel infrastructure, such as Hydrogenated Vegetable Oil (HVO) and other drop-in biofuels. According to Pääkkönen et al. (2019), transport sectors such as aviation and heavy-duty vehicles remain dependent on on-board fuels. Furthermore, recent studies indicate that by 2030, biofuels will be the only technology that can have a major impact in all transport applications (Kloo and Larsson, 2019). Other alternatives require an extensive expansion of fuel infrastructure as well as continued development of vehicles, such as BEV, electric road systems and hydrogen fuel cells. In the short run, BEV's can have an impact on local freight transport. Electric roads may start to have an impact on some regional transport. The market for liquified hydrogen is expanding but its contribution to reducing GHG emissions depend on the energy mix used for its production (Lee et al., 2018). Liquefied Biogas (LBG) is one of the potentially important substitutes for fossil fuels for heavy trucks but have received somewhat less attention in previous literature than the previously mentioned technologies. Trucks are already available on the market, and fuel infrastructure is expanding. The results of a recent well-to wheel assessment show that, compared to conventional fuels, in both transport applications and for all vehicle classes including heavy duty vehicles, the use of compressed and liquefied renewable natural gas has an 81–212% GHG emissions reduction effect per km travel. The reduction depends on the type and source of feedstock used, the type of vehicle engine, assumed methane leakage and methane slip, and the allocated energy and environmental digestate credits, in each pathway (Hagos and Ahlgren, 2018).

This study investigates barriers, opportunities, and potential solutions for the diffusion of LBG use in heavy trucks. By investigating the LBG case, knowledge can be gained not only about LBG diffusion, but also about other alternative energy sources for transport purposes with characteristics similar to those of LBG.

Biogas can be produced from sewage sludge, manure, organic household/industrial waste, agricultural residues, and energy crops. It is produced either through the anaerobic (oxygen-free) digestion of organic waste or the gasification of energy crops (Börjesson et al., 2013). The digestate, produced as a by-product of anaerobic digestion, can be used as fertilizer in agriculture and forestry, as it retains the nutrients and minerals (Larsson et al., 2016).

Biogas has properties similar to those of fossil-based methane (natural gas) and can be distributed to fuelling stations either by pipeline (the gas network) or truck, in the latter case, in either compressed (CBG/CNG) or liquefied (LBG/LNG) form. Biogas for transport purposes can ultimately be used in both heavy- and light-duty vehicles and can be used interchangeably with natural gas in these vehicles. The main benefits of using LBG-trucks instead of CBG-trucks is that the range obtainable with LBG is significantly greater than that of CBG, making LBG particularly suitable for long-distance and heavy transport (Johansson, 2017). According to Röck et al. (2020) the operating range of a CBG heavy duty truck is somewhere between 560 and 650 km, while the range of an LBG heavy duty truck is somewhere between 1000 and 1750 km. However, propulsion systems based on LBG is a newer technology than CBG, which have been used for several years in for example private vehicles, buses, and light duty trucks. The infrastructure for CBG/CNG is also more extensive than that of LBG/LNG.

Biogas, compared with fossil fuels, generally results in lower well-to-wheel CO_2 emissions. However, the climate impact of alternative fuels depends on the raw material. Negative net CO_2 emissions can potentially be achieved from biogas produced from, for example, manure when the digestate produced is used as fertilizer, since no emissions will occur from the production of fertilizers (Börjesson et al., 2013; Larsson et al., 2016). However, the net GHG emissions depend on the type of land use and on other factors, such as the magnitude of the methane slip (Lantz and Börjesson, 2014). The reduction in GHG emissions can in some cases be offset. For example, converting rainforests, peatlands, savannas, or grasslands to produce food crop-based biofuels can release up to 400 times more CO_2 than the reduction caused by displacing fossil fuels (Fargione et al., 2008) while biofuels made from organic waste or from biomass grown degraded land results in reduced net CO_2 emissions (Andersson-Sköld et al., 2014a, 2014b; Börjesson, 2016; Fargione et al., 2008; Yano et al., 2015). Furthermore, other unwanted environmental impacts, such as deforestation and reduced biodiversity, may occur when land cultivated for food production is converted to produce crops for gasification (Börjesson and Tufvesson, 2011). Alternatives such as the conversion of moderately contaminated land or brownfield areas for energy crop cultivation could reduce the net CO_2 emissions while improving biodiversity, soil properties, and land values due to higher vegetation density, remediation, and risk reduction (Andersson-Sköld et al., 2014a; Suer and Andersson-Sköld, 2011). To counteract negative impacts, the sustainability criteria's of the Renewable Energy Directive (Art. 17 & Art. 18, 2009/28/EC) should be met.

In addition to the raw material, also the energy efficiency of the fuel is of importance. Recent well to wheel studies indicate that biogas result in less CO_2 emissions than HVO (Börjesson, 2016; Börjesson et al., 2013; Fagerström et al., 2019) and may also produce less net CO_2 emissions than electric vehicles (Fagerström et al., 2019), depending on raw material for biogas, production method, and source of electricity.

Despite several potential advantages of using biogas in the transport sector, use is far below the theoretical potential in view of physical feedstock availability (Börjesson and Ahlgren, 2012). Yet, the literature on the diffusion of biogas for transport purposes is scarce. Ammenberg et al. (2018) investigated the preconditions for biogas transport solutions in the Stockholm region of Sweden from a demand-side perspective. Fenton and Kanda (2017) investigated barriers to the diffusion of biogas for transport purposes in Basel (Switzerland) and Copenhagen (Denmark). Furthermore, Lantz et al. (2007) identified and evaluated factors that influence the potential expansion of biogas systems in general in Sweden. Common barriers found in these studies concern financial restrictions and policy uncertainties. The focus of previous biogas literature is on CBG and transport in general. To our knowledge, no previous study has investigated the diffusion of LBG use in heavy trucks, so more relevant knowledge is needed to accelerate the diffusion of LBG for heavy trucks.

The purpose of this study is to investigate barriers, opportunities, and potential solutions for the diffusion of LBG for use in heavy trucks in Sweden. The study also estimates the costs of using LBG-vehicles instead of diesel-vehicles. The paper is based on group and individual interviews with relevant actors in Sweden. The study distinguishes itself from the existing literature by focusing specifically on LBG for use in heavy trucks. The study addresses not only barriers and opportunities, but also potential solutions. Furthermore, stakeholder perspectives from throughout the LBG value chain are considered in the analysis.

Sweden was selected as a case study as it is a world leader in collecting and recycling waste to produce biogas (Energigas Sverige, 2018), and as Sweden uses a higher share of the produced biogas as vehicle fuel compared with other countries (IEA Bioenergy, 2018). Furthermore, Sweden is the European country with the highest share of renewable energy in the transport sector resulting in the CO_2 emissions from transports being reduced by 4.9% between 1990 and 2016. This is in contrast to for example Finland, Denmark and the EU where the CO_2 emissions increased by 11%, 26% and 28% respectively during the same period (European Environment Agency, 2019, 2020). Sweden and Denmark report drops in CO_2-emissions from freight transport to around 19% over the last decade while the emissions in Norway and Finland have been at a relative standstill (Pinchasik et al., 2018). In addition, Sweden has a specific target for the transport sector to reduce the greenhouse gas-emissions by 70% between 2010 and 2030, well above the Finnish target of 50% and EU's ambition on reducing greenhouse gas emissions to at least 55% below 1990 levels by 2030 (European Commission, 2020). In Norway the Government have set a target that all new light vans are to be zero-emission vehicles by 2025, and by 2030 all new vans and 50% of new heavy goods vehicles are to be driven on electricity or hydrogen (Miljødirektoratet et al., 2020).

2. Analytical framework

2.1. Literature review

Despite the scarce literature regarding renewable fuel diffusion, some papers have striven to improve our understanding of the diffusion of renewable technologies in general. This section summarizes findings from previous studies of biogas diffusion in particular, and from studies of opportunities and barriers for the diffusion of renewable energy in general.

Among the ***opportunities*** for biogas diffusion mentioned in the literature, environmental and climate objectives are seen as important (Fallde and Eklund, 2015; Lantz et al., 2007), as are high ambitions in Sweden and the EU regarding creating a circular and bio-based economy (Ammenberg et al., 2018). For renewable energy in general, opportunities arising from the scarcity of oil (Engelken et al., 2016) and the increased energy security of using renewable alternatives (Sen and Ganguly, 2017) have also been cited.

Ammenberg et al. (2018) noted that long-term progress towards more efficient and improved collaborative services in the renewable energy sector has led to a well-functioning sociotechnical biogas system in Sweden. Furthermore, public procurement has been an important driver of biogas solutions by increasing the biogas demand for bus transport (Ammenberg et al., 2018). Waste management strategies have also been identified as a factor favouring biogas solutions in Sweden (Fallde and Eklund, 2015).

One important ***barrier*** identified in previous literature is a dynamic policy landscape and a lack of long-term policies (Ammenberg et al., 2018; Fenton and Kanda, 2017). In an in-depth interview study from the demand-side perspective, Ammenberg et al. (2018) found that a dynamic policy landscape with uncertainties about decision makers' objectives and views, as well as the lack of a long-term national strategy are among the most important barriers. Fenton and Kanda (2017) also found that conflicting political priorities and shifting strategic objectives have resulted in different signals regarding the viability of biogas for transportation.

Financial challenges, such as higher vehicle retail prices, have also been identified as a barrier to the use of biogas and other alternative fuels (Ammenberg et al., 2018; Hovi et al., 2020; Lantz et al., 2007; Steenberghen and López, 2008). Fenton and Kanda (2017) found that the private sector has been unwilling to pay for a transition to biogas in the transport sector, indicating that municipalities and the public sector need to take on a leading role. However, there are some examples where own-account transporters have been leading the change towards biogas and other renewable energy options, such as Asko in Norway (Asko, 2021). Furthermore, Lyng et al. (2018) find that it is marginally more profitable for large scale plants in Norway to upgrade the gas to biomethane than using it for heating purposes (given current tax exemption in Norway from CO_2- and energy tax), and that only a small increase in existing incentives is needed to make it profitable for all biogas plants to upgrade the gas for transport purposes.

Competition between different renewable energy options, such as an increasing interest in electric vehicles or fuel cells, might make the expansion of biogas use in vehicles more challenging (Ammenberg et al., 2018; Dahlgren, 2020; Remøy, 2020). For example, Fenton and Kanda (2017) found that public investment decisions have favoured electric vehicles at the expense of biogas in Copenhagen and Basel. Path dependence leading to a "lock-in" of existing technologies is another barrier to technology diffusion, as new technology must compete with both the existing technology and the existing system (Foxon and Pearson, 2008). For example, Schulte et al. (2014) found that the existing diesel infrastructure, and the possibility to use pure biodiesel in most diesel vehicles, is one factor contributing to the faster introduction of biodiesel than biogas in the German transport sector.

There is also a competition between different sectors regarding access to different renewable energy sources. For example, supply side policy instruments in Denmark have favoured the use of biogas in the gas grid, while demand side policy instruments in Norway have favoured the use of biogas in the transport sector (Lyng et al., 2020).

The lack of physical infrastructure is also noted as a barrier to the diffusion of biogas and other alternative fuels (Ammenberg et al., 2018; Jensen and Ross, 2000; Romm, 2006). Ammenberg et al. (2018) also mentioned insecurity regarding the supply of biogas as a potential barrier. However, according to Börjesson and Ahlgren (2012), current biogas use is still far from its theoretical potential.

Behavioural challenges, such as rumours, as well as a lack of knowledge and information are also challenges for the diffusion of biogas (Ammenberg et al., 2018). For example, Lantz et al. (2007) found that some barriers to the diffusion of biogas for general use (not only for transport purposes) are limited public acceptance and limited knowledge among farmers.

2.2. Frameworks for technology diffusion

Several theories and models have tried to describe the diffusion of renewable energy technologies (e.g., Browne et al., 2012; Kanda et al., 2015; Mignon and Bergek, 2016; Romm, 2006). These theoretical frameworks take several different approaches, for example, focusing on technology suppliers (Kanda et al., 2015), technology adoption (Montalvo, 2008), and sociotechnical systems seen from multilevel perspectives (Geels, 2012). Based on previous literature, Browne et al. (2012) tested a framework for classifying barriers to alternative fuels and vehicles; the framework divides the barriers to sustainable transport into seven main categories, as suggested by Banister (2005):

1. Financial barriers
2. Technical or commercial barriers
3. Institutional and administrative barriers
4. Public acceptability
5. Legal or regulatory barriers
6. Policy failures and unintended outcomes
7. Physical barriers

Mignon and Bergek (2016) developed a framework for analysing challenges in the later-stage diffusion of renewable electricity. Their framework is based on several other studies investigating technology diffusion barriers. They include an important factor in their framework, as they distinguish between system- and actor-level challenges. System-level challenges can, for example, be found in institutional routines, while actor-level challenges can, for example, be behavioural characteristics. They divide the system-level challenges into six categories:

1. Market structure challenges
2. Infrastructure challenges

3. Financial challenges
4. Institutional challenges
5. Interaction challenges
6. Technology supply challenges

The actor-level challenges are divided into two categories:

1. Adopter resources
2. Behavioural factors

2.3. Framework applied in this study

This study combines both these frameworks, primarily by including the barrier categories of Browne et al. (2012) while distinguishing between system- and actor-level challenges as in Mignon and Bergek (2016) framework. In addition, several more changes were made, merging the categories from both frameworks, as follows:

1. Financial barriers
2. Technical, commercial, and physical barriers
3. Policy barriers
4. Public acceptability
5. Interaction challenges and market structure

In each of these categories, system- and actor-level challenges are distinguished from each other. Table S1 in the Supplementary Material briefly describes each category. The study seeks to apply this framework in performing a systematic analysis of the diffusion of LBG use in heavy trucks in Sweden.

3. Methodology

This study is part of a project aiming to investigate the potential for implementing renewable energy in the Swedish transport sector. Another part of the project aimed to specifically investigate the preconditions for liquefied biogas for heavy trucks in Sweden (Takman et al., 2018). The purpose of that study was to make an inventory of where and for which freight flows demonstration projects could be set up. The study identified major freight flows as well as property owners and other stakeholders in several Swedish regions where it would be interesting to invest in biogas technology. During the interviews in the previous study, barriers and opportunities were identified, but not analysed. In the part of the project presented here we analyse the results by developing and applying a framework to be used to perform a systematic analysis of barriers, opportunities, and potential solutions for the diffusion of renewable energy use in general with focus on the transport sector but applicable also for other purposes, such as working machines, the industry sector or different circular economy applications.

3.1. The Swedish context

The study is based on group and individual interviews with experts and stakeholders in Sweden. Sweden was selected as it is a world leader in collecting and recycling waste to produce biogas (Energigas Sverige, 2018). Compared with other countries, Sweden uses a higher share of the produced biogas as vehicle fuel (IEA Bioenergy, 2018). Although, several European countries produce a larger amount of biogas than Sweden, such as Germany and Denmark. Sweden is also the European country with the highest share of renewable energy in the transport sector (Takman et al., 2020a), where about 1.6% of the energy used came from biogas in 2018 (Swedish Energy Agency, 2020). The transport sector accounts for around a third of Sweden's CO_2 emissions, 20% of which come from heavy-duty trucks (Swedish Transport Administration, 2018). In 2019, 1034 heavy trucks in Sweden were registered as biogas or gas bi-fuel vehicles, which represent 1.27% of the heavy trucks (Transport Analysis Sweden, 2020). Of these, about 140 where LBG trucks (Klackenberg, 2019). In 2018, 2 TWh biogas was produced in Sweden. However, there is a growing interest of biogas and it was suggested to the government after a public inquiry to set a goal of producing 10 TWh biogas in 2030 (Statens Offentliga Utredningar, 2019). Thus, there seem to be a potential to increase the use of biogas in the transport sector in Sweden as one of many measures to reach the Paris Agreement targets.

There are currently several policy instruments that affect liquefied biogas and heavy trucks in Sweden, both at national level and at EU level. Some policy instruments affect biogas directly, while other policy instruments can have an indirect effect on biogas as they for example make diesel more expensive. Supplementary Material Table S2 summarizes the most relevant policy instruments affecting the use of LBG for heavy trucks in the Swedish transport sector.

3.2. Expert and stakeholder interviews

The aim of the group and individual interviews was to identify opportunities, barriers, and potential solutions for LBG diffusion. The group interviews included representatives of waste producers, biogas producers, vehicle manufacturers, fuel distributors, transporters (including own-account transporters), transport buyers, and local and regional planners. In one region, a politician also participated. To be selected, respondents had to play important roles in their regions. For transport buyers and haulers, it was important that the represented organisations were involved in large transport volumes.

The group interviews were conducted in four Swedish regions, i.e., Blekinge Län, Region Jönköping Län, Region Örebro Län, and Västra Götalandsregionen, selected for several reasons. These regions are already active in increasing awareness of opportunities to develop alternative fuels in the transport sector. They also have large networks extending from waste producers to transport users. Those responsible for awareness-building activities in the regions contributed to the study by supplying stakeholder and expert contacts, as well as telling of their own experiences and perceptions in the group interviews.

The group interviews were semi-structured. As the study aimed to amass information on barriers, opportunities, and potential solutions, group interviews were selected as they provide data via replies to questions. This is in contrast to focus group discussions, whose main aim is to foster discussion among group members (Parker and Tritter, 2006). The group interviews were complemented with semi-structured individual interviews with transporters and transport buyers/users who had been invited but were unable to attend any of the group interviews. In total, representatives of 30 organisations participated in the study, seven of whom participated in the individual interviews. A summary of the respondents' roles and organisations is presented in Supplementary Material Table S3.

In the group interviews, at least two researchers took notes; in addition, the sessions were recorded and transcribed and the results subsequently analysed. The complementary individual interviews were conducted by phone. In both types of interviews, the same main questions were asked, as well as several sub-questions (Supplementary Material Table S4). The two main questions were:

- What incentives and barriers for LBG use exist?
- What would be required for LBG to gain a larger market share in heavy road freight transport?

The questions were not categorised according to the framework during the group and individual interviews, though the answers were sorted according to the categories of the applied framework.

The respondents were promised confidentiality in relation to their specific replies. They are referred to here as respondents, actors, organisations, and only in specific cases (agreed to by the relevant respondents) by their specific roles in the biogas chain. During the group interviews, each person answered the same questions. Therefore, the respondents' answers often complemented previous respondents' answers. In some cases, the questions also led to discussions. Given how the group interviews were organised, this study does not try to quantify the answers. For example, when it says "the actors mentioned …" in the "Results" section, this implies that more than one actor mentioned a particular matter. However, this does not imply that the results were quantified or that factors mentioned by only one actor were not necessarily agreed to by other respondents.

3.3. Estimating costs

Costs are an important factor when choosing vehicle type and energy source (Ammenberg et al., 2018; Lantz et al., 2007; Steenberghen and López, 2008). Although not being the primary objective of this paper, costs of using LBG vehicles compared to conventional diesel vehicles have been estimated to give an example of how the costs may differ between these vehicles and fuel types. A common measure to estimate the costs of different vehicle alternatives is the total cost of ownership (TCO) (see for example Engholm et al., 2020; Lee et al., 2013; Vora et al., 2017). In this paper, we are not interested in the total cost of ownership per se, but rather in the cost savings, or the additional costs, of using LBG-vehicles instead of conventional diesel vehicles. Therefore, we estimate a relative TCO, which measure the annualized cost savings (or additional costs) per vehicle kilometre. Some cost components that would normally be included in a TCO are excluded in this analysis as these costs will likely not differ between an LBG-truck and a conventional diesel truck (for example driver costs, loading and unloading costs etc.). Moreover, insurance costs have been excluded as there was no available data. However, the differences in insurance costs (if any at all) is likely to be small. Further details about the dataset and how the costs have been estimated can be found in Supplementary Material Equations 1 to 6 and Supplementary Material Table S5.

4. Results

One conclusion of the analysis of results is that there were no major differences in answers depending on the part of the biogas value chain to which the actors belonged. In the following section, the results are categorised according to the framework applied in this study. Each category includes results regarding opportunities and barriers for the diffusion of LBG use in heavy trucks as well as actors' suggestions on how to overcome the barriers, as summarised in Supplementary Material Table S6.

The actors suggested activities for both accelerating implementation and overcoming barriers, as described below, as well as describing who should be responsible for these activities.

4.1. Financial opportunities and challenges

4.1.1. System-level opportunities

At the system level, financial opportunities such as Sweden's existing investment support programme, "The Climate Leap", are seen as major incentives for biogas use (the interviews were performed before a purchase grant for heavy trucks was implemented in 2020). However, some actors considered the process of applying for support overly time consuming and complicated. Local raw material production was said to be another financial opportunity for biogas in Sweden, leading to increased energy security, which was considered an important advantage, especially from a political perspective.

4.1.2. Actor-level opportunities

Potential profitability and competitive advantages due to, for example, energy efficiency and a strengthened environmental profile were identified as opportunities at the actor level. Some respondents mentioned the potential profitability of producing biogas from their own waste. Furthermore, by using biogas, organisations could show that they are part of a circular economy in which waste is reused as a resource. However, potential profitability has so far not been a major driving force, though it is expected to become a greater incentive in a few years. As expressed by one of the actors:

> *A shift in the transport industry will come whether you want it or not. When it does, LBG [for long-distance heavy trucks] is a good alternative.*

4.1.3. System-level challenges

Despite financial opportunities, costs are still considered among the greatest system-level barriers to LBG use, as the total operating costs are currently higher for driving fuelled by LBG than by diesel in general (according to the actors). Vehicle investment costs are currently higher and service intervals more frequent for LBG trucks than for equivalent diesel trucks. Furthermore, uncertainties regarding vehicle resale value are another barrier. Fuel production cost was also mentioned as a barrier to biogas adoption in Sweden. Today, both biogas infrastructure operators and biogas suppliers face financial challenges, for example, due to low LBG demand per station.

Several suggestions were made for how to overcome the system-level economic barriers. Subsidies will initially be needed to overcome additional costs and to stimulate the market for LBG vehicles. Investment support initiatives, such as "The Climate Leap", currently implemented in Sweden are seen as one way to address the economic barriers but need to be easier to apply for (this was stated before the implementation of the heavy truck purchase grant in 2020). Production support (at higher levels and/or for more raw materials than existing production support) was identified as a potential way to reduce biogas costs in Sweden. However, the actors argued that support systems directly targeting the demand side of biogas are especially important. Currently, biogas in Sweden is exempted from the carbon and energy taxes applied to fossil energy and fuels (only approved up to 2020 during the time of the interviews, but now approved up to 2030). The actors argued that abandoning this tax exemption would make biogas too expensive.

Demonstration projects were also cited as a potential solution. For example, the previous Swedish project "BiMe trucks", which provided investment support for the purchase of biogas trucks, was perceived as effective in encouraging more organisations to buy such trucks. Similar projects were suggested to stimulate the market for LBG trucks, as there are new and well-functioning vehicles on the market.

4.1.4. Actor-level challenges

Financial challenges are important on the actor level. Among the barriers noted were a lack of financial resources and unwillingness to take financial risks with unknown or low returns. The shipping industry has small margins, and economic factors seem to matter more than climate performance for both the shipping companies/haulers and the goods owners. Few companies can afford the additional investment costs of current LBG trucks and/or get paid extra for offering biogas-driven transport.

Transport buyers occasionally ask the haulers what fuel they use, though it is very unusual for customers other than public-sector customers to demand renewable fuels or request follow-up. One actor said:

> *One major barrier for shippers is that the company that first sets requirements on the haulers will also have to carry the full additional cost of the new vehicle being purchased.*

One important solution suggested for the actor-level challenges is joint procurement by multiple actors, to spread the costs and risks.

4.1.5. Estimation of biogas costs compared to diesel

Based on the data and methodology presented in Supplementary Material Equations 1-6 and Table S5, costs have been estimated for a diesel vehicle and two different LBG-vehicles: Positive Ignition (PI) and High-Pressure Direct Injection (HPDI) (the vehicle types are based on Röck et al., 2020). The vehicles are assumed to drive an annual distance of 125 000 km per year (based on Swedish Transport Administration, 2020). Table 1 present the annualized costs excluding taxes and other policy instruments for the different vehicles, measured in € per vehicle kilometre. As can be seen in the table, using a diesel vehicle is cheaper than the LBG-alternatives. Given the assumptions presented in section 3.3 and in the Supplementary Material Equations 1-6 and Table S5, using an LBG-HPDI truck comes with an additional cost of 0.16 €/km compared to using a diesel-truck, while an LBG-PI truck comes with an additional of 0.19 €/km.

Table 2 also present the annualized costs for the different vehicles (in €/km). However, these estimations also consider existing policies. Since September 2020, companies in Sweden can receive a climate grant when purchasing heavy trucks driven on biogas, bioethanol or electricity. Up to 20% of the investment cost of purchasing the truck can be received. However, the grant may not exceed 40% of the eligible costs, which is the difference between the “climate truck” and the closest comparable diesel vehicle. The estimations in Table 2 consider this purchase grant for heavy trucks, as well as the current CO_2- and energy tax for diesel and the current tax exemption from CO_2- and energy tax for biogas. These calculations therefore reflect the current policy-landscape in Sweden in April 2021. When these policy instruments are added to the estimations, the results change. Due to the tax exemption and the purchase grant, using LBG-vehicles comes with costs comparable to those of the equivalent diesel alternative. Using the LBG-HPDI truck costs 0.01 €/km more than the diesel-truck, while using the LBG-PI truck costs 0.04 €/km more than a diesel-truck. Therefore, given the current policy landscape, it should be possible to achieve similar operating costs of using LBG-vehicles as when using the equivalent diesel-vehicles. However, without the policies, both LBG options are more expensive than the diesel-truck, indicating a sensibility to changes in the current policy landscape.

In Tables 1 and 2, the 2020 diesel price average in Sweden was used for the estimations. However, the diesel price average during 2020 was lower than during previous years. Therefore, a sensitivity analysis, using the 2019 price average for diesel in Sweden, was performed in order to test how sensitive the costs are to price changes of diesel. Table 3 presents the results from the estimations of the current policy scenario, but with the more expensive diesel price average of 2019. As can be seen in Table 3, using LBG HPDI vehicles comes with cost savings of 0.03 €/km compared to the diesel vehicle, while using LBG PI vehicles comes with an additional cost of 0.01 €/km. This show that the relative costs of using LBG vehicles compared to diesel vehicles are sensitive to price changes in the diesel price.

4.2. Technical, commercial, or physical opportunities and challenges

4.2.1. System-level opportunities

Among the identified opportunities were the development of new technology and the availability of new Euro VI LBG trucks on the market. Sweden’s being a leader in biogas use in transport, having a functional organic waste recovery system, large biogas potential, and considerable waste from forest products useable for biogas production were mentioned as opportunities. Even if there is a lack of LBG stations today (according to the respondents in 2018), those that exist are located at strategic locations along major freight routes; furthermore, several LBG stations are planned to be built in Sweden in the near future.

4.2.2. Actor-level opportunities

Some of the actors saw technical advantages to using LBG, for example, the long range of LBG trucks combined with climate benefits. Compared with electrical vehicles, these trucks also have an advantage for long distances, as expressed by one respondent:

> *We want to use our trucks 20 h a day, which makes LBG more attractive than electricity, as LBG vehicles don’t need to stop and recharge for a long time.*

4.2.3. System-level challenges

Lack of infrastructure

A lack of refuelling stations for liquefied biogas was cited as a major barrier. In 2018 when the present interviews were conducted, only six liquefied biogas stations existed in Sweden, all located in the larger cities in the south. If there is no possibility of refuelling the trucks, no one will buy them; however, few operators want to build the infrastructure before they know that there will be demand. As expressed by one actor: *“It is simply a ‘chicken or egg’ conundrum”*.

Getting land in strategic places for building fuel stations was said to be another challenge by supply-side respondents. Currently, biogas producers and suppliers themselves must finance and build the fuel stations, but larger logistics centres are also funding and contributing to their construction.

Demonstration projects were mentioned as a possible solution for overcoming the infrastructure challenges. Another possibility is to offer LBG and CBG at the same fuel stations, as LBG not used for heavy trucks can be “steamed up” to CBG for other vehicles. Since the interviews were conducted in 2018, several new refuelling stations have been built and in January 2021, at least 17 public LBG stations exists in Sweden (Gasum, 2021). Several of these stations received investment support through the “Climate Leap” (Gasum, 2019). Therefore, the challenge of lacking infrastructure might not be as relevant anymore.

Gas availability

With the new LBG trucks on the market, more LBG plants might be needed to meet increasing demand. New plants currently planned in Sweden will likely be able to meet this possible increasing demand.

A lack of biogas resources in the longer term was also identified as a potential challenge. However, as the biogas potential from waste products is currently high in Sweden, this was not seen as a major problem for LBG use in the short term.

The importance of being prepared to meet increasing demand if the market grows was stressed, but no additional solution was mentioned for this barrier.

Technology supply

In addition to new technology risks associated with, for example, fuel costs, retail value, and future policy instruments, there are also risks related to service, maintenance, and the technology itself. As maintenance and service costs might increase with the introduction of new

Table 1
Annualized costs in € per vehicle kilometre (2020 diesel price average). Excluding taxes.

Technology	Acquisition cost (€/km)	Maintenance cost (€/km)	Fuel cost (€/km)	Total cost (€/km)	Additional costs to diesel (€/km)	Relative to diesel (%)
Diesel	0.37	0.20	0.19	0.76	0.00	100%
LBG HPDI	0.44	0.20	0.27	0.92	0.16	121%
LBG PI	0.40	0.20	0.34	0.94	0.19	125%

Table 2
Annualized costs in € per vehicle kilometre (2020 diesel price average). Including taxes, tax deduction for fuel, and subsidy for the acquisition of trucks.

Technology	Acquisition cost (€/km)	Maintenance cost (€/km)	Fuel cost (€/km)	Total cost (€/km)	Additional costs to diesel (€/km)	Relative to diesel (%)
Diesel	0.37	0.20	0.32	0.89	0.00	100%
LBG HPDI	0.41	0.20	0.28	0.90	0.01	101%
LBG PI	0.39	0.20	0.34	0.93	0.04	105%

Table 3
Annualized costs in € per vehicle kilometre (2019 diesel price average). Including taxes, tax deduction for fuel, and subsidy for the acquisition of trucks.

Technology	Acquisition cost (€/km)	Maintenance cost (€/km)	Fuel cost (€/km)	Total cost (€/km)	Additional costs to diesel (€/km)	Relative to diesel (%)
Diesel	0.37	0.20	0.35	0.92	0.00	100%
LBG HPDI	0.41	0.20	0.29	0.90	− 0.03	97%
LBG PI	0.39	0.20	0.34	0.93	0.01	101%

technology, it is important that the vehicles have high technical credibility.

To overcome new technology risks, the actors emphasised the importance of vehicle manufacturers' taking responsibility for new vehicles and ensuring that the aftermarket organisation has the skills to quickly repair the vehicles if problems arise. As expressed by one actor:

For example, if the truck stops working at night, it means that the freight might be delayed to its final destination. It is therefore important to have good connections with the vehicle supplier and to quickly get service so that the trucks are always in service.

To accelerate LBG diffusion, the new technology also needs to be available in more vehicle models and tailored to operators' special needs.

4.3. Policy related opportunities and challenges

4.3.1. System-level opportunities

Only system-level policy-related opportunities were noted. The "Bonus Malus" policy that came into force in Sweden in July 2018 is expected to have positive effects on biogas development. This policy promotes the use of non-fossil-fuel light-duty vehicles but might indirectly influence heavy trucks by steering the market, infrastructure, and interest towards biogas and other renewables.

High awareness and requirements in the public sector were also said to play an important role in the diffusion of biogas. As stated by one respondent:

For example, for public procurements of buses, taxis, or school shuttles, the requirements are crucial for the company's fuel decisions.

Other global and national factors are also expected to increase the use of LBG in heavy trucks, for example, the creation of urban environmental zones, "diesel gate", and price increases of HVO. One actor said that Sweden's fuel sustainability criteria and assessment tools had recently changed in favour of biogas solutions.

4.3.2. System-level challenges

Policy uncertainties

Despite policy-related opportunities, policy was one of the most frequently cited barriers. Uncertainties regarding future policy instruments, the absence of long-term and stable policies, and the weaknesses of existing policies were mentioned as major obstacles by all types of actors. Due to policy uncertainties, investing in LBG trucks to be used for at least seven years is considered a major risk by the demand-side actors. One actor said:

Without long-term policies, we risk ending up in a situation where we have biogas vehicles that cannot be used if the gas is too expensive and if there is no gas in the refuelling stations.

Policy uncertainty is considered a problem for all types of fuels. The respondents noted that political fluctuations have changed conditions several times for different energy options, affecting what fuel types are considered good options in terms of commercial, environmental, and climate performance.

To overcome barriers to the diffusion of LBG and other renewable options, the actors argued that it is important to develop a clear, long-term, and stable policy context that lets companies know "the rules of the game" for a longer period. This also might positively affect the resale value of renewable-fuel vehicles.

Conflicting policies within the European Union

Supply-side actors argued that there are uneven competitive conditions within the EU, as policies affecting biogas are not uniform within the Union. Sweden distinguishes itself from other EU countries by focusing on support to the demand side of biogas instead of the supply side (Swedish Waste Management, 2017). Biogas imported from countries with production support for biogas benefits from dual support when sold in Sweden where it is exempted from the CO_2- and energy taxes. Imported biogas, for example, from Denmark, is therefore sold at substantially lower prices in Sweden than is local gas, resulting in uneven competition for Swedish biogas producers. Although the uneven competition was considered a challenge by the supply-side actors, the cheap Danish gas comes with positive aspects from the demand-side perspective.

To overcome this barrier, policies need to be more uniform throughout the EU. For example, the supply-side actors argued that Sweden needs more support systems favouring biogas production to be able to compete with EU countries with dual support systems (at the time of the interviews, only the production support for biogas produced from manure existed in Sweden, a temporary additional support has been implemented since then, however, at lower levels than the Danish support.).

4.4. Public acceptability

4.4.1. System-level opportunities

One of the most important opportunities for LBG, according to all types of actors, is that it is renewable and contributes to a fossil-fuel-free transport sector. Furthermore, awareness of climate change is generally considered high in Sweden, and the country has ambitious climate goals for the transport sector.

4.4.2. Actor-level opportunities

This high awareness also has great impact on the actor level. One respondent argued that Sweden's stated goal of becoming fossil fuel free has encouraged various organisations, including their own, to set their own objectives to that end. In line with this are increasing demands and requirements from customers and consumers, considered a strong incentive for companies to strengthen their climate profile.

4.4.3. Actor-level challenges

Only actor-level challenges were mentioned regarding public acceptability.

Knowledge and experience

One challenge is that adopters (e.g., haulers and shippers) and individual actors within the companies lack resources in terms of knowledge and experience. This includes lack of knowledge of the different fuel options available on the market, how they work, and their environmental performance. The actors argued that it is generally difficult to know which fuel options are the best alternatives from both the climate change and broader environmental/sustainability perspectives. Therefore, it is important to conduct sustainability assessments and to make information about their results publicly available. Furthermore, there is a lack of sufficient resources to build knowledge of renewable options within the companies and organisations, leading to insufficient knowledge and related rationales to support making demands of their haulers. As a solution, the actors suggested that, for example, inter-branch organisations should provide information and rationales to stakeholders to influence what fuels are used by haulers and shippers.

Previously negative experiences of LBG also seem to be a barrier. Some organisations experienced technical problems with the Euro V LBG trucks and might avoid using LBG vehicles again. It is therefore important to show these actors that the technology is now working properly.

Information and rumours

There is a lack of information and few practical examples demonstrating the benefits throughout the value chain of biogas. There is also a lack of innovation awareness among adopters.

Rumours were cited regarding, for example, explosion risks of gas vehicles and previous vehicle deficiencies (corrected in today's models) attributable to the gas itself instead of the vehicles.

Also, pure conservatism and ingrained habits were identified as barriers. Some companies have little ability to change and are hard to convince to try something new; for example, it is easier to keep the same hauler as before and to drive to the same fuel stations.

To overcome these barriers, the actors argued that information efforts are needed to educate actors throughout the value chain, encompassing drivers, factories, equipment, etc. Demonstration projects showing the technology on the roads can be one way to spread information and increase operator willingness to adopt innovations. It is important that actors cooperate to highlight good solutions and relevant information.

4.5. Interaction challenges and market structure

4.5.1. System-level opportunities

The actors mentioned several advantages of LBG over certain other options in terms of, for example, the circular economy, local production, and increased energy security. Furthermore, in July 2018 the reduction obligation was implemented in Sweden, obliging fuel suppliers to increase the share of biofuels in existing diesel and petrol. This might increase the demand for and price of HVO and other limited-supply renewables that can be blended with diesel and petrol. This may strengthen the competitiveness of biogas relative to these other fuels.

4.5.2. Actor-level opportunities

Some organisations (e.g., food industries) could use their own waste to create biogas, potentially increasing profits and showing that they are part of the circular economy. Furthermore, the advantages of using LBG in long-distance heavy trucks were also mentioned as a market opportunity, while electricity was considered a better option for shorter distances and in urban environments, as it has positive impacts on urban air quality and noise.

4.5.3. System-level challenges

Market structure challenges

The existing system of infrastructure, vehicles, costs, and knowledge currently favours fossil fuels, and the market is structured to fit the existing diesel and oil system. After fossil fuels, HVO is the most common fuel in Sweden. According to the actors, this is partly because of its simplicity: the infrastructure already exists, and HVO can be blended with existing diesel and used in most diesel vehicles. Large investments will be needed to overcome this barrier and fit LBG into the market structure.

Competition between fuels

Achieving a fossil-fuel-free transport sector will require more than one renewable energy source. Competition with fossil diesel is a major obstacle. However, the actors also noted strong competition between renewable energy options today, instead of their complementing one another. For example, in society there is currently an emphasis on electric vehicles, for example, in the media and among politicians and the public. HVO is also said to be a strong competitor to biogas, as it has been an almost cost-neutral alternative to diesel. However, the actors expressed concern regarding the future supply of HVO from sustainable raw materials, as well as expected price increases and climate impacts.

Lack of requirements

A lack of requirements from both public and private actors is another barrier to LBG diffusion in the long haulage heavy truck segment. In general, only the public sector, and still rarely, makes demands or requests follow-ups regarding renewable fuels. The requirements in public procurements of bus services were cited as an illustrative example, as they have led to a large increase in the share of renewable bus fuels in Sweden. A suggested solution for long haulage heavy trucks is therefore that public actors, such as municipalities and the Swedish Transport Administration, should specify requirements for LBG in freight procurements as well, to set good examples and influence the market. This is also in line with the Clean Vehicles Directive, which promotes certain "clean vehicles" in public procurements. However, as most freight transport is run by private companies in a competitive market, requirements in public procurements may not have as large effects in the long haulage heavy truck segment as in for example public transport.

Other suggested solutions are information campaigns to spread knowledge and related rationales to transport buyers, so that they can present better demands to haulers and shippers. The actors also said that it should be possible, for example, to bring together the major transport buyers in smaller regions to cooperate in setting common demands.

As a solution to most of the barriers, the participants considered it important to bring industry actors together to cooperate, both within the biogas industry and with representatives of other renewable alternatives. One respondent said that it often takes time to get needed information and that it is hard to know who the experts are and how to get help from the right people. The actors therefore called for more cooperation so that they can benefit from one another's expertise. One actor argued that it is important to bring industry actors together to identify suitable projects and resolve funding issues. By bringing together the entire biogas chain and mixing private and public actors around the same table, it would also be easier to overcome barriers.

5. Discussion and conclusions

This study investigates the diffusion of LBG for use in heavy trucks, based on expert and stakeholder interviews in Sweden. The study uses a framework for categorising barriers, opportunities, and suggested solutions. The framework comprises five categories: financial, technical/commercial/physical, policy, public acceptability, and market structure/interaction barriers. In each category, system- and actor-level opportunities and challenges are distinguished from each other. Furthermore, the study also estimates the costs of using heavy duty LBG-trucks for long haulage missions compared to conventional diesel-trucks.

Even though the interview questions did not follow the framework, the responses from the group and individual interviews fit the categories of the framework. Although this study specifically concentrates on LBG for use in heavy trucks, the results largely confirm the barriers and opportunities identified in previous literature on the use of biogas and other renewable fuels for transport purposes. The framework applied here is accordingly applicable to assessing the potentials, barriers, and solutions for the diffusion of LBG for use in heavy trucks in Sweden, as well as for any large-scale deployment of alternative fuels with market properties similar to those of LBG. Such a framework can be useful in future studies and to policymakers for analysing the diffusion of renewable energy use in transport.

The respondents gave answers regarding the challenges and opportunities for LBG diffusion at both the system and actor levels. Several system-level opportunities were identified in accordance with previous studies (Ammenberg et al., 2018; Fallde and Eklund, 2015; Lantz et al., 2007), such as ambitious climate/environmental targets, striving to create a circular economy, and recently adopted policies in Sweden. New LBG trucks on the market and increased energy security due to local production were mentioned as other opportunities. Actor-level incentives were also identified, such as climate objectives within organisations, increased demand for renewable products, and potential profitability.

Barriers were identified on both the system and actor levels. At the system level, common barriers concerned an unstable policy context, lack of physical infrastructure, and financial risks such as high investment costs, unknown maintenance costs, and resale values. These findings are also in accordance with previous findings in the literature on CBG and other renewable fuels (Ammenberg et al., 2018; Browne et al., 2012; Fenton and Kanda, 2017). Moreover, at the actor level, insufficient awareness, knowledge, and experience were noted, along with the small profit margins of transport companies.

The present results indicate that it is important to understand both the perspective of the potential innovation adopters and the system in which they are embedded in order to explain the factors affecting the diffusion of LBG. For example, at the actor level, the results indicate that several potential innovation adopters have ambitious climate targets and are willing to invest in LBG for heavy trucks or in other renewable technologies. However, both system- and actor-level challenges prevent them from doing so today. At the actor level, a lack of resources in terms of small profit margins and lack of knowledge are examples of challenges. To be able to invest, they want to see that system-level challenges such as policy uncertainties, financial risks, and lack of infrastructure are overcome. Considering both the system and actor levels when dealing with policy design is therefore important.

The results of this study indicate a need to consider a third level that highlights the networks linking the system and actor levels among various actors. Considering a network level in addition to the system and actor levels could advance our understanding of renewable energy diffusion. Increased knowledge and the encouragement of network formation between the system and actor levels would be useful in order to improve interactions to favour the diffusion of alternative energy sources.

Recognising potentials and barriers is a crucial basis for improving renewable energy diffusion but does not automatically show us how to overcome the barriers by policy instruments and other measures. The respondents were therefore also asked how these barriers could be overcome. Previous literature has not included discussions of how to overcome barriers within a framework that identifies both barriers and opportunities. Discussing solutions within the present framework is an important step in understanding how the diffusion of LBG can accelerate. Financial support and a more stable policy context were called for by the interviewed actors. Furthermore, information campaigns and demonstration activities were suggested in order to raise awareness of LBG vehicle capacity, climate performance, and financial benefits. Good examples on the roads, for example, through public procurements or demonstration projects, highlighting vehicle functionality and potential market benefits were also mentioned as potential solutions.

The results of this study bring some interesting policy implications. Several of the barriers mentioned in the study are barriers that were already targeted by different types of policy instruments at the time of the interviews. For example, financial aspects were mentioned as a main barrier, despite several existing economic policy instruments, such as tax-exemption from CO_2- and energy tax, "the Climate Leap", and production support to biogas produced from certain raw materials. Furthermore, after the interviews were performed, a purchase grant for the acquisition of LBG-trucks (and some other renewable alternatives) have been implemented, which is one of the solutions that the respondents suggested. The cost estimations in this study show that given the current policy landscape (in April 2021), it should be possible to achieve similar costs to those of using conventional diesel trucks when using LBG-trucks. However, without the purchase grant for the vehicles and the tax exemption from CO_2- and energy tax for biogas, the costs of using LBG-vehicles are higher than the cost of using diesel-trucks. Thus, it is understandable that the respondents request a stable policy landscape, as changes to the current policy landscape can have high effects on the costs.

The respondents also request solutions such as better demands at public procurements and more LBG fuel stations. The Clean Vehicles Directive already require the member states to favour certain types of vehicles (for example LBG) at public procurements, the directive on alternative fuels infrastructure set minimum distances between LBG stations, and the Climate Leap gives investment support to investments such as fuel stations. The fact that several of the mentioned barriers already are targeted by policy instruments stress the importance of continuously evaluating existing policy instruments in order to understand if they are effective and efficient, or if changes or new policies are needed.

The respondents were aware of the need to bring together the entire value chain. Such cooperation may accelerate sustainable diffusion, as exemplified in the pulp and paper industry (CEPI, 2013). By bringing together and involving additional actors from the biogas value chain during the group interviews, this study also managed to promote cooperation and information exchange between the participating actors. In response, the actors suggested both activities for accelerating implementation as well as who could be responsible for them.

Respondents in this study, as well as previous literature (e.g., Ammenberg et al., 2018), identified the need for several alternative fuels on the market to facilitate the sustainable transformation of the transport sector. Cooperation platforms accordingly need to involve not only the producers within the biogas chain but also representatives of other non-fossil fuels in order to achieve a sustainable fuel market.

The work presented here is based on responses from actors representing the full biogas chain, comprising biowaste, biogas, and vehicle producers, as well as fuel distributors, haulers, transporters and transport buyers. Most of the studied actors are already active in addressing biogas questions, which might bias the results. However, because the actors are active, they also have considerable knowledge and understanding of biogas systems that other actors lack. A few transport buyers who are not active biogas users were also included in this study to ensure that their perspectives were also considered.

Only one transport buyer (aside from buyers such as municipalities) attended the group interviews; most representatives attending the group interviews were biogas producers and distributors. This highlights the importance of having one's interests at stake or gaining something from spending time on activities outside one's daily business, such as the group interviews held in this project. This is a dilemma when seeking information from relevant actors in stakeholder-driven research. In this study, complementary individual interviews with transporters and transport buyers were performed by phone to save their time while still soliciting their views and opinions. Ways to encourage their participation were suggested by the respondents in this study, such as information campaigns and demonstration projects to illustrate the benefits for transport buyers.

There is an urgent need to combat climate change, simultaneous with a call by the respondents for improved knowledge and information about the sustainability benefits of biogas use. Before initiating and running large information campaigns, making financial investments in demonstration projects, or establishing financial support systems, it is important to conduct sustainability assessments in order to avoid sub-optimisation. Such assessments must include estimates and valuations of the climate, environmental, health, and social impacts in the short and long terms related to the required and expected benefits. To ensure sustainable development, thorough environmental analysis is needed that considers a life-cycle perspective as well as socioeconomic impacts and involves representatives of the most important players and impacted actors.

Acknowledgements

This work was initiated by Closer and financially supported by Vinnova, Västra Götalandsregionen, Region Skåne, and Region Blekinge. Furthermore, Region Jönköping, Region Örebro Län, and Region Blekinge contributed their time to the study. VTI further funded the process of writing this paper. Thanks are due to the funders of this study as well as to the participants in the group and individual interviews.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tranpol.2021.05.021.

Role of the funding source

This work was initiated by Closer and financially supported by Vinnova, Västra Götalandsregionen, Region Skåne, and Region Blekinge. Region Jönköping, Region Örebro Län, and Region Blekinge contributed their time to the study and helped by supplying contacts as well as a venue for the group interviews. VTI further funded the process of writing this paper.

CRediT author statement

Johanna Takman: Writing – Original Draft, Conceptualization, Methodology, Formal Analysis, Investigation. **Yvonne Andersson-Sköld**: Funding acquisition, project administration, supervision, Conceptualization, Methodology, Formal Analysis, Investigation.

Declarations of interest

None.

References

Ammenberg, J., Anderberg, S., Lönnqvist, T., Grönkvist, S., Sandberg, T., 2018. Biogas in the transport sector - actor and policy analysis focusing on the demand side in the Stockholm region. Resour. Conserv. Recycl. 129, 70–80. https://doi.org/10.1016/j.resconrec.2017.10.010.

Andersson-Sköld, Y., Bardos, P., Chalot, M., Bert, V., Crutu, G., Phanthavongsa, P., Delplanque, M., Track, T., Cundy, A.B., 2014a. Developing and validating a practical decision support tool (DST) for biomass selection on marginal land. J. Environ. Manag. 145, 113–121. https://doi.org/10.1016/j.jenvman.2014.06.012.

Andersson-Sköld, Y., Hagelqvist, A., Crutu, G., Blom, S., 2014b. Bioenergy grown on contaminated land - a sustainable bioenergy contributor? Biofuels 5, 487–498. https://doi.org/10.1080/17597269.2014.996728.

Asko, 2021. ASKOs ambisjon er kun fornybart. ASKO. URL. https://asko.no/om-oss/fokus-pa-miljo/biodrivstoff/. (Accessed 29 January 2021).

Banister, D., 2005. Overcoming barriers to the implementation of sustainable transport. In: Rietveld, P., Stough, R.R. (Eds.), Barriers to Sustainable Transport: Institutions, Regulation and Sustainability.

Börjesson, P., 2016. Potential för ökad tillförsel och avsättning av inhemsk biomassa i en växande svensk bioekonomi (Rapport nr 97). Lund University. Department of Technology and Society. Environmental and Energy Systems Studies.

Börjesson, M., Ahlgren, E.O., 2012. Cost-effective biogas utilisation – a modelling assessment of gas infrastructural options in a regional energy system. Energy 48, 212–226. https://doi.org/10.1016/j.energy.2012.06.058.

Börjesson, P., Tufvesson, L., 2011. Agricultural crop-based biofuels – resource efficiency and environmental performance including direct land use changes. J. Clean. Prod. 19, 108–120. https://doi.org/10.1016/j.jclepro.2010.01.001.

Börjesson, P., Lundgren, J., Ahlgren, S., Nyström, I., 2013. Dagens Och Framtidens Hållbara Biodrivmedel. The Swedish Knowledge Centre for Renewable Transportation Fuels.

Browne, D., O'Mahony, M., Caulfield, B., 2012. How should barriers to alternative fuels and vehicles be classified and potential policies to promote innovative technologies be evaluated? J. Clean. Prod. 35, 140–151. https://doi.org/10.1016/j.jclepro.2012.05.019.

CEPI, 2013. Unfold the Future, the Two Team Project 2050.

Dahlgren, S., 2020. Biogas-based fuels as renewable energy in the transport sector: an overview of the potential of using CBG, LBG and other vehicle fuels produced from biogas. Biofuels. https://doi.org/10.1080/17597269.2020.1821571.

Energigas Sverige, 2018. Förslag till Nationell Biogasstrategi 2.0. Energigas Sverige.

Engelken, M., Römer, B., Drescher, M., Welpe, I.M., Picot, A., 2016. Comparing drivers, barriers, and opportunities of business models for renewable energies: a review. Renew. Sustain. Energy Rev. 60, 795–809. https://doi.org/10.1016/j.rser.2015.12.163.

Engholm, A., Pernestål, A., Kristoffersson, I., 2020. Cost analysis of driverless truck operations. Transport. Res. Rec. 2674, 511–524. https://doi.org/10.1177/0361198120930228.

European Commission, 2019. Transport emissions – European commission. URL. https://ec.europa.eu/clima/policies/transport_en. (Accessed 28 October 2019).

European Commission, 2020. 2030 Climate Target Plan. Climate Action – European Commission. URL. https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en. (Accessed 28 January 2021).

European Environment Agency, 2019. Transport greenhouse gas emissions – European Environment Agency. URL. https://www.eea.europa.eu/airs/2018/resource-efficiency-and-low-carbon-economy/transport-ghg-emissions. (Accessed 28 January 2021).

European Environment Agency, 2020. National Emissions Reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism. European Environment Agency. URL. https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16. (Accessed 28 January 2021).

Fagerström, A., Lönnqvist, T., Anderson, S., 2019. Kunskapssyntes: Samhällsekonomisk Analys Av Förnybara Drivmedel Och Drivlinor (No. Nr B 2360). IVL Svenska Miljöinstitutet, Stockholm.

Fallde, M., Eklund, M., 2015. Towards a sustainable socio-technical system of biogas for transport: the case of the city of Linköping in Sweden. J. Clean. Prod. 98, 17–28. https://doi.org/10.1016/j.jclepro.2014.05.089.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. Science 319, 1235–1238. https://doi.org/10.1126/science.1152747.

Fenton, P., Kanda, W., 2017. Barriers to the diffusion of renewable energy: studies of biogas for transport in two european cities. J. Environ. Plann. Manag. 60, 725–742. https://doi.org/10.1080/09640568.2016.1176557.

Foxon, T., Pearson, P., 2008. Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime. J. Clean. Prod. 16, 148–161. https://doi.org/10.1016/j.jclepro.2007.10.011.

Gasum, 2019. Gasum Får Investeringsstöd Från Klimatklivet För Ny Biogasanläggning Och Fyra Tankstationer. Gasum. URL. https://www.gasum.fi/sv/gasum/nyheter/20192/gasum-far-investeringsstod-fran-klimatklivet-for-ny-biogasanlaggning-och-fyra-tankstationer/. (Accessed 30 January 2021).

Gasum, 2021. Tankstationer för gas. Gasum. URL. https://www.gasum.fi/sv/hallbara-transporter/tung-trafik/tankstationer/. (Accessed 30 January 2021).

Geels, F.W., 2012. A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. J. Transport Geogr. 24, 471–482. https://doi.org/10.1016/j.jtrangeo.2012.01.021.

Gota, S., Huizenga, C., Peet, K., 2016. Implications of 2DS and 1.5DS for Land Transport Carbon Emissions in 2050. Partnership on Sustainable Low-Carbon Transport (SLoCaT).

Hagos, D.A., Ahlgren, E.O., 2018. Well-to-wheel assessment of natural gas vehicles and their fuel supply infrastructures – perspectives on gas in transport in Denmark.

Transport. Res. Transport Environ. 65, 14–35. https://doi.org/10.1016/j.trd.2018.07.018.
Hovi, I.B., Pinchasik, D.R., Figenbaum, E., Thorne, R.J., 2020. Experiences from battery-electric truck users in Norway. World Electric Vehicle Journal 11, 5. https://doi.org/10.3390/wevj11010005.
IEA Bioenergy, 2018. IEA bioenergy task 37 - country reports summary 2017, 37. IEA Bioenergy Task.
Jensen, M.W., Ross, M., 2000. The ultimate challenge: developing an infrastructure for fuel cell vehicles. Environment 42, 10–22. https://doi.org/10.1080/00139150009605747.
Johansson, H., 2017. Flytande biogas till land och till sjöss. Energikontor Sydost AB.
Kanda, W., Sakao, T., Hjelm, O., 2015. Components of business concepts for the diffusion of large scaled environmental technology systems. J. Clean. Prod. 128, 156–167. https://doi.org/10.1016/j.jclepro.2015.10.040.
Klackenberg, L., 2019. Biomethane in Sweden – Market Overview & Policies.
Kloo, H., Larsson, M.-O., 2019. Jämförelse av tekniker för klimatsmarta tunga godstransporter (No. C 384). IVL Svenska Miljöinstitutet.
Lantz, M., Börjesson, P., 2014. Greenhouse gas and energyassessment of the biogas from co-digestion injected into the natural gas grid: a Swedish case-study including effects on soil properties. Renew. Energy 71, 387–395. https://doi.org/10.1016/j.renene.2014.05.048.
Lantz, M., Svensson, M., Björnsson, L., Börjesson, P., 2007. The prospects for an expansion of biogas systems in Sweden - incentives, barriers and potentials. Energy Pol. 35, 1830–1843. https://doi.org/10.1016/j.enpol.2006.05.017.
Larsson, M., Grönkvist, S., Alvfors, P., 2016. Upgraded biogas for transport in Sweden – effects of policy instruments on production, infrastructure deployment and vehicle sales. J. Clean. Prod. 112, 3774–3784. https://doi.org/10.1016/j.jclepro.2015.08.056.
Lee, D.-Y., Thomas, V.M., Brown, M.A., 2013. Electric urban delivery trucks: energy use, greenhouse gas emissions, and cost-effectiveness. Environ. Sci. Technol. 47, 8022–8030. https://doi.org/10.1021/es400179w.
Lee, D.-Y., Elgowainy, A., Kotz, A., Vijayagopal, R., Marcinkoski, J., 2018. Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks. J. Power Sources 393, 217–229. https://doi.org/10.1016/j.jpowsour.2018.05.012.
Lyng, K.-A., Stensgård, A.E., Hanssen, O.J., Modahl, I.S., 2018. Relation between greenhouse gas emissions and economic profit for different configurations of biogas value chains: a case study on different levels of sector integration. J. Clean. Prod. 182, 737–745. https://doi.org/10.1016/j.jclepro.2018.02.126.
Lyng, K.-A., Skovsgaard, L., Jacobsen, H.K., Hanssen, O.J., 2020. The implications of economic instruments on biogas value chains: a case study comparison between Norway and Denmark. Environ. Dev. Sustain. 22, 7125–7152. https://doi.org/10.1007/s10668-019-00463-9.
Mignon, I., Bergek, A., 2016. System- and actor-level challenges for diffusion of renewable. J. Clean. Prod. 128, 105–115. https://doi.org/10.1016/j.jclepro.2015.09.048.
Miljødirektoratet, Statens Vegvesen, Kystverket, Landbruksdirektoratet, 2020. Norges Vassdrags- Og Energidirektorat Og Enova. Klimakur 2030: Tiltak og virkemidler mot 2030 (No. M–1625).
Montalvo, C., 2008. General wisdom concerning the factors affecting the adoption of cleaner technologies: a survey 1990–2007. J. Clean. Prod. 16, 7–13. https://doi.org/10.1016/j.jclepro.2007.10.002.
Pääkkönen, A., Aro, K., Aalto, P., Konttinen, J., Kojo, M., 2019. The potential of biomethane in replacing fossil fuels in heavy transport – a case study on Finland. Sustainability 11, 4750. https://doi.org/10.3390/su11174750.
Parker, A., Tritter, J., 2006. Focus group method and methodology: current practice and recent debate. Int. J. Res. Method Educ. 29, 23–37. https://doi.org/10.12691/ajap-1-2-2.
Pinchasik, D.R., Hovi, I.B., Vierth, I., Mellin, A., Liimatainen, H., Kristensen, N.B., 2018. Reducing CO2 Emissions from Freight : Recent Developments in Freight Transport in the Nordic Countries and Instruments for CO2 Reductions (No. TemaNord, ISSN 0908-6692 ; 2018:554). Nordic Council of Ministers. https://doi.org/10.6027/TN2018-554.
Remøy, T.D., 2020. Virkemidler for Økt Bruk Og Produksjon Av Biogass (No. M–1652) (Miljødirektoratet).
Röck, M., Martin, R., Hausberger, S., Hanarp, P., Bersia, C., Colombano, M., Gräser, H., Gomes Marques, G., Mikaelsson, H., De Prada, L., Prussi, M., Lonza, L., Yugo, M., Hamje, H., 2020. JEC Tank-To-Wheels Report V5: Heavy Duty Vehicles (No. EUR 30271 EN). European Commission, Luxembourg. https://doi.org/10.2760/541016.
Romm, J., 2006. The car and fuel of the future. Energy Pol. 34, 2609–2614. https://doi.org/10.1016/j.enpol.2005.06.025.
Schulte, I., Hart, D., van der Vorst, R., 2014. Issues affecting the acceptance of hydrogen fuel. Int. J. Hydrogen Energy 29, 677–685. https://doi.org/10.1016/j.ijhydene.2003.09.006.
Sen, S., Ganguly, S., 2017. Opportunities, barriers and issues with renewable energy development – a discussion. Renew. Sustain. Energy Rev. 69, 1170–1181. https://doi.org/10.1016/j.rser.2016.09.137.
Statens Offentliga Utredningar, 2019. Mer Biogas! För Ett Hållbart Sverige. Betänkande Av Biogasmarknadsutredningen. (No. SOU 2019:63) (Stockholm).
Steenberghen, T., López, E., 2008. Overcoming barriers to the implementation of alternative fuels for road transport in Europe. J. Clean. Prod. 16, 577–590. https://doi.org/10.1016/j.jclepro.2006.12.001.
Suer, P., Andersson-Sköld, Y., 2011. Biofuel or excavation? - life cycle assessment (LCA) of soil remediation options. Biomass Bioenergy 35, 969–981. https://doi.org/10.1016/j.biombioe.2010.11.022.
Swedish Energy Agency, 2020. Energiindikatorer. Swed. Energy agency. URL. http://www.energimyndigheten.se/statistik/energiindikatorer/. (Accessed 10 November 2020).
Swedish Transport Administration, 2018. Transportsektorns utsläpp. Trafikverket. URL. https://www.trafikverket.se/for-dig-i-branschen/miljo—for-dig-i-branschen/energi-och-klimat/Transportsektorns-utslapp/. (Accessed 12 February 2018).
Swedish Transport Administration, 2020. Analysmetod Och Samhällsekonomiska Kalkylvärden För Transportsektorn: ASEK 7.0 (No. ASEK 7.0). Swedish Transport Administration.
Swedish Waste Management, 2017. Utredning Och Analys Av Lämpliga Styrmedel För Svenskproducerad Biogas Efter 2020. Swedish Waste Management.
Takman, J., Andersson-Sköld, Y., Johansson, J., Johansson, M., Johansson, H., Uhlin, L., Kantelius, Å., 2018. Biogas För Tunga Lastbilstransporter - Barriärer Och Möjligheter (VTI Rapport No. 981). VTI.
Takman, J., Sedehi Zadeh, N., Trosvik, L., Vierth, I., 2020a. Triple F Systemövergripande Uppföljning 2020 – Uppföljning Av Hur Godstransporter Närmar Sig Det Svenska Klimatmålet 2030. Triple F. Triple F – Rapport No. 2020.2.11).
The renewable energy directive Art 17 & Art 18 (2009/28/EC), Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC.
U, Directive (Eu) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources.
Transport Analysis Sweden, 2020. Fordon på väg. Transp. Anal. URL https://www.trafa.se/vagtrafik/fordon/. (Accessed 10 November 2020).
Vora, A.P., Jin, X., Hoshing, V., Saha, T., Shaver, G., Varigonda, S., Wasynczuk, O., Tyner, W.E., 2017. Design-space exploration of series plug-in hybrid electric vehicles for medium-duty truck applications in a total cost-of-ownership framework. Appl. Energy 202, 662–672. https://doi.org/10.1016/j.apenergy.2017.05.090.
Yano, J., Aoki, T., Nakamura, K., Yamada, K., Sakai, S., 2015. Life cycle assessment of hydrogenated biodiesel production from waste cooking oil using the catalytic cracking and hydrogenation method. Waste Manag. 38, 409–423. https://doi.org/10.1016/j.wasman.2015.01.014.

vti

A review of public policy instruments to promote freight modal shift in Europe: Evidence from evaluations

VTI Working Paper 2021:6

Johanna Takman[1], Marta Gonzalez-Aregall[2]

1. Transport Economics, VTI, Swedish National Road and Transport Research Institute
2. School of Business, Economics and Law, University of Gothenburg

Abstract

This paper presents a review of past and present public policy instruments in Europe promoting a modal shift of freight transports. The identified policy instruments are categorized based on several shared characteristics. To the extent that ex-post evaluations are available, policy performance is discussed, and the evaluations are compared.

The study identifies 93 public policy instruments in Europe. The most common type of policy is subsidies/grants to rail and/or water implemented at the national level. Most policy instruments only focus on the promotion of one specific transport mode, which most commonly is rail.

Evaluations of policy performance were found for 20 policy instruments. The evaluated policy instruments are mainly subsidies/grants at the national level, or policy instruments at EU level. The bias in evaluation towards these types of policy instruments is partly explained by the commitment to evaluation at EU level, and the need for permission by the European Commission to implement and prolong subsidies/grants classified as state aid. The evaluations differ in methodology and regarding what type of performance indicators that are evaluated. The evaluation guidelines and criteria that exist at EU level are often followed to some extent but interpreted differently depending on for example type of policy and data availability. Thus, comparing policy performance is difficult.

In general, there seem to be a more positive performance of policy instruments promoting a modal shift to rail than to waterborne transports. Several evaluations of EU-policy instruments describe a poor or a mixed performance of the policy instruments, while the performance of subsidies/grant at national level are often considered positive by the evaluations. A commonly mentioned factor for underachievement of the policy instruments is problems related to outreach of the policy, lack of applications, long and complicated application processes and a high administrative burden for the companies applying for financial support. Targets for the policy instruments are often broad and general, with a lack of clarity, making it difficult to meet all objectives, as well as to evaluate the policy instruments effectiveness and efficiency. Thus, well-defined targets, as well as better outreach and simpler processes could be one way forward in improving modal shift policy instruments in Europe.

Keywords
Modal shift; freight transport; public policy instruments; evaluation, effectiveness, efficiency

JEL Codes
H21, H23, R41, R48, Q58

A review of public policy instruments to promote freight modal shift in Europe: Evidence from evaluations

Johanna Takman[1], Marta Gonzalez-Aregall[2]

1. The Swedish National Road and Transport Research Institute (VTI)

2. School of Business, Economics and Law, University of Gothenburg

Abstract

This paper presents a review of past and present public policy instruments in Europe promoting a modal shift of freight transports. The identified policy instruments are categorized based on several shared characteristics. To the extent that ex-post evaluations are available, policy performance is discussed, and the evaluations are compared.

The study identifies 93 public policy instruments in Europe. The most common type of policy is subsidies/grants to rail and/or water implemented at the national level. Most policy instruments only focus on the promotion of one specific transport mode, which most commonly is rail.

Evaluations of policy performance were found for 20 policy instruments. The evaluated policy instruments are mainly subsidies/grants at the national level, or policy instruments at EU level. The bias in evaluation towards these types of policy instruments is partly explained by the commitment to evaluation at EU level, and the need for permission by the European Commission to implement and prolong subsidies/grants classified as state aid. The evaluations differ in methodology and regarding what type of performance indicators that are evaluated. The evaluation guidelines and criteria that exist at EU level are often followed to some extent but interpreted differently depending on for example type of policy and data availability. Thus, comparing policy performance is difficult.

In general, there seem to be a more positive performance of policy instruments promoting a modal shift to rail than to waterborne transports. Several evaluations of EU-policy instruments describe a poor or a mixed performance of the policy instruments, while the performance of subsidies/grant at national level are often considered positive by the evaluations. A commonly mentioned factor for underachievement of the policy instruments is problems related to outreach of the policy, lack of applications, long and complicated application processes and a high administrative burden for the companies applying for financial support. Targets for the policy instruments are often broad and general, with a lack of clarity, making it difficult to meet all objectives, as well as to evaluate the policy instruments effectiveness and efficiency. Thus, well-defined targets, as well as better outreach and simpler processes could be one way forward in improving modal shift policy instruments in Europe.

Keywords: Modal shift; freight transport; public policy instruments; evaluation; effectiveness; efficiency

Authors:

Johanna Takman, T.: +46(0)8-555 770 31, E-mail: Johanna.takman@vti.se

Marta Gonzalez-Aregall, T.: +46(0)31-786 1509, E-mail: marta.gonzalez-aregall@gu.se

Funding: This work was supported by Naturvårdsverket (the Swedish Environmental Agency).

Project Title: MOSEL- MOdal Shift for an Environmental Lift (2018-2021)

Content

1. Introduction

The objective of this study is to identify and classify past and present public policy instruments implemented in Europe with the aim to achieve a modal shift, as well as reviewing their performance to the extent that ex-post evaluations exist. The research is important as it helps us understand if and how public policy instruments contribute to a modal shift of freight transport in Europe.

The current growth of freight transportation, due to the development of national and international trade, has not only enlarged volumes of road freight tonnage but also intensified freight's negative externalities, including road congestion, greenhouse gas (GHG) emissions[1], air emissions, noise pollution, and accidents (Ambra et al., 2019; Lin, 2019; Nocera et al., 2018). A modal shift from road to rail and waterborne transport (short sea shipping and inland waterways), for parts of the distance (multimodal transports) or wholly, could help reduce some of the negative externalities from freight transports (Bickford et al., 2014; Nealer et al., 2012). In general, using rail and waterborne transport consumes less energy per ton and emits fewer GHG-emissions than using road transport exclusively (Breathen, 2011).

In order to reduce the negative externalities from freight transports, several public actors in Europe have set up targets and adopted policy instruments to promote a modal shift from road to rail and water. Several of these policy instruments and targets are driven by the European commission's Transport White Paper which specifies a modal shift of 30% for long distance road freight transport (above 300 km) by 2030, and more than 50% by 2050 (European Commission, 2021a; Pinchasik et al., 2020). So far, however, a modal shift from road to rail and inland waterways transport (IWT) has not been achieved at the aggregate level in the European Union (Eurostat, 2020) and several countries are far from meeting their modal shift objectives (Pinchasik et al., 2020). Road transport remains the dominant transport mode, representing more than three-quarters of all inland freight movement. Furthermore, tendencies of a modal back-shift can be seen over time as rail and IWT are losing market shares to road transports (Eurostat, 2020; Pinchasik et al., 2020). This indicates that current policy instruments have not yet been very successful in achieving the desired modal shift in Europe, at least not at the aggregate level. In response to this, it is important to evaluate the performance of past and present public policy instruments to identify efficient and effective policy instruments with potential for furthering modal shift and reduce the negative externalities from freight transport.

The performance of modal shift policy instruments has previously been investigated by several *ex-ante* studies. These studies analyse modal shift policy instruments by including simulations, models, estimations, and different types of impact assessments of how certain policy instruments are *expected* to affect modal shift. For example, Pinchasik et al. (2020) simulates the effect on transport and modal distribution for different policy scenarios in the Nordic countries, finding, among other things, that an ecobonus for rail will have a larger impact on modal shift than an ecobonus for waterborne transport. Santos et al. (2015) simulate how three different policy instruments will contribute to a modal shift to rail in Belgium and finds that while subsidies have a large potential in promoting intramodality, the internalization of external costs could in some cases have a negative impact on promoting intramodality. There are also a few academic papers which evaluate the *ex-post* performance of already implemented policy instruments. For example, Suárez-Alemán (2016) investigate the case of short sea shipping policy within the EU and find that we are not achieving sufficient modal shift in order to meet the objectives stated in the European commission's Transport White Paper. Similarly, Aperte and Baird (2013) investigate policy instruments to promote Motorways of the Sea and find that while some actions at national level have been effective in promoting modal shift to short sea shipping, there has been a limited

[1]"The main greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), as well as ozone depleting chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs)" (Eurostat Statistics)

success of policy instruments at EU level. There are also some studies within the grey literature that has investigated the performance of either specific policy instruments, or a group of policy instruments. For example, KombiConsult GmbH et al. (2015) analyse combined transports in EU and discuss some of the implemented policy instruments within the region. They argue that direct grants to combined transport operations, as well as grant to intermodal facilities, could have a potential in promoting combined transports.

Even though several studies investigate policy instruments for modal shift, we are missing an updated review of the performance (ex-post) of the various public policy instruments implemented in Europe to promote modal shift. This study intends to fill this research gap by answering the following 3 research questions (RQ: s):

RQ1 - What policy instruments have been implemented in Europe with the aim to achieve a modal shift?

RQ2 - Which policy instruments have been evaluated, and which evaluation methods and performance indicators have been applied?

RQ3 - Which conclusions can be drawn regarding the effectiveness and efficiency of European policy instruments in terms of achieving modal shift and reducing negative externalities?

The research intends to improve our knowledge of what types of policy instruments that can effectively and efficiently contribute to a modal shift of freight transport in Europe.

The study delimits itself to public policy instruments in Europe and focus on a modal shift of long-distance heavy freight transports (above 300km) from road to rail and water, as it is mainly these transports that can take advantage of economies of scale and distance (European Commission, 2011a). Furthermore, the focus is on policy instruments being active at some time period from 2000 and onward.

The remainder of the paper is structured as follows: Section 2 presents state of the art regarding policy instruments and modal shift, Section 3 presents the methodology applied in the study including delimitations, Section 4 presents and discuss the results of the study, and Section 5 concludes.

2. State of the art

2.1. Modal shift

Modal shifts include both “pure” shifts to other transportation modes, e.g., from road to rail, and partial shifts to transports including both road and rail and/or waterborne transport, so-called multimodal transports. Multimodal transports also include intermodal transport, which refers to goods that are transported with a combination of at least two transport modes, but without changing loading unit (Santos et al., 2015). Furthermore, the term combined transport refer to intermodal transports where the road leg of the transport is as short as possible (European Commission, 2016a). A modal shift can be a shift of already existing transports or a mode choice of rail or water for new transport services.

A modal shift from road to rail and/or waterborne transport is desirable for many transports as it can help reduce some of the negative externalities from freight transports (Bickford et al., 2014; Nealer et al., 2012). Several researchers investigate the environmental effectiveness and feasibility of modal shift (Ambra et al., 2019; Beuthe and Jourquin, 2001; Bickford et al., 2014; Dong et al., 2018; Kreutzberger, 2008; Lin, 2019; López et al., 2009; Nealer et al., 2012). In general, freight transports by rail and waterborne transport emit less GHG-emissions than truck and result in a reduced number of accidents and congestion on road. For example, in the Handbook on the external costs of transport provided by CE Delft (2020), the external costs for the different transport modes are estimated, including accidents, air pollution, climate, noise, congestion, well-to-tank and habitat damage. According to the estimations, external costs in 2016 for heavy trucks, rail, and IWT were 4.2, 1.3 and 1.9 €-cent per tonne kilometre (tkm) respectively. However, the external costs of the different transport modes vary depending on several factors such as load factor, where the transport is performed, and what energy sources that are used. For example, according to Nocera et al. (2018) the external costs are about four times higher in the alpine areas than at flat areas.

Even though the literature generally mentions advantages of a modal shift to rail and water, it is important to note that the climate- and environmental benefits of a modal shift from road to waterborne transports have been questioned and that under certain circumstances these might be negative. For example, Svindland and Hjelle (2019) estimate the comparative CO_2 emissions of maritime freight transport compared to road and base their data on CO_2 emissions from actual container feeder transport operations in Europe over a year. They find that short sea container shipping is more CO_2 efficient than road in general, but that the comparative advantage to road is only marginal in several scenarios. They find that a relatively high capacity utilization is needed in order for maritime transport to be considered better than road in terms of CO_2 emissions. Furthermore, even though the external costs are generally lower for rail freight and IWT than for road, this is not always the case for intermodal transportation (Kaack et al., 2018). For example, Santos et al. (2015) finds that, depending on the length of the road haul, internalizing external costs can even disadvantage intermodal transport operations.

There are several factors which influence the mode choice for freight transport services. Transport costs and prices are one of the most important factors (Elbert and Seikowsky, 2017). In this study, the focus is on the shift from long distance heavy road transports (above 300 km) to rail and water, as it is mainly these transports that can take advantage of economies of scale and distance (European Commission, 2011a). However, there are also other factors which may influence the mode choice (and indirectly affect the costs), such as reliability, flexibility, transit time, frequency, accessibility, and security (Dong et al., 2018; Elbert and Seikowsky, 2017). Furthermore, the characteristics of the goods being shipped, such as volume, weight, perishability, and value may also be considered when choosing transport mode (Lindgren and Vierth, 2017). According to Pinchasik et al. (2020) the competitive advantage of road is increasing as longer and heavier vehicles are allowed (for example in the Nordic Countries) and as technological improvements and changes influence the energy efficiency and emissions from trucks. Furthermore, Pinchasik et al. (2020) emphasise the importance of recognizing the geographical differences in countries as policy instruments might have different effects on modal split given the countries certain conditions. An international perspective is also important as the likeliness for goods to continue by rail or water is higher if the goods enter the country by rail or water rather than by road.

According to Tsamboulas et al. (2007) there has been a focus on the supply side of modal shift in research and policy when trying to strengthen the position of rail and waterborne transports compared to road. However, the mode choice decision-making process is complicated and vary between supply chains and segments. Different actors have different priorities and possibilities to achieve a modal shift, and the decision power may lay at different actors depending on supply chain and segment. It is therefore important that the above-mentioned mode choice criteria are considered when designing policy instruments, and that differences between segments and supply chains are acknowledged.

2.2. Policy instruments and theory

In this study, *public policy instruments* refer to political tools that are employed to correct for market failures and to reach one or several societal objectives, such as a modal shift to reduce the negative externalities from road freight transports. These public policy instruments are expected to make private or public actors take *measures* that are in line with the overarching goals. Measures may also be taken at own initiative, for example if a private firm shares the same goal as the government. However, this study delimits itself from private initiatives and thereby only focus on policy instruments initiated by *public* actors.

There exist several different types of policy instruments, which can be categorized in different ways. In this study we use the categories: economic (eg. taxes and subsidies), administrative (e.g., legislations, technical requirements, environmental classifications) and information (e.g., eco-labelling, advising, education, training, research, and development). These policies are mainly based on the Swedish Environmental Protection Agency (2021) where policy instruments are classified according to if they are market based (using prices and other market-mechanisms) or non-market based (e.g., regulations, informative policy instruments etc.), and on Swedish Environmental Protection Agency (2012) where policy instruments are classified as economic, administrative, informative and research.

The effectiveness and efficiency of different types of policy instruments has previously been discussed in the literature. For example, in theory, a global CO_2-tax representing the external costs of CO_2-emissions is often mentioned as the most cost-effective policy instrument for reducing CO_2-emissions (Pigou, 1920). However, the policy instruments that are considered the most optimal according to theory are not always possible to implement in practice due to for example political factors. Therefore, while the first best policy would be desirable from a theoretical perspective, the second-best policy might be the one that is possible to implement given the circumstances.

To understand the functioning and performance of a policy instrument, as well as understand if it is relevant for its purpose and achieve its objectives at a minimum cost to society, performing policy evaluations is a helpful tool (European Commission, 2017a). By performing evaluations, decision making regarding current and future policy instruments can be improved and based on lessons learned from previous experiences. According to the European Commission (2017) an ex-post evaluation should be an evidence-based judgement looking for causality between the policy instrument and the observed changes (if any), and it should be performed after a time period long enough to allow for any changes to be identified and measured.

There are several factors that need to be considered when a policy is evaluated. The OECD/DAC Network on Development Evaluation (2019) provides evaluation criteria, that were first laid out in 1991, but later revisited following the Paris Agreement and the 2030 Agenda for sustainable development. The criteria describe desired characteristics of policy instruments (included in the term "*interventions*") and include the following:

- **"Relevance:** is the intervention doing the right things?"

- **“Coherence:** how well does the intervention fit?”
- **“Effectiveness:** is the intervention achieving its objectives?”
- **“Efficiency:** how well are resources being used?”
- **“Impact:** what difference does the intervention make?”
- **“Sustainability:** will the benefits last?”

The European Commission (2017a) also provides guidelines for how to perform policy evaluations in their “Better Regulation Guidelines”. Their evaluation criteria largely overlap with the criteria provided by the OECD/DAC Network on Development Evaluation (2019), and include: effectiveness, efficiency, relevance (given current needs), coherency (given other policy instruments), and EU added value. Furthermore, the European Commission (2017a) also highlights the importance of the evaluations having a high quality and following principles such as being comprehensive, proportionate, independent, objective and evidence based.

The European Commission (2017a) emphasize that even if there exists several different types of reports and activities that cover some of the above-mentioned questions, not all of them include all of the necessary elements to qualify as an evaluation. In this paper, we include evaluations that reach the European Commission (2017a) standards as well as evaluations that do not. We will call all these attempts to evaluate the performance of an already implemented policy for *evaluations*.

Although there are several different guidelines and criteria for how to perform evaluations, difficulties in evaluating policy instruments in practice exist for various reasons and may, among other things, differ between different types of policy instruments. According to Crabb and Leroy (2012), evaluating environmental policy instruments is a special case presenting new complexities compared to other policy areas. Difficulties in finding relevant and reliable data, as well as distinguishing between changes that has occurred due to a policy instrument and what changes that has occurred for other reasons are some of the problems that arise for evaluators in the environmental policy area (Crabb and Leroy, 2012; European Commission, 2017a).

Both Huitema et al. (2011) and Christie (2003) find that there is a gap between evaluation theory and how ex-post evaluations are performed in practice. Harmelink et al. (2008) study 20 policy instruments and their ex-post evaluations and find that energy policy instruments often lack quantified targets and clear timeframes, and that monitoring information is not collected at a regular basis. Furthermore, they find that policy evaluations often have different characteristics and use a large variation of methodologies to determine the effects of a policy, making comparisons between evaluation results difficult. There is also a variation in quality between different evaluations, which may jeopardize the evaluations possibilities to improve public policy (Cooksy and Caracelli, 2005). According to Haug et al. (2010) climate policy evaluations performed in the EU are in many cases not systematic which makes evidence-based policy and decision-making difficult.

A recently published paper in the Swedish journal “Ekonomisk Debatt” find that even though the same types of methodologies are used, evaluations performed by private consultant firms often generate a more positive description of policy performance than evaluations performed by other types of evaluators (Colin et al., 2021). They argue that one explanation to this could be that the evaluated public authorities have incentives to choose evaluators from which they expect more positive results, as this could lead to continued financing for the authority. Thus, the consultant firms might over time generate more positive evaluations if this constitutes a competitive advantage towards other evaluators.

2.3. Previous literature on policy instruments for modal shift

Policy instruments targeting a modal shift have been investigated through several different perspectives and a number of research projects have sought to inform policymaking with respect to facilitating freight modal shift from road to rail and/or water. Several papers that investigate modal shift from a policy instrument context use models and simulations to estimate the *expected* modal shift from different policy instruments. A study by Pinchasik et al. (2020) simulates effects from different policy scenarios where modal shift policy measures are strengthened, expanded, combined, and harmonized across borders by using the National Freight Model for Norway. Among other things, they find that an ecobonus (subsidy/grant system) for rail leads to a higher modal shift than a corresponding ecobonus for waterborne transport. They also find that the effects on GHG-emissions are relatively small even in scenarios with strong policy instruments and that some of these scenarios comes with increased local air pollution. In another study, Santos et al. (2015) simulate how three different policy instruments will contribute to a modal shift to rail in Belgium. They find that subsidies have a significant impact on promoting intermodality and that optimizing terminal location also increase the competitiveness of intermodal transport, but to a less extent than subsidies. However, they find that internalizing external costs can have a negative effect on the promotion of intermodality and that innovative last-mile transports are needed to overcome this obstacle. Beuthe et al. (2002) also investigate the case of Belgium and simulate the effect on freight transport on road, rail and IWT when external costs are internalized. In contrast to Santos et al. (2015), they find that the internalization of external cost could be very effective in achieving a modal shift from road to rail and IWT. However, they emphasize that such a policy instrument cannot be introduced in isolation only in Belgium but need to be coordinated with road pricing policy instruments in other European countries. Tsamboulas et al. (2015) investigate the implementation of the Ecobonus financial incentive in Italy and develop a model to try to estimate how modal shift will be affected by the implementation of new maritime routes under the subsidy. Based on data regarding the performance of the previous Ecobonus program, they find that the effectiveness of the policy is most significant in a context where the Ro-Ro ("roll-on/roll-off" ships) market is not very well developed, and the number of potential road haulier users is high. They therefore recommend that these characteristics should form the basis for allocating funding.

Tao et al. (2017) model the potential for freight modal shift of containers and a corresponding reduction in CO_2 emissions from introducing a subsidy policy to rail users in Yiwu City (China). They find that CO_2 emissions can be reduced by 2,2% compared to the scenario without a subsidy. Furthermore, they find that subsidies are successful in stimulating a short-term modal shift, but that a policy package encompassing financial, technological, operational, and managerial measures is required in the long-term.

Potential possibilities of policy instrument combination and integration has also been mentioned by several other papers investigating policy instruments for reducing externalities from the transport sector, such as Santos et al. (2010) and Vieira et al. (2007). In economics it is often referred to the so-called Tinbergen Rule, which states that for each and every policy target there must also be at least one policy tool (Tinbergen, 1952). This has some implications for climate and environmental policy instruments. It is common that policy instruments affect more than one target, both in positive and negative ways (Knudson, 2009). Therefore, selectivity is a positive attribute for a policy as it will lead to a better matching between policy and target. Furthermore, Knudson (2009) argue that it is important for policy makers to realise that it doesn't exist any "magic bullets" that can fix all climate and environmental problems, and that a series of policy tools need to be developed to match policy instruments and targets.

A few papers evaluate the performance of already implemented policy instruments. For example, Suárez-Alemán (2016) investigate how EU policy have contributed to shifting transports to short sea shipping. They find that maritime transport has not been properly promoted and that we are not yet on the right path to meet the objectives stated in the transport White Paper. The author argues that modal shift policy instruments in the form of outright grants to companies that shift transport mode (such as the Marco Polo Programmes) lack incentives to promote the efficiency in short sea shipping. Furthermore, little attention is being paid to efficiency in ports. Looking into EU investments in infrastructure, ports have only received 5 % of the transport investments at EU level while road has received 60%. The lack of policy instruments targeting ports is considered problematic as the role of ports are crucial in intermodal transport chains. Aperte and Baird (2013) also investigate policy instruments for maritime transports, focusing on policy instruments to promote Motorways of the Sea. Just like Suárez-Alemán (2016), they find that there has been a limited success of policy instruments at EU level, such as the Marco Polo Programmes. However, they find that some policy instruments at national level have been effective in promoting modal shift to short sea shipping, such as the Italian Ecobonus scheme which is paid in the form of a subsidy (tariff rebate) to the users of maritime transport. They argue that some of the success of the Italian Ecobonus scheme may depend on the simplicity of the programme and the user-friendly approach. However, the policy could be further improved by more frequent payments, for example monthly, instead of once a year. Furthermore, it is important to supervise how the maritime charges evolve as there is a risk that subsidies and grants to the users of transport services, like the Ecobonus, may be followed by price increases in tariffs. In a report on Combined Transport in EU, KombiConsult GmbH et al. (2015) investigate several policy instruments promoting combined transport within the region. In accordance with Aperte and Baird (2013), they argue that direct grants to combined transport operations, as well as grant to intermodal facilities, could have a potential in promoting combined transports. However, they also discuss the different downsides of direct grants. For example, transport operations by rail or water risk being shifted back to road when the grant or subsidy expires. Therefore, policy instruments like these tend to be permanent to eliminate the risk of a modal backshift. Furthermore, the direct grants may also lead to distorted competition.

Other streams of research regarding policy instruments and modal shift involve the direct involvement of governments, which is explored by Pallme et al. (2015). The study investigates the ability of local governments to influence the success of intermodal terminals through support or direct participation in a public private partnership. They find that securing commitment and positive collaboration between the railroads, shippers and government is critical to achieving a positive outcome from public policy to influence a modal shift from road to rail. Furthermore, Meers and Macharis (2015) suggest that if geographic entities are ranked and then targeted according to their modal shift potential, then this will allow policymakers to focus their modal shift efforts on a limited number of transport flows and achieve a higher success rate. Frey et al. (2014) model the potential impact of a raft of policy instruments on freight modal choice within Germany. Applying a systems dynamic model, they find that although targets are more easily achieved in times of strong economic growth, serious capacity problems on rail are likely to emerge. Other work advocates the case of modal backshift. For example, a study by Meers et al. (2018) investigate the possibilities of a reversed modal shift to road when policy instruments allow longer and heavier trucks on the roads. According to the study, there is limited evidence of a reverse modal shift from countries which already allow longer and heavier trucks. However, the study shows that the impact of longer and heavier trucks on the Belgian market could be substantial if road transport prices are also decreased.

3. Methodology

3.1. Identification and classification of policy instruments

To understand how policy instruments can contribute to a modal shift, it is important to increase the understanding of what policy instruments that already exist, as well as the performance of these policy instruments. This study presents a review of public policy instruments within the European region and classify them according to several categories. To the extent that ex-post evaluations exist, a discussion regarding the policy instruments effectiveness and efficiency is included, as well as a discussion regarding the characteristics of the evaluations.

As there is no database, webpage or other source that already includes information regarding all modal shift policy instruments in Europe, information has been gathered from a variety of different sources to compile a comprehensive list of as many modal shift policy instruments as possible. To start with, already existing databases were examined to identify policy instruments aiming for a modal shift. This mainly included the European Commissions (2021b) database for state aid cases and the OECD (2021) database on policy for the environment. Second, we have searched for policy instruments in both grey and white literature, mainly using Google and Google Scholar. Search words included among other things “policy instrument”, “freight”, “modal shift”, “multimodal transport”, “intermodal” etc. More detailed searches were also conducted such as “subsidy, rail, Italy”. This search strategy resulted in the identification of various modal shift policy instruments from several different sources. For example, information regarding existing policy instruments were identified in academic studies, websites of governmental institutions, reports published by public organizations, etc. Snowball techniques were used to further identify policy instruments, for example by checking the reference lists to academic studies and reports. The last searches for policy instruments were conducted in April 2021. Thus, policy instruments implemented after that are not included in the study.

All relevant policy instruments found during the search process were included in a database constructed during this project. For a policy instrument to be included in the database it had to fulfil the following requirements:

- Implemented by a public actor in Europe.
- Targeting a freight modal shift from road to rail and/or waterborne transports as well as policy instruments with a clear focus on reducing freight transport by truck (e.g., internalizing external costs).
- The policy being active at any time after 2000. To identify past and present public policy instruments implemented as well as their performance through ex-post evaluation, only already implemented policy instruments were included and not planned policy instruments.

As a result of the search process, 93 modal shift policy instruments have been included in the database and sorted according to several different categories to understand the policy instruments’ incidence and interrelationships. The main categories that the policy instruments have been sorted to are geographical level of the policy instrument, which transport mode the policy instrument promotes, and what policy group the policy instrument belongs to.

The geographical level category sort the policy instruments according to if they are implemented at the regional, national, or local level. First, the regional perspective mainly reflects policy instruments applied by the European Commission, but it can also include cooperation between a few European countries. A national perspective encompasses policy instruments implemented by the government in a specific country[2], for example, the Ecobonus systems implemented in Sweden, Italy, and Norway. Beyond that, the local perspective represents policy instruments applied by local governments within a specific country's region or province. For instance, the Ecobonus system promoted by the Basque Country region in Spain is a subsidy scheme for road carriers that aims to shift freight transports from road to sea.

The categorization of policy instruments according to targeted transport mode include whether the policy promotes rail, shortsea shipping, IWT, and/or road discourage.

The policy instruments are also sorted according to several policy categories and sub-categories, based on the categorization of policy instruments according to the Swedish Environmental Protection Agency (2021, 2012). Using these references, we developed a set of criteria for analysing and structuring policy instruments in two dimensions. The first was a classification of the primary categories of the policy instruments in three groups: administrative, economic, and information. The second was the identification of which sub-category the policy instrument belonged to. As a result, 3 primary categories and 14 sub-categories were considered, presented in Table 1 below.

Table 1 – Primary categories and sub-categories of policy instruments

Administrative	**Economic**	**Information**
Agreement	Fee	Advising
Infrastructure planning	Funding of infrastructure	Development research
Inspection	Grant	
Legislation	Subsidy	
Limit	Tax	
	Tax deduction	
	Toll/vignette	

3.2. Identification and classification of evaluations

For every policy instrument that was included in the database, we also searched for *ex-post* evaluations of the policy instruments to achieve information regarding their performance. The searches were conducted in Google and Google Scholar, including both grey and white literature. The last searches were conducted in April 2021. For each of the included policy instruments, we searched for the name of the policy in combination with the words "evaluation", "impact", and "assessment", in each search engine. However, some evaluations had already been found during the process of identifying the policy instruments and were therefore found using different search words and snowball techniques. We included all type of studies and documents that attempts to evaluate the performance of an already implemented policy instrument and not only those that reach the European Commission (2017a) standards for classifying as an evaluation.

3.2.1. Evaluation characteristics

It is important to not only gather information regarding the performance of the policy instruments (according to the evaluations), but also gather information regarding how the evaluations have been

[2] National category covers: Member States, European Free Trade Association (EFTA) countries (Iceland, Liechtenstein, Norway, and Switzerland) and United Kingdom.

performed. By doing so, we can increase our understanding of how policy evaluations for modal shift policy instruments are evaluated today, as well as the quality of these evaluations. This helps us understand how the performance of the policy instruments have been evaluated by the different evaluations, as well as if they are comparable with each other. As policy evaluations may vary in for example methodology, quality, and what performance criteria they evaluate, we have included information regarding the policy evaluations characteristics in the database.

Based on the different papers examining performance of policy instruments and quality of policy evaluations presented in section 2.2, we have selected four performance and quality criteria to search for in the policy evaluations:

- Actor performing the evaluation.
- Purpose of evaluation.
- Performance criteria considered by the evaluation.
- Methodology to evaluate the performance.

Some policy instruments have several different targets, where modal shift just is one of them. Therefore, we distinguish between the performance criteria that are considered by the evaluation as a whole, and the performance criteria that are considered in terms of evaluating the modal shift performance. To determine what performance criteria that were considered, we used the European Commission (2017a) definitions for relevance, coherence, effectiveness, efficiency and EU added value.

Information regarding the above performance and quality criteria were included in the database and is further described in the results and discussion (section 4).

3.2.2. Policy performance

As described in section 2.2, the performance of a policy instrument can be described according to several different criteria such as those mentioned by the better regulation and evaluation guidelines provided by the European Commission (2017a) and OECD/DAC Network on Development Evaluation (2019): relevance, coherence, effectiveness, efficiency, impact, sustainability, and EU value added. In this study, the focus is on identifying the policy instruments' *effectiveness* and *efficiency*. Therefore, information regarding effectiveness and efficiency, as well as the policy instruments targets was summarized for each of the identified evaluations.

The definitions of effectiveness and efficiency formulated by the European Commission (2017a) and OECD/DAC Network on Development Evaluation (2019) where used as guidelines when gathering information from the evaluations. The performance criteria *effectiveness* should analyse the progress towards the policy instruments objectives (European Commission, 2017a; OECD/DAC Network on Development Evaluation, 2019). This includes looking at the quantitative and qualitative effects of the policy instruments, as well as looking for evidence of why, whether and how the observed changes are linked to the policy instrument (European Commission, 2017a). Furthermore, to investigate factors such as distribution of the effects among groups in society, the performance criteria *effectiveness* should also include "results" and "differential results" to look beyond the objectives (OECD/DAC Network on Development Evaluation, 2019). According to the European Commission (2017a) the performance criteria *efficiency* should investigate costs and benefits of the policy, as well as how they accrue to different stakeholders. The OECD/DAC Network on Development Evaluation (2019) define the *efficiency* criteria as "A measure of how economically resources/inputs (funds, expertise, time, etc.) are converted to results".

3.3. Delimitations of methodology

The search process has resulted in 93 public policy instruments over Europe of which we have found evaluations for 20. This does most likely not cover *all* modal shift policy instruments and evaluations in Europe and there might be some bias in the database that have been constructed within the project. For example, language barriers might have caused a bias towards policy instruments and evaluations in those countries that provides information in English. Furthermore, there might be a bias in the database towards economic and administrative policy instruments at a regional or national level as these are often more well documented than policy instruments at the local level.

Some policy instruments are closely linked to each other. For example, the EU-programme “Motorways of the Sea” has been financed through several other EU funding programs such as CEF, TEN-T, and the Marco Polo I and II programmes. Because of these interrelations, some policy instruments are “double counted” in the database, at both the funding level and implementation level. We have chosen to include both levels, as the implementation level does not lie directly under the funding level but is governed outside the program. Often, funding from more than one source is used. At the same time, we believe it makes sense to include the overarching measures on EU-level, as these make up a large share of the total funding and enable many programs, and hence are important to evaluate.

In this study we have mainly considered policy instruments with modal shift as primary target. However, policy instruments with other primary targets, such as internalization of freight transport’s external costs or funding of rail infrastructure, have also been included if modal shift is considered as a sub target or desired effect. There are however policy instruments that do not target a modal shift, but which may in fact contribute to a modal shift. For example, a CO_2 tax on fuel might lead to higher costs in the road transport sector compared to other transport modes and indirectly lead to a modal shift. These type of policy instruments have not been included in this study.

4. Results and discussion

4.1. Identified policy instruments.

The first research question (RQ1) that we aim to answer in this study is: “What policy instruments have been implemented in Europe with the aim to achieve a modal shift?”. The search strategy applied within the study to answer RQ1 resulted in the identification of 93 public policy instruments within Europe (see Annex A for a list of the identified policy instruments). All identified policy instruments were included in a database, where they were sorted according to different categories, as described below in section 4.1.1 to 4.1.3.

4.1.1. Geographical level

First, we have analysed the geographical level, i.e., in the place where the policy instrument has been implemented. At the regional level, 27 public policy instruments have been identified, which includes both policy instruments implemented by the European Union but also specific collaborations between countries. Most policy instruments (53 out of 93) have been identified at the national level. Finally, 13 public policy instruments have been identified at the local level, targeting specific areas of a country.

4.1.2. Transport modes targeted by policy.

Second, we have categorised the policy instruments according to what transport modes they aim to promote. First, 58 percent of the identified policy instruments focus on promoting one specific transport mode, primarily railway (34 percent), followed by waterborne transport (24 percent). Second, 22 percent of the policy instruments promotes the use of both rail and waterborne transport simultaneously. Finally, 19 percent of the identified policy instruments indirectly promotes a modal shift by discouraging road transportation, for example by internalizing the external costs of road transport by vignette/toll systems (see for example the Eurovignette Directive). Figure 1 shows the categorization of the identified policy instruments according to targeted transport mode.

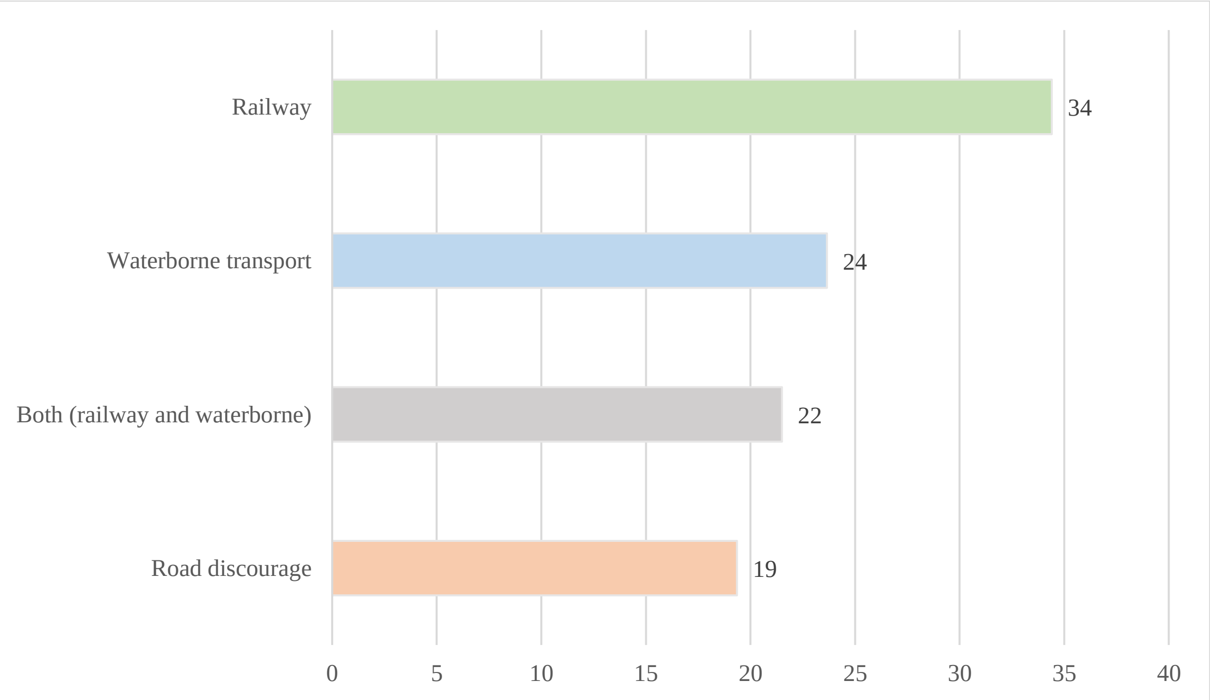

Figure 1 – Targeted transport mode by public policy instrument (%)

4.1.3. Primary categories and sub-categories of the policy instruments

Finally, the identified policy instruments are categorized into 3 different primary policy categories, as well as 14 sub-categories, as presented in Table 2. Sorted according to primary categories, the most identified policy instruments are economic (70%) followed by administrative (21%) and information (9%). The most identified administrative policy instruments are legislations, mainly EU directives and specific regulations. Second, in the case of economic policy instruments, 35% of the total cases considered are grants, such as the EU: s Marco Polo Programs or the Mode Shift Revenue Support and Waterborne Freight Grant implemented in Great Britain. This is followed by subsidies like the Ecobonus systems implemented in for example Italy and Sweden. Finally, development research, which accounts for 6 percent of the total policy instruments, comprise the most common information policy, for example the Shift2Rail Joint Undertaking. As previously discussed in section 3.3, there might be a bias in the database towards economic and administrative policy instruments at the regional and national level as these are often more well documented than policy instruments at the local level.

Table 2 – Primary categories and sub-categories of public policy instruments (%)

Administrative	**21 %**	**Economic**	**70 %**	**Information**	**9 %**
Legislation	12 %	Grant	35 %	Development research	6 %
Infrastructure planning	5 %	Subsidy	19 %	Advising	2 %
Limit	2 %	Toll/vignette	8 %		
Agreement	1 %	Funding of infrastructure	4 %		
Inspection	1 %	Fee	1 %		
		Tax	1 %		
		Tax deduction	1 %		

4.2. Policy evaluations

The second research question (RQ2) that we aim to answer in this study is: "Which policy instruments have been evaluated, and which evaluation methods and performance indicators have been applied?". Below, section 4.2.1 presents the policy instruments for which evaluations have been identified, and section 4.2.2 discuss the evaluation characteristics.

4.2.1. Identified evaluations.

The search strategy applied to answer RQ2 resulted in the identification of publicly available evaluations for 20 out of the 93 modal shift policy instruments. Table 3 present the policy instruments for which we have found evaluations. As some policy instruments have been evaluated more than once, and some evaluations consider more than one policy instrument, the number of evaluations is not the same as the number of evaluated policy instruments. For further information regarding the evaluated policy instruments, Annex B presents a table describing the evaluation characteristics of the evaluated policy instruments, and Annex C presents a brief description of the evaluated policy instruments, as well as their targets, effectiveness, and efficiency.

As can be seen in Table 3 about half (11) of the evaluated policy instruments are implemented at EU-level, and the other half are implemented at the national level (8), or the local level (1). Only the category of economic policy instruments is covered by the evaluations at the national and local level, as all of them evaluate either subsidies or grants promoting rail and/or waterborne transports. However, the evaluated policy instruments at EU-level covers all three primary policy categories: economic, administrative and information.

Table 3 - Evaluated policy instruments.

Name of the Public Policy Instrument	**Region / country**	**Promotion of transport mode**	**Primary category**	**Sub-category**	**References regarding policy performance**
Connecting Europe Facility (CEF)	European Union	Rail and Water	Economic	Funding of infrastructure	(European Commission, 2018)
Directive 1992/62 and 2011/76/EU - Eurovignette	European Union	Road discourage	Administrative	Legislation	(European Commission, 2013)
Directive 92/106/EEC - Combined Transport of goods between Member States	European Union	Rail and Water	Administrative	Legislation	(European Commission, 2016a, 2016b)
EU Regulation 561/2006 - Rest periods on rolling/floating roads and social legislation relating to road transport	European Union	Rail and Water	Administrative	Legislation	(Windisch et al., 2016)
EU Regulation 913/2010 - European rail network for competitive freight	European Union	Rail	Administrative	Legislation	(European Commission, 2016c)
European Shortsea Network – (Evaluation for the Norwegian Short Sea Promotion Centre)	European Union	Water	Information	Development research	(Askildsen, 2005)
Marco Polo I and II	European Union	Rail and Water	Economic	Grant	(Europe Economics, 2011; European Court of Auditors., 2013; Innovation and Networks Executive Agency (INEA), 2020)
Motorways of the Sea	European Union	Water	Economic	Grant	(ICF et al., 2017)
NAIADES - Navigation and Inland Waterway Action and Development in Europe	European Union	Water	Administrative	Infrastructure planning	(European Commission, 2011b; European Court of Auditors, 2015)
National Aid - "The Mode Shift Revenue Support- MSRS	Great Britain	Rail and Water	Economic	Grant	(Department for Transport, 2014, 2020a).

National Aid - "The Waterborne Freight Grant Scheme"	Great Britain	Water	Economic	Grant	(Department for Transport, 2014, 2020a; European Commission, 2020a)
National Aid - Freight Facilities Grant - FFG	Great Britain	Rail and Water	Economic	Grant	(Woodburn, 2007)
Shift2Rail	European Union	Rail	Information	Development research	(Fontanel et al., 2017)
State aid to transfer goods to rail - the Province of Emilia Romagna	Italy (Emilia Romagna Region)	Rail	Economic	Subsidy	(European Commission, 2019a, 2014a).
State aid to transfer goods from road to rail "Ferrobonus"	Italy	Rail	Economic	Subsidy	(European Commission, 2020b, 2016d, 2011c)
State Aid - to transfer goods from road to rail "Nuovo Ferrobonus"	Italy	Rail	Economic	Subsidy	(European Commission, 2019b; Marzano et al., 2018)
State Aid - to transfer goods from road to water "Ecobonus"	Italy	Water	Economic	Subsidy	(European Commission, 2012a; RAM S.p.a, 2019; Tsamboulas et al., 2015)
State Aid - to transfer goods from road to rail "Miljökompensation"	Sweden	Rail	Economic	Grant	(Swedish Transport Administration, 2020)
State Aid - Financial support for rail operations	Austria	Rail	Economic	Grant	(European Commission, 2017b)
Trans European Transport Network (TEN-T)	European Union	Rail and Water	Economic	Funding of infrastructure	(European Commission, 2020c; Steer Davis Gleave, 2011)

4.2.2. Evaluation characteristics

Annex B presents a full list of the evaluated policy instruments and details regarding their evaluation characteristics in terms of actors performing the evaluations, purpose of the evaluations, performance criteria considered (for the evaluation in total, as well as with respect to modal shift and associated externalities), as well as methodologies applied. Below we briefly summarize and discuss the main findings regarding the evaluation characteristics.

4.2.2.1. Actors performing the evaluations.

At the EU level, the evaluations have been performed by actors such as the European Court of Auditors, different consultant firms, and/or expert groups. However, some Commission Staff working documents are lacking details regarding what specific actors and authors that has performed the evaluations.

The type of evaluators also varies at the national and local level. For example, the evaluation of the scheme on environmental compensation for rail freight transport in Sweden ("Miljökompensation för järnväg") has been evaluated by the Swedish Transport Administration (2020), which is also the organisation that administrates the policy (but the budget is decided by the government). Instead, in for example Great Britain, private consultant firms has performed the evaluations for the Mode Shift Revenue Support (grant for rail and IWT) and the Waterborne Freight Grant (grant for shortsea shipping), while an independent researcher has performed an evaluation of the Freights Facilities Grant (Woodburn, 2007). For some of the state aid cases at national and local level, the original evaluation reports have not been found. Instead, information regarding the policy performance has been found in the European Commission's decision letters regarding the prolongation of the policy instruments. In those decision letters, it is not always mentioned by the European Commission what specific actor that performed the original evaluation.

As the number of evaluations identified in this project are few, and the number of identified evaluators are even fewer, we cannot draw any conclusions regarding the relationship between evaluators and evaluation methods and/or results at the European level. Positive, as well as negative, performance of policy instruments is described by all types of evaluators. Thus, we can neither confirm nor deny the findings by Colin et al. (2021), showing that evaluations performed by private consultant firms often generate a more positive description of policy performance than evaluations performed by other types of evaluators. Further research, as well as a larger sample of policy evaluations, would be needed to understand if such a relationship exists at the European level.

4.2.2.2. Purpose of the evaluations.

It is important to understand why some policy instruments are evaluated and why some are not, as the results from the evaluations can show a biased picture of the effectiveness of modal shift policy instruments. Several different purposes are mentioned in the evaluations, ranging from legal requirements and prolongation of policy instruments, to understanding the performance and providing recommendations for further improvements.

Article 318 of the Treaty on the Functioning of the European Union (TFEU) include a commitment to evaluation, which may explain why EU policy instruments are evaluated to a higher extent than other policy instruments (European Commission, 2017a). Furthermore, there are several guidelines and frameworks within the EU such as the better evaluation guidelines and The Regulatory Fitness and Performance (REFIT) programme. In several cases it is also specifically mentioned in the legal framework of a policy instrument that it should be evaluated after a certain amount of time. This is for example the case for Connecting Europe Facility (CEF), EU Regulation 913/2010 regarding a European rail network for competitive freight, and the Shift2Rail Joint Undertaking.

As grants and subsidies at the national level are classified as state aid, the member states need permission by the European Commission to implement and continue such programs (European Commission, 2014b). Therefore, the evaluations of such policy instruments have in most cases been performed when the different member states have applied for permission by the European Commission to prolong the aid scheme. However, other purposes than just the prolongation itself are also mentioned in the evaluations, such as evaluating the performance of the policy, suggesting improvements, as well as revising the grant/subsidy levels.

A general observation in this study is that the evaluations that has been performed with the purpose of prolonging subsidies/grants at the national/local level, describe an overall positive policy performance. There are several possible explanations to this result. It could simply reflect that subsidies and grant are effective in achieving a modal shift, which would also confirm the findings from several simulation studies such as Pinchasik et al. (2020) and Santos et al. (2015). However, it could also be a result of member states only wanting to prolong a policy instrument if they already believe that the policy instrument is effective or will be effective in the future. Furthermore, if the likeliness of being allowed to prolong the policy instrument is higher with a positive evaluation, this could provide incentives to describe a more positive performance, which highlights the importance of independent evaluators. Thus, there is a possibility that evaluations with the purpose of prolongation might show a more positive performance than evaluations with other purposes. However, it would also be reasonable to evaluate policy instruments if there are any suspicions that the policy instrument is not achieving its objectives efficiently, as it would then exist incentives to evaluate if it can be improved or if it should be discontinued.

4.2.2.3. Performance criteria considered by the evaluation.

The policy instruments at EU-level most commonly follow the Better Regulation Guidelines provided by the European Commission (2017a) in terms of what performance criteria that are evaluated (relevance, coherence, effectiveness, efficiency and EU value added). However, these criteria are in some cases interpreted differently in the evaluations depending on for example type of policy instrument, type of evaluation, available data, and when the evaluation was performed (the better regulation guidelines were updated in 2017). For example, some evaluations have evaluated the management or the project selection process of the policy, rather than the effects of the policy instrument on modal shift and negative externalities from freight. This is for example the case for Shift2Rail and CEF, where management efficiency is discussed under the performance criteria “efficiency”, rather than the resulting costs and benefits to society of the policy instrument. In several evaluations, it is discussed under the performance criteria “effectiveness” how much funds that have been allocated to different actions, but there is a lack of discussion regarding if the funds have effectively and efficiently contributed to policy targets, a modal shift, and reduced external costs. It is important to mention that some of the EU policy instruments have several different objectives, other than modal shift. Therefore, some of the evaluations are very well performed in terms of addressing the performance criteria of the policy in relation to the overarching objectives but are only briefly discussing the effectiveness and efficiency associated with modal shift.

The policy evaluations at the national and local level vary a bit more in what performance criteria that are considered. All of them discuss effectiveness to some extent, and most of them also discuss the relevance of the policy instrument. Out of the 9 policy evaluations at national/local level, 6 of them estimate costs and/or benefits to society of the policy instrument. However, these estimates might include different types of external costs and benefits. Coherence with other policy instruments is not commonly discussed in the evaluations for national/local policy instruments, other than the coherence with the EU internal market, which is a requirement for policy instruments classified as state aid.

As the evaluations include different performance criteria, and as the same performance criteria are sometimes interpreted differently in the evaluations, making comparisons of policy performance on an equal basis is difficult. Further clarifications regarding how the performance criteria should be interpreted in the evaluations could be needed in the European Commission’s Better Regulation

Guidelines to further harmonize policy evaluations. Moreover, common guidelines for evaluations at national and local level would also be desirable to facilitate comparisons of policy instruments between countries.

4.2.2.4. Methodologies to evaluate the performance.

To the extent that evaluations exist, they differ in methodology, quality and what performance criteria that are evaluated, which confirm the findings from for example Cooksy and Caracelli (2005), Harmelink et al. (2008) and Huitema et al. (2011). Out of the 24 evaluations (note that the number of evaluations is higher than the number of evaluated policy instruments), 11 evaluations use both qualitative and quantitative methods, 7 use only qualitative methods, and 6 use only quantitative methods. Within each of these categories, a wide range of more specific methodologies are applied. For example, qualitative evaluations methods range from analysing policy and strategy documents, to targeted stakeholder consultations and on-spot audit visits. Furthermore, the quantitative approaches may include analyses of trends in freight traffic over time, comparing expected and achieved modal shift, as well as estimating the costs and benefits of a policy instrument.

According to Crabb and Leroy (2012) and the European Commission (2017a), difficulties in finding relevant and reliable data, as well as difficulties to measure causality between the policy instruments and observed changes, are important problems that may arise for evaluators in the environmental policy area. This is confirmed by several evaluations, especially those at EU-level. Most of the policy instruments at EU level that lack a quantitative analysis, do instead include a qualitative discussion and an explanation of why the effectiveness and efficiency has not been estimated quantitatively. One potential solution to overcome the problem of lacking data would be to formulate policy instruments in a way that require the firms receiving payments to collect data that are needed in evaluations.

4.3. Effectiveness and efficiency of modal shift policy instruments

The third research question (RQ3) that we aim to answer within this project is: Which conclusions can be drawn regarding the effectiveness and efficiency of European policy instruments in terms of achieving modal shift and reducing negative externalities? To answer RQ3, information from the policy evaluations regarding objectives/targets, effectiveness and efficiency have been summarised and is presented in detail for each policy instrument in Annex C. Due to the limited amount of policy evaluations, it is difficult to say something general about the performance of the different policy instruments. For example, it has not been possible to draw any conclusions regarding how the effectiveness and efficiency differs depending on the policy instruments' primary categories and sub-categories. Still, some general observations regarding policy performance have been made. Below, we summarise and discuss the most important findings regarding the policy instruments objectives/targets, effectiveness and efficiency.

4.3.1. Objectives/targets

Previous literature (e.g. Svindland and Hjelle, 2019) show that external costs are not automatically lower for waterborne transports than for road. Therefore, it may be problematic when modal shift is considered as an objective itself, rather than a means to achieve reduced external costs from freight transports (Björk and Vierth, 2021). This is the case for several of the identified policy instruments in this study. Furthermore, several of the evaluations identified in this study focus only on the modal shift achieved, and do not evaluate the effect on negative externalities. Therefore, it is important that modal shift is treated as a means to reduce negative external costs, rather than as an objective itself when policy instruments are designed and evaluated.

According to the European Commission (2017a) and the OECD/DAC Network on Development Evaluation (2019), the performance criteria *effectiveness* should analyse the progress towards the policy instruments objectives. However, in accordance with Harmelink et al. (2008), this study finds that there is a lack of well-defined objectives and measurable targets for the identified policy instruments. Furthermore, there is a lack of quantitative policy evaluations comparing the achieved results with the objectives/targets. Several evaluations for policy instruments at the EU level, such as TEN-T, CEF, NAIADES and Motorways of the Sea, mention that the lack of well-defined targets and performance indicators lead to difficulties in achieving objectives, as well as evaluating the policy instruments performance. Thus, the lack of quantified targets makes it difficult to draw conclusions regarding the effectiveness and efficiency of the identified policy instruments. This is problematic as GHG-emissions need to be drastically reduced over the coming years, making knowledge on the effectiveness of policy instruments is exceedingly valuable if climate targets are to be reached. The lack of quantitative evaluations for the policy instruments may well follow from the lack of quantitative targets to start with, which would further strengthen the argument to set measurable targets already from the start.

Even though well-defined objectives and targets are important for assessing the effectiveness and efficiency of a policy instrument, it is important that other aspects are also considered to measure policy performance. The consequences of determining policy performance in terms of target achievement are illustrated in the evaluations of the Marco Polo Programmes (2003-2013), which aimed at promoting a modal shift of freight transports by providing grant to greener transport modes (European Court of Auditors., 2013). The policy instruments had clearly defined quantitative targets, as well as information regarding expected modal shift from granted projects. In terms of target fulfilment, both Marco Polo programmes experienced a significant underachievement, and the modal shift was far below the expected levels. This underachievement is central in the discussions regarding the policy instrument's effectiveness in two evaluation reports of the Marco Polo Programmes (Europe Economics, 2011; European Court of Auditors, 2013). However, in a third evaluation report performed by INEA (2020), as well as in a reply to the European Court of Auditors (2013) by the European Commission, the Marco Polo programmes are also seen in the light of their actual achievements and their benefits to society. For example, the European Commission considers the objectives as very ambitious, and argue that deciding the effectiveness based on target fulfilment may lead to the Marco Polo programmes being considered less effective than they are (European Court of Auditors, 2013). Furthermore, the European Commission also argue that the performance of the Marco Polo Programmes should be seen in the light of the economic crisis. According to INEA (2020) the Marco Polo II programme resulted in the avoidance of 3.5 billion tonnes of CO_2-emissions, and the program generated €2.9-3.1 of environmental benefits (including air quality, noise, climate change, accidents, and congestion) for every euro spent. Thus, depending on where the focus of the evaluations is directed, the performance of the Marco Polo programmes is considered negative or positive.

4.3.2. Effectiveness and efficiency

Several evaluations of EU-policy instruments describe a poor or a mixed performance of the policy instruments. For example, the evaluations found for the Marco Polo Programmes, Motorways of the Sea, NAIADES, TEN-T and the Eurovignette all describe a poor or a mixed performance in terms of achieving a modal shift and reaching desired outputs. However, some of these policy instruments do not have a primary target of achieving a modal shift and mainly focus on other objectives. Furthermore, as previously mentioned, the negative performance of the Marco Polo Programmes is questioned in the evaluation report by INEA (2020).

For some of the evaluated EU policy instruments (Eurovignette Directive, Combined Transport Directive, EU Regulation 561/2006 regarding rest periods on rolling/floating roads) it is problematised that they are enforced differently in the member states. For example, the definition of combined transport in the Combined Transport Directive has been interpreted differently between member states, leading to delays and fines for combined transport operations in some countries (European Commission, 2016a). Furthermore, the Eurovignette directive is implemented with different charging systems, technologies and different price signals over the EU, which impose unnecessarily high administrative costs to haulers (European Commission, 2013).

The evaluations for the EU funding programmes CEF and TEN-T argue that the policy instruments contribute to a modal shift by directing funding to for example rail and IWT. However, Steer Davis Gleave (2011) mention that there is a lack of TEN-T investment in projects focusing on multimodality, which have led to several projects not meeting their full potential due to a lack of investment in other parts of the transport system. Furthermore, in the evaluation of the Shift2Rail Joint Undertaking, it is argued that when all rail research is organized by the rail sector, there is a focus on rail only and less focus on multimodal solutions and innovation.

As previously mentioned, most evaluations for subsidies and grants at the national and local level describe a positive performance of the policy instruments. The evaluations for policy instruments favouring rail transports generally describe a more positive performance than for the policy instruments favouring waterborne transports. For example, evaluations of subsidy/grant systems favouring rail freight in Austria and Great Britain estimate benefit to cost ratios of 3.39:1 to 4.27:1 (including reduced negative externalities from road transport) and have both been effective in achieving a modal shift. Also, the evaluations of different grants/subsidies in Italy show that the policy instruments have led to increased freight by rail. One exemption is the Swedish aid scheme for rail transports, which is paid retroactively to operators that perform or organize transport services at the Swedish railway network. According to the evaluation, the policy has rather prevented a modal backshift from rail to road, than promoting an actual modal shift to rail. The policy instrument is criticized in the evaluation for lacking continuity, predictability, and a long-term perspective. Furthermore, it is also criticised for including all freight transport on rail, which has resulted in about 22 % of the total funds in 2018 and 2019 going to the company LKAB (mining company) for transports of ore, where rail already is the dominating transport mode.

A lack of applications is described as an important problem for several policy instruments, especially for waterborne transports, both at national level (e.g. the Mode Shift Revenue Support for bulk and waterways and the Waterborne Freight Grant in Great Britain) as well as at EU-level (e.g the Marco Polo Programmes, Motorways of the Sea, and NAIADES). Several evaluations find that the lack of applications partly depends on long and complicated application processes and a heavy administrative burden. In an evaluation of the Mode Shift Revenue Support in Great Britain, it is mentioned that the application process for grant to rail services (intermodal) is easier to apply for than the grant for waterborne transport (Department for Transport, 2014). This is explained by the intermodal rail grant being standardised, while the waterborne grant level is decided case by case. This can partly explain the low number of applications. However, they also argue that the low number of applications might reflect the difficulties in moving freight by inland waterways in Great Britain.

5. Conclusions

The objective of this study is to identify and classify past and present public policy instruments implemented in Europe with the aim to achieve a modal shift, as well as reviewing their performance to the extent that ex-post evaluations exist. The study aims to answer the following research questions (RQs):

1. What policy instruments have been implemented in Europe with the aim to achieve a modal shift?
2. Which policy instruments have been evaluated, and which evaluation methods and performance indicators have been applied?
3. Which conclusions can be drawn regarding the effectiveness and efficiency of European policy instruments in terms of achieving modal shift and reducing negative externalities?

To answer the research questions, a search strategy was applied to identify as many public policy instruments and policy evaluations as possible. All identified policy instruments and evaluations were included in a database where they were described and sorted according to several categories and shared characteristics.

The search process applied to answer RQ1 resulted in the identification of 93 public policy instruments targeting a modal shift in Europe. Most of the identified policy instruments are subsidies or grants to rail or waterborne transports implemented at the national level. The identified policy instruments most commonly focus on the promotion of one specific transport mode, which most commonly is transports by rail.

The search process applied to answer RQ2 only resulted in the identification of policy evaluations for 20 out of the 93 policy instruments. Furthermore, the evaluations do not fully represent the actual distribution of policy instruments, and there is a bias towards economic policy instruments, mainly subsidies and grants. The lack of evaluations, as well as the homogeneity of the policy instruments for which we have identified evaluations, complicates comparisons of policy performance over different policy categories. Therefore, further research regarding the performance of different types of modal shift policy instruments is needed.

A wide range of evaluators have performed the evaluations, including among others consultant firms, public authorities, the European Court of Auditors, expert groups, and independent researchers. The sample of evaluations in this study is too small to draw any conclusions regarding possible relationships between evaluators and evaluation methods and/or results. Positive, as well as negative, policy performance is found in evaluations by all type of evaluators. Thus, further research, with larger samples, is needed to improve the understanding of the relationship between policy evaluations and how the evaluating actors may influence the evaluation outcomes.

About half of the policy instruments with evaluations are subsidies or grants at national level, while the other half represent policy instruments governed at EU-level. The large share of evaluated EU policy instruments might depend on the commitment to evaluation formulated in Article 318 of the Treaty on the Functioning of the European Union and on other evaluation guidelines and frameworks within the EU (e.g. the REFIT programme). The large share of evaluated subsidies/grants at national level could be explained by them being the most identified policy instrument in this study, but also by them being classified as state aid and therefore needing permission by the European Commission to be implemented or prolonged. Most of these evaluations have been performed when applying for prolongation by the European Commission and show an overall positive policy performance. The positive evaluation outcomes may have several explanations. It could for example reflect that subsidies/grant are effective in achieving a modal shift, but it could also reflect that member states only apply for prolongation if the policy instrument is considered effective. Thus, knowing the purpose of an evaluation is important to understand how it may affect the evaluation outcomes.

There is a large variation between evaluation studies regarding how policy performance is evaluated, both in terms of methodologies used, performance criteria considered, and how the performance criteria are interpreted. There seem to be a gap between evaluation theory and how evaluations are performed in practice, which has previously been found by Huitema et al. (2011) and Christie (2003). This makes comparisons between evaluation results difficult. Thus, further research and discussions are needed regarding how policy evaluations should be performed in a systematic way and how they can be better harmonized in order to facilitate comparisons and improve evidence-based policy and decision-making.

Difficulties in finding relevant and reliable data, as well as difficulties to measure causality between the policy instruments and observed changes, are mentioned as a problem by several evaluations. One way to overcome this problem, would be to design policy instruments in a way that facilitate evaluation, for example by requiring firms receiving funding to collect and present data.

In order to answer RQ3, we summarised targets, effectiveness and efficiency for each evaluated policy instrument. The findings show that the objectives for the policy instruments are often broad and general. Several evaluations mention that the lack of well-defined targets and specified performance indicators makes it difficult to meet all policy objectives, as well as to evaluate the policy instruments effectiveness and efficiency. Therefore, it is important that targets and objectives for policy instruments are formulated in such way that they can be evaluated. For several policy instruments, modal shift is considered as an objective itself, rather than a means to achieve reduced external costs from freight transports. This is problematic as modal shift do not automatically result in reduced externalities. Thus, when formulating policy targets, it is important to treat modal shift as a means to reach the ultimate objective of reduced external costs. Further research is needed regarding what type of objectives and targets that exist, as well as how they can be formulated in a way to improve policy performance and facilitate evaluation.

Several evaluations of EU-policy instruments describe a poor or a mixed performance of the policy instruments, while the performance of subsidies/grant at national level are often considered positive by the evaluations. In general, there seem to be a more positive performance of policy instruments promoting a modal shift to rail than to waterborne transports. A commonly mentioned factor for underachievement of the policy instruments is problems related to outreach of the policy, lack of applications, long and complicated application processes and a high administrative burden for the companies applying for financial support. Thus, a focus on better outreach and simpler application processes could be one way forward in improving modal shift policy instruments in Europe.

Even though this study has brought several interesting results, there are some limitations of the study. The sample of evaluations in this study is small, making it difficult to draw any general conclusions regarding policy performance. Furthermore, there might be a bias in the study towards policy instruments and evaluations available in English. Thus, there is still a need for improved knowledge regarding what types of policy instruments that can effectively and efficiently contribute to a modal shift and reduced external costs from the European freight transport sector.

References

Ambra, T., Caris, A., Macharis, C., 2019. Towards freight transport system unification: reviewing and combining the advancements in the physical internet and synchromodal transport research 7543. https://doi.org/10.1080/00207543.2018.1494392

Aperte, X.G., Baird, A.J., 2013. Motorways of the sea policy in Europe. Marit. Policy Manag. 40, 10–26. https://doi.org/10.1080/03088839.2012.705028

Askildsen, T.C., 2005. Evaluering av Short Sea Promotion Centre Norway (TØI report No. 773/2005). Transportøkonomisk institutt, Oslo.

Beuthe, M., Degrandsart, F., Geerts, J.-F., Jourquin, B., 2002. External costs of the Belgian interurban freight traffic: a network analysis of their internalisation. Transp. Res. Part Transp. Environ. 7, 285–301. https://doi.org/10.1016/S1361-9209(01)00025-6

Beuthe, M., Jourquin, B., 2001. Freight transportation demand elasticities: a geographic multimodal transportation network analysis 37.

Bickford, E., Holloway, T., Karambelas, A., Johnston, M., Adams, T., Janssen, M., Moberg, C., 2014. Emissions and Air Quality Impacts of Truck-to-Rail Freight Modal Shifts in the Midwestern United States. https://doi.org/10.1021/es4016102

Björk, L., Vierth, I., 2021. Freight modal shift in Sweden – means or objective? Work. Pap. Swed. Natl. Road Transp. Res. Inst. VTI 2021:5.

Breathen, N., 2011. Environmental Impacts of International Shipping: The Role of Ports. OECD, Paris.

CE Delft, 2020. Handbook on the external costs of transport: version 2019 – 1.1. European Commission. Publications Office, Luxembourg.

Christie, C., 2003. What guides evaluation? A study of how evaluation practice maps onto evaluation theory. New Dir. Eval. 97.

Colin, E., Sandström, C., Wennberg, C., 2021. Utvärderingar av näringspolitik – en intressekonflikt mellan myndigheter, konsultföretag, politik och skattebetalare? Ekon. Debatt 49, 30–41.

Cooksy, L.J., Caracelli, V.J., 2005. Quality, Context, and Use: Issues in Achieving the Goals of Meta evaluation. Am. J. Eval. 26, 31–42. https://doi.org/10.1177/1098214004273252

Crabb, A., Leroy, P., 2012. The Handbook of Environmental Policy Evaluation. Routledge. https://doi.org/10.4324/9781849773072

Decision no 884/2004/EC of the European Parliament and of the Council of 29 April 2004

Department for Transport, 2020a. Review of revenue support freight grant schemes. Final report, Issue 4. Department for Transport.

Department for Transport, 2020b. Guide to the Waterborne Freight Grant (WFG) Scheme.

Department for Transport, 2014. Review of Revenue Support Freight Grant Schemes. Summary Report IR002 Issue 21. Department for Transport.

Directive 2011/76/EU of the European Parliament and of the Council of 27 September 2011 amending Directive 1999/62/EC on the charging of heavy goods vehicles for the use of certain infrastructures.

Dong, C., Boute, R., Mckinnon, A., Verelst, M., 2018. Investigating synchromodality from a supply chain perspective. Transp. Res. Part D 61, 42–57. https://doi.org/10.1016/j.trd.2017.05.011

Elbert, R., Seikowsky, L., 2017. The influences of behavioral biases, barriers and facilitators on the willingness of forwarders' decision makers to modal shift from unimodal road freight transport to intermodal road–rail freight transport. J. Bus. Econ. 87, 1083–1123. https://doi.org/10.1007/s11573-017-0847-7

Europe Economics, 2011. Evaluation of the Marco Polo Programme 2003-2010 Final Report. Europe Economics, London.

European Commission, 2021a. White paper 2011 [WWW Document]. Mobil. Transp. - Eur. Comm. URL https://ec.europa.eu/transport/themes/european-strategies/white-paper-2011_en (accessed 3.2.21).

European Commission, 2021b. Case search - Competition - European Commission [WWW Document]. Eur. Comm. - Compet. URL https://ec.europa.eu/competition/elojade/isef/index.cfm?clear=1&policy_area_id=3 (accessed 4.28.21).

European Commission, 2021c. CEF Transport [WWW Document]. Innov. Netw. Exec. Agency - Eur. Comm. URL https://ec.europa.eu/inea/en/connecting-europe-facility/cef-transport (accessed 4.19.21).

European Commission, 2021d. State Aid SA.60383 (2021/N) – Sweden Prolongation and amendments to the scheme on environmental compensation for rail freight transport. European Commission, Brussels.

European Commission, 2020a. State Aid SA.54911 (2019/N) – UK Waterborne Freight Grant. European Commission, Brussels.

European Commission, 2020b. Subject: State Aid SA.56718 (2020/N) – Italy Incentives for Rail Transport (No. C (2020) 2528 final). European Commission, Brussels.

European Commission, 2020c. Progress report on implementation of the TEN-T network in 2016-2017- Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Com (2020) 433 final. European Commission, Brussels.

European Commission, 2019a. State Aid SA.54990 (2019/N) – Italy Aid in favour of rail freight transport in Emilia-Romagna region. European Commission, Brussels.

European Commission, 2019b. State Aid SA.55025 – Italy Prolongation of Rail Freight Transport scheme 2020-2022. European Commission, Brussels.

European Commission, 2019c. Trans-European Transport Network (TEN-T) [WWW Document]. Mobil. Transp. - Eur. Comm. URL https://ec.europa.eu/transport/themes/infrastructure/ten-t_en (accessed 4.19.21).

European Commission, 2018. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the mid-term evaluation of the Connecting Europe Facility (CEF). COM (2018) 66 final/2. European Commission, Brussels.

European Commission, 2017a. Better Regulation Guidelines. Commission Staff Working Document No. Swd (2017) 350. European Commission, Brussels.

European Commission, 2017b. State aid SA.48390 – Austria Prolongation of aid scheme for transport of goods by rail in certain combined transport services for 2018-2022. European Commission, Brussels.

European Commission, 2016a. Refit Ex-Post Evaluation of Combined Transport Directive 92/106/EEC. Commission Staff Working Document No. SWD (2016) 141 final. European Commission, Brussels.

European Commission, 2016b. Mobility and transport - Combined Transport [WWW Document]. REFIT Scorebrd. URL https://op.europa.eu/webpub/com/refit-scoreboard/en/policy/14/14-1.html (accessed 3.23.21).

European Commission, 2016c. Report on the analysis of the Open public consultation on the Evaluation of Regulation (EU) 913/2010 concerning a European rail network for competitive freight. European Commission.

European Commission, 2016d. Subject: SA.44627 - Italy - ‘Ferrobonus’ - incentive for rail transport (No. C(2016) 7676 final). European Commission, Brussels.

European Commission, 2014a. State aid No SA.38152 (2014/N) – Italy - Emilia Romagna region - aid in favour of rail freight transport (State Aid). European Commission, Brussels.

European Commission., 2014b. EU competition law: rules applicable to state aid: Situation as of 15 April 2014. Publications Office, LU.

European Commission, 2014c. Subject: SA.39354 – United Kingdom Prolongation of the Mode Shift Revenue Support Scheme. European Commission, Brussels.

European Commission, 2013. Commission staff working document: Ex-post evaluation of Directive 1999/62/EC, as amended, on the charging of heavy goods vehicles for the use of certain infrastructures. European Commission, Brussels.

European Commission, 2012a. SA.33412 (2011/N) – Italy Prolongation of the aid scheme for the development of logistics chains and the upgrading of intermodality (Ecobonus). European Commission, Brussels.

European Commission, 2012b. Subject: State aid SA.34604 (2012/N) – United Kingdom Prolongation of the Freight Facilities Grant scheme. No. C(2012) 9834 final. European Commission, Brussels.

European Commission, 2011a. WHITE PAPER Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. No. COM (2011) 144 final. European Commission, Brussels.

European Commission, 2011b. Mid-term progress report on the implementation of the NAIADES Action Programme for the promotion of inland waterway transport. Commission Staff Working Document No. SEC (2011) 453 final. European Commission, Brussels.

European Commission, 2011c. Subject: State aid No SA.32603 – Italy – Subsidy scheme “Ferrobonus” for combined transport. No. C (2011) 9794 final. European Commission, Brussels.

European Court of Auditors, 2015. Inland waterway transport in Europe: no significant improvements in modal share and navigability conditions since 2001: pursuant to Article 287(4), second subparagraph, TFEU.

European Court of Auditors., 2013. Have the Marco Polo programmes been effective in shifting traffic off the road? Special Report No 3, 2013. Publications Office, Luxembourg.

Eurostat, 2020. Freight transport statistics - modal split [WWW Document]. Eurostat - Stat. Explain. URL https://ec.europa.eu/eurostat/statistics-explained/index.php/Freight_transport_statistics_-_modal_split#Modal_split_in_the_EU (accessed 4.26.21).

Fontanel, E., Smith, R., Allen, H., Dooms, M., European Commission, Directorate General for Mobility and Transport, 2017. Interim evaluation of Shift2Rail joint undertaking (2014-2016) interim evaluation report.

Frey, K., Hartwig, J., Doll, C., 2014. Accelerating a shift from road to rail freight transport in Germany – Three scenarios 10.

Harmelink, M., Nilsson, L., Harmsen, R., 2008. Theory-based policy evaluation of 20 energy efficiency instruments. Energy Effic. 1, 131–148. https://doi.org/10.1007/s12053-008-9007-9

Haug, C., Rayner, T., Jordan, A., Hildingsson, R., Stripple, J., Monni, S., et al., 2010. Navigating the dilemmas of climate policy in Europe: evidence from policy evaluation studies. Clim. Change 101, 427–445.

Huitema, D., Jordan, A., Massey, E., Rayner, T., van Asselt, H., Haug, C., Hildingsson, R., Monni, S., Stripple, J., 2011. The evaluation of climate policy: theory and emerging practice in Europé. Policy Sci. 44, 179–198.

ICF, TRT, ISL, 2017. Motorways of the Sea: An ex-post evaluation on the development of the concept from 2001 and possible ways forward. European Commission.

Innovation and Networks Executive Agency (INEA), 2020. Marco Polo II: 2007 2013: final report. Publications Office, LU.

Kaack, L.H., Vaishnav, P., Morgan, M.G., Azevedo, I.L., Rai, S., 2018. Decarbonizing intraregional freight systems with a focus on modal shift. Environ. Res. Lett. 13, 083001. https://doi.org/10.1088/1748-9326/aad56c

Knudson, W.A., 2009. The Environment, Energy, and the Tinbergen Rule. Bull. Sci. Technol. Soc. 29, 308–312. https://doi.org/10.1177/0270467608325375

KombiConsult GmbH, Intermodality Ltd, PLANCO Consulting GmbH, Gruppo CLAS S.p.A., 2015. Analysis of the EU Combined Transport. Contract No FV355/2012/MOVE/D1/ETU/SI2.659386. European Commission, Frankfurt.

Kreutzberger, E.D., 2008. Distance and time in intermodal goods transport networks in Europe: A generic approach 42, 973–993. https://doi.org/10.1016/j.tra.2008.01.012

Lin, N., 2019. CO 2 emissions mitigation potential of buyer consolidation and rail-based intermodal transport in the China-Europe container supply chains. J. Clean. Prod. 240, 118121. https://doi.org/10.1016/j.jclepro.2019.118121

Lindgren, S., Vierth, I., 2017. Vad styr valet av trafikslag för godstransporter?

López, I., Rodríguez, J., Burón, J.M., Garciía, A., 2009. A methodology for evaluating environmental impacts of railway freight transportation policies Manuel Bur on 37, 5393–5398. https://doi.org/10.1016/j.enpol.2009.07.060

Marzano, V., Tocchi, D., Papola, A., Aponte, D., Simonelli, F., Cascetta, E., 2018. Incentives to freight railway undertakings compensating for infrastructural gaps: Methodology and practical application to Italy. Transp. Res. Part Policy Pract. 110, 177–188. https://doi.org/10.1016/j.tra.2018.01.040

Meers, D., Macharis, C., 2015. Prioritization in modal shift: determining a region's most suitable freight flows. Eur. Transp. Res. Rev. 7, 23. https://doi.org/10.1007/s12544-015-0172-6

Meers, D., van Lier, T., Macharis, C., 2018. Longer and heavier vehicles in Belgium: A threat for the intermodal sector? Transp. Res. Part Transp. Environ. 61, 459–470. https://doi.org/10.1016/j.trd.2016.08.007

Nealer, R., Matthews, H.S., Hendrickson, C., 2012. Assessing the energy and greenhouse gas emissions mitigation effectiveness of potential US modal freight policies. Transp. Res. Part A 46, 588–601. https://doi.org/10.1016/j.tra.2011.11.010

Nocera, S., Cavallaro, F., Irranca Galati, O., 2018. Options for reducing external costs from freight transport along the Brenner corridor. Eur. Transp. Res. Rev. 10, 53. https://doi.org/10.1186/s12544-018-0323-7

OECD, 2021. Database on Policy for the Environment [WWW Document]. OECD. URL https://pinedatabase.oecd.org/Default.aspx?isid=07ff0e7c-96fe-43f6-8deb-85dfc6f97035 (accessed 4.28.21).

OECD/DAC Network on Development Evaluation, 2019. Better Criteria for Better Evaluation Revised Evaluation Criteria Definitions and Principles for Use.

Pallme, D., Lambert, B., Miller, C., Lipinski, M., 2015. A review of public and private intermodal railroad development in the Memphis region. Res. Transp. Bus. Manag. 14, 44–55. https://doi.org/10.1016/j.rtbm.2014.10.011

Pigou, A., 1920. The Economics of Welfare. Macmillan, London.

Pinchasik, D.R., Hovi, I.B., Mjøsund, C.S., Grønland, S.E., Fridell, E., Jerksjö, M., 2020. Crossing Borders and Expanding Modal Shift Measures: Effects on Mode Choice and Emissions from Freight Transport in the Nordics. Sustainability 12, 894. https://doi.org/10.3390/su12030894

RAM S.p.a, 2019. Capitalization and Harmonization of the Adriatic Region Gate of Europe - Policy Framework for the Adriatic Freight Transport Sustainability - D 5.1.1 – Analysis of practices to support multimodality (No. Project number: 10041221). European Regional Development Fund.

Regulation (EC) No 561/2006 of the European Parliament and of the Council of 15 March 2006 on the harmonisation of certain social legislation relating to road transport and amending Council Regulations (EEC) No 3821/85 and (EC) No 2135/98 and repealing Council Regulation (EEC) No 3820/85.

Regulation (EU) No 913/2010 of the European Parliament and of the Council of 22 September 2010 concerning a European rail network for competitive freight.

Santos, B.F., Limbourg, S., Carreira, J.S., 2015. The impact of transport policies on railroad intermodal freight competitiveness – The case of Belgium. Transp. Res. Part Transp. Environ. 34, 230–244. https://doi.org/10.1016/j.trd.2014.10.015

Santos, G., Behrendt, H., Teytelboym, A., 2010. Part II: Policy instruments for sustainable road transport. Res. Transp. Econ., Road Transport Externalities, Economic Policies And Other Instruments For Sustainable Road Transport 28, 46–91. https://doi.org/10.1016/j.retrec.2010.03.002

Steer Davis Gleave, 2011. Mid-term evaluation of the TEN-T Programme (2007-2013). European Commission, Brussels.

Suárez-Alemán, A., 2016. Short sea shipping in today’s Europe: A critical review of maritime transport policy. Marit. Econ. Logist. 18, 331–351. https://doi.org/10.1057/mel.2015.10

Svindland, M., Hjelle, H.M., 2019. The comparative CO2 efficiency of short sea container transport. Transp. Res. Part Transp. Environ. 77, 11–20. https://doi.org/10.1016/j.trd.2019.08.025

Swedish Environmental Protection Agency, 2021. Styrmedel för att förändra val och beslut som orsakar miljöproblem [WWW Document]. Naturvårdsverket. URL https://www.naturvardsverket.se/Stod-i-miljoarbetet/Vagledningar/Samhallsekonomisk-konsekvensanalys/Hur-losa-miljoproblem/Utforligare-stod/Styrmedel/ (accessed 4.7.21).

Swedish Environmental Protection Agency, 2012. Styrmedel för att nå miljökvalitetsmålen: en kartläggning. Naturvårdsverket, Stockholm.

Swedish Transport Administration, 2020. Miljökompensation till järnvägsföretag. Uppföljning enligt 15 § förordning (2018:675) om miljökompensation för godstransporter på järnväg. TRV 2020/20665. Swedish Transport Administration.

Tao, X., Wu, Q., Zhu, L., 2017. Mitigation potential of CO2 emissions from modal shift induced by subsidy in hinterland container transport. Energy Policy 101, 265–273. https://doi.org/10.1016/j.enpol.2016.11.049

Tinbergen, J., 1952. On the Theory of Economic Policy. North-Holland Publishing Company, Amsterdam.

Tsamboulas, D., Chiappetta, A., Moraiti, P., Karousos, I., 2015. Could Subsidies for Maritime Freight Transportation Achieve Social and Environmental Benefits?: The Case of Ecobonus. Transp. Res. Rec. 2479, 78–85. https://doi.org/10.3141/2479-10

Tsamboulas, D., Vrenken, H., Lekka, A.-M., 2007. Assessment of a transport policy potential for intermodal mode shift on a European scale. Transp. Res. Part Policy Pract. 41, 715–733. https://doi.org/10.1016/j.tra.2006.12.003

Vieira, J., Moura, F., Manuel Viegas, J., 2007. Transport policy and environmental impacts: The importance of multi-instrumentality in policy integration. Transp. Policy 14, 421–432. https://doi.org/10.1016/j.tranpol.2007.04.007

Windisch, E., Gibson, G., Loehr, E., Rass-Masson, N., Meura, L., Morel, S., Markowska, A., Pastori, E., Sitran, A., 2016. Ex-post evaluation of social legislation in road transport and its enforcement (No. Study contract no. MOVE/D3/2014-256). Europeiska Kommissionen, Bryssel.

Woodburn, A., 2007. Evaluation of Rail Freight Facilities Grant Funding in Britain. Transp. Rev. 27, 311–326. https://doi.org/10.1080/01441640600990418

Annex A: List of Public Policy instruments

Name of the Public Policy Instrument	Geographical level (Implementation)	Specific name of the region / country	Organization responsible for the Public Policy Instrument	Promotion (transport mode)	Category of policy instrument/measure	Subcategory of policy instrument/measure
Connecting Europe Facility (CEF)	Regional	European Union	Regional organization (Intergovernmental: EU)	Both (Railway and Waterborne)	Economic	Funding of infrastructure
Directive 1992/62 and 2011/76/EU- *Eurovignette*	Regional	European Union	Regional organization (Intergovernmental: EU)	Road (discourage)	Administrative	Legislation
Directive 2015/719 - Weights and Dimensions of higher weight ILU in intermodal transport	Regional	European Union	Regional organization (Intergovernmental: EU)	Both (Railway and Waterborne)	Administrative	Legislation
Directive 92/106/EEC - Combined Transport of goods between Member States	Regional	European Union	Regional organization (Intergovernmental: EU)	Both (Railway and Waterborne)	Administrative	Legislation
Double track Iron Ore Line (*Norrbotniabanan*) between Umeå-Luleå (Sweden)	Local	Sweden (Umeå-Luleå Region)	Local government (province/specific region)	Railway	Administrative	Infrastructure planning
Ecobonus system to transfer goods from road to water -MoS (The Basque Country, Spain)	Local	Spain (The Basque Country Region)	Local government (province/specific region)	Waterborne transport	Economic	Subsidy
ERTMS corridors	Regional	European Union	Regional organization (Intergovernmental: EU)	Railway	Economic	Grant
E-toll, network wide (dist) - Several EU Member States	National*	Austria, Germany, Czech Republic, Poland (prev vignette), Slovakia (prev vignette)	Regional organization (Intergovernmental: EU)	Road (discourage)	Economic	Toll/vignette
EU agreement- Electronic documents for freight transport	Regional	European Union	Regional organization (Intergovernmental: EU)	Railway	Administrative	Inspection
EU Regulation 2017/1084 GBER Ports	Regional	European Union	Regional organization (Intergovernmental: EU)	Both (Railway and Waterborne)	Administrative	Legislation
EU Regulation 561/2006 - Rest periods on rolling/floating roads and social legislation relating to road transport	Regional	European Union	Regional organization (Intergovernmental: EU)	Road (discourage)	Administrative	Legislation
EU Regulation 931/2010 - European rail network for competitive freight	Regional	European Union	Regional organization (Intergovernmental: EU)	Railway	Administrative	Legislation
European Inland Barging Innovation Platform	Regional	European Union	Regional organization (Intergovernmental: EU)	Waterborne transport	Information	Development research
European Shortsea Network (of Shortsea Promotion Centres)	Regional	European Union	Regional organization (Intergovernmental: EU)	Waterborne transport	Information	Development research
Eurovignette (time) (Belgium)	National	Belgium	National government (State / Country)	Road (discourage)	Economic	Toll/vignette
Eurovignette (time) (Germany)	National	Germany	National government (State / Country)	Road (discourage)	Economic	Toll/vignette
Eurovignette (time)- Several EU Member States	Regional*	Denmark, Luxembourg, the Netherlands, Sweden	National government (State / Country) - Multiple	Road (discourage)	Economic	Toll/vignette
Exemption from the night driving ban (Austria)	National	Austria	National government (State / Country)	Road (discourage)	Administrative	Agreement
Exemption from the Summer holidays driving ban on lorries (Austria)	National	Austria	National government (State / Country)	Road (discourage)	Administrative	Limit
Exemption from the Weekend and holiday driving ban on lorries (Austria)	National	Austria	National government (State / Country)	Road (discourage)	Administrative	Limit

Freight Facilities Grant- FFG (Wales)	Local	Wales	Local government (province/specific region)	Railway	Economic	Grant
Freight Facilities Grant- FFG (Scotland)	Local	Scotland	Local government (province/specific region)	Both (Railway and Waterborne)	Economic	Grant
Freight Transfer Act of Heavy Goods across the Alps from Road to Rail	National	Switzerland	National government (State / Country)	Railway	Administrative	Legislation
Horizon 2020 / TEN-T	Regional	European Union	Regional organization (Intergovernmental: EU)	Both (Railway and Waterborne)	Information	Development research
INE - Inland Navigation EU	Regional	European Union	Regional organization (Intergovernmental: EU)	Waterborne transport	Information	Development research
Inland Waterways Development Fund (Poland)	National	Poland	National government (State / Country)	Waterborne transport	Economic	Funding of infrastructure
Km-tax for heavy goods vehicles (Sweden)	National	Sweden	National government (State / Country)	Road (discourage)	Economic	Tax
Liberalised area for rolling roads (Austria)	National	Austria	National government (State / Country)	Road (discourage)	Administrative	Legislation
Liberalised corridors for rolling roads (Austria)	National	Austria	National government (State / Country)	Road (discourage)	Administrative	Legislation
Liberalised initial and final road leg in combined transport (Austria)	National	Austria	National government (State / Country)	Road (discourage)	Administrative	Legislation
Marco Polo I	Regional	European Union	Regional organization (Intergovernmental: EU)	Both (Railway and Waterborne)	Economic	Grant
Marco Polo II	Regional	European Union	Regional organization (Intergovernmental: EU)	Both (Railway and Waterborne)	Economic	Grant
Motorways of the Sea	Regional	European Union	Regional organization (Intergovernmental: EU)	Waterborne transport	Economic	Grant
Mälarprojektet- Mälarregionen (Sweden)	Local	Sweden (Mälarregionen)	Local government (province/specific region)	Waterborne transport	Administrative	Infrastructure planning
NAIADES - Navigation And Inland Waterway Action and Development in Europe	Regional	European Union	Regional organization (Intergovernmental: EU)	Waterborne transport	Administrative	Infrastructure planning
NAIADES II	Regional	European Union	Regional organization (Intergovernmental: EU)	Waterborne transport	Administrative	Infrastructure planning
National Aid - "The Mode Shift Revenue Support- MSRS (Great Britain)	National	Great Britain (England, Scotland and Wales)	National government (State / Country)	Both (Railway and Waterborne)	Economic	Grant
National Aid - "The Waterborne Freight Grant Scheme" (Great Britain)	National	Great Britain (England, Scotland and Wales)	National government (State / Country)	Waterborne transport	Economic	Grant
National Aid - "Tilskudd til godsoverføring fra vei til sjø" (Norway)	National	Norway	National government (State / Country)	Waterborne transport	Economic	Grant
National Aid - Company Neutral Revenue Support Scheme (CNRS)	National	Great Britain (England, Scotland and Wales)	National government (State / Country)	Railway	Economic	Grant
National Aid - Freight Facilities Grant - FFG (Great Britain)	National	Great Britain (England, Scotland and Wales)	National government (State / Country)	Both (Railway and Waterborne)	Economic	Grant
National Aid - Rail Environmental Benefit Procurement Scheme (REPS) - replace CNRS and TAG	National	United Kingdom	National government (State / Country)	Railway	Economic	Grant
National Aid - Track Access Grant (TAG)	National	Great Britain (England, Scotland and Wales)	National government (State / Country)	Railway	Economic	Grant

Operational Programme Transport and transport infrastructure (Bulgaria)	National	Bulgaria	National government (State / Country)	Railway	Administrative	Infrastructure planning
PLATINA	Regional	European Union	Regional organization (Intergovernmental: EU)	Waterborne transport	Information	Advising
PLATINA II	Regional	European Union	Regional organization (Intergovernmental: EU)	Waterborne transport	Information	Advising
Reduction or exemption from Motor Vehicle Tax (Austria)	National	Austria	National government (State / Country)	Road (discourage)	Economic	Tax deduction
Road user charges for heavy goods vehicles (HGV)	Regional	European Union	Regional organization (Intergovernmental: EU)	Road (discourage)	Economic	Toll/vignette
Shift2Rail	Regional	European Union	Regional organization (Intergovernmental: EU)	Railway	Information	Development research
State Aid - Rail freight transport - the Province of Emilia Romagna (Italy)	Local	Italy (Emilia Romagna Region)	Local government (province/specific region)	Railway	Economic	Subsidy
State Aid - Promote shift of freight traffic from road to rail (the Netherlands)	Regional	The Netherlands	National government (State / Country)	Railway	Economic	Subsidy
State Aid - (Ecobonus system) to transfer goods from road to rail "Ferrobonus" (Italy)	National	Italy	National government (State / Country)	Railway	Economic	Subsidy
State Aid - (Ecobonus system) to transfer goods from road to rail "Miljökompensation" + Extension (Sweden)	National	Sweden	National government (State / Country)	Railway	Economic	Grant
State Aid - (Ecobonus system) to transfer goods from road to rail "Nuovo Ferrobonus" (Italy)	National	Italy	National government (State / Country)	Railway	Economic	Subsidy
State Aid - (Ecobonus system) to transfer goods from road to water "Marebonus" (Italy)	National	Italy	National government (State / Country)	Waterborne transport	Economic	Subsidy
State Aid - (Ecobonus system) to transfer goods from road to water "Ecobonus" (Italy)	National	Italy	National government (State / Country)	Waterborne transport	Economic	Subsidy
State Aid - (Ecobonus system) to transfer goods from road to water "Eko-bonus" (Sweden)	National	Sweden	National government (State / Country)	Waterborne transport	Economic	Grant
State Aid - Alternative transportation for the period 2014-2020- the Walloon Region (Belgium)	Local	Belgium (Walloon Region)	Local government (province/specific region)	Waterborne transport	Economic	Subsidy
State Aid - Combined transport - the Province of Trento (Italy)	Local	Italy (Trento Region)	Local government (province/specific region)	Railway	Economic	Subsidy
State Aid - Combined transport in Belgium 2017-2020 (Belgium)	National	Belgium	National government (State / Country)	Railway	Economic	Subsidy
State Aid - Development of intermodal transport and combined transport projects on the Danube (Austria)	National	Austria	National government (State / Country)	Waterborne transport	Economic	Grant
State Aid - Development of public inland terminals 'Subsidieregeling Openbare Inland Terminals' (the Netherlands)	National	the Netherlands	National government (State / Country)	Waterborne transport	Economic	Subsidy
State Aid - Financial support for operation (Austria)	National	Austria	National government (State / Country)	Railway	Economic	Grant
State Aid - Guidelines on the construction and replacement of railway sidings (Germany)	National	Germany	National government (State / Country)	Railway	Economic	Grant
State Aid - Innovation programme for Combined Freight transport (Austria)	National	Austria	National government (State / Country)	Both (Railway and Waterborne)	Economic	Grant

State Aid - Intermodal transport on waterway in the Brussels Region 2016-2020 (Belgium)	Local	Belgium (Brussels Region)	Local government (province/specific region)	Waterborne transport	Economic	Grant
State Aid - Intermodal Transport Units (Czech Republic)	National	Czech Republic	National government (State / Country) + Cofinanced by EU	Both (Railway and Waterborne)	Economic	Grant
State Aid - Modernisation and construction of combined transport terminals 2015-2020 (Czech Republic)	National	Czech Republic	National government (State / Country)	Railway	Economic	Grant
State Aid - Operation of regular combined freight services 2018-2022 (France)	National	France	National government (State / Country)	Both (Railway and Waterborne)	Economic	Grant
State Aid - Operational Program Infrastructure and Environment for the years 2014-2020 (Poland)	National	Poland	National government (State / Country) + Cofinanced by EU	Both (Railway and Waterborne)	Economic	Grant
State Aid - Programme to support innovation in rail freight transport (Germany)	National	Germany	National government (State / Country)	Railway	Economic	Grant
State Aid - Promotion of rail freight transport (Germany)	National	Germany	National government (State / Country)	Railway	Economic	Grant
State Aid - Rail freight transport services (Austria)	National	Austria	National government (State / Country)	Railway	Economic	Subsidy
State Aid - Rail freight transport support scheme + Extension (Italy)	Local	Italy (South and Islands)	Local government (province/specific region)	Railway	Economic	Subsidy
State Aid - Reduce cost disadvantage of bundling to promote modal shift 2018-2023 (Belgium)	National	Belgium	National government (State / Country)	Both (Railway and Waterborne)	Economic	Subsidy
State Aid - Support combined transport equipment 2006-2010 (Czech Republic)	National	Czech Republic	National government (State / Country) + Cofinanced by EU	Railway	Economic	Grant
State Aid - Support of sidings and intermodal terminals (road/rail/ship) + Extension (Austria)	National	Austria	National government (State / Country)	Both (Railway and Waterborne)	Economic	Grant
State Aid - Supporting combined transport in the Province of Bolzano (Italy)	Local	Italy (Bolzano region)	Local government (province/specific region)	Railway	Economic	Subsidy
State Aid - Transhipment facilities of the combined transport of non-federally owned enterprises (Germany)	National	Germany	National government (State / Country)	Waterborne transport	Economic	Subsidy
State Aid - transport of goods by rail 2014-1017 (Denmark)	National	Denmark	National government (State / Country)	Railway	Economic	Subsidy
State Aid- Incentives for Combined Transport (Croatia)	National	Croatia	National government (State / Country)	Both (Railway and Waterborne)	Economic	Subsidy
State Aid- Intermodal rail transport of iron slabs in the Friuli Venezia Giulia Region (Italy)	Local	Italy (Friuli Venezia Giulia Region)	Local government (province/specific region)	Railway	Economic	Grant
State Aid- Modernisation and construction of combined transport terminals (France)	National	France	National government (State / Country)	Railway	Economic	Grant
State Aid- Promote investment to rail freight transport in Saxony-Anhalt (Germany)	Local	Germany (Saxony-Anhalt)	Local government (province/specific region)	Railway	Economic	Funding of infrastructure
State Aid- Promotion of Combined Transport (Luxembourg)	National	Luxembourg	National government (State / Country)	Both (Railway and Waterborne)	Economic	Grant
State Aid- Support for rail freight transport - single wagon (Germany)	National	Germany	National government (State / Country)	Railway	Economic	Grant
Supplementary permits for using rolling roads (Austria)	National	Austria	National government (State / Country)	Both (Railway and Waterborne)	Administrative	Legislation
Swiss Heavy Vehicles charges (Switzerland)	National	Switzerland	National government (State / Country)	Road (discourage)	Economic	Fee

The INTERREG Programme - The North West Europe - Several EU Member States and countries	Regional	Ireland, the United Kingdom, Belgium, Luxembourg, Switzerland, and parts of France, Germany and the Netherlands	Regional organization (Intergovernmental: EU)	Railway	Economic	Grant
Toll (distance and emission based) (Germany)	National	Germany	National government (State / Country)	Road (discourage)	Economic	Toll/vignette
Trans-European Transport Network (TEN-T)	Regional	European Union	Regional organization (Intergovernmental: EU)	Both (Railway and Waterborne)	Economic	Funding of infrastructure
Watertruck +	Regional	European Union	Regional organization (Intergovernmental: EU)	Waterborne transport	Information	Development research
Vignette (time)- Several EU Member States	National*	Lithuania, Hungary, Bulgaria, Romania, Latvia (recent), United Kingdom (recent)	National government (State / Country)	Road (discourage)	Economic	Toll/vignette

Source: Own elaboration

Note: Regional*: Implementation of the public policy among different countries simultaneously. National*: Implementation of the public policy in each country (independently).

State Aid: EU State. National Aid: Non-EU State (i.e. European Free Trade Association countries - Iceland, Liechtenstein, Norway and Switzerland- and United Kingdom)

Annex B: Characteristics of policy evaluations

Name of the Public Policy Instrument	Actor performing evaluation	Purpose of evaluation	Performance criteria considered (total evaluation)	Performance criteria considered (regarding modal shift and associated externalities)	Methodology for analysing effectiveness and efficiency
Connecting Europe Facility (CEF)	The evaluation is a Commission staff working document (European Commission, 2018), which was performed by the Commission DGs responsible for CEF (DG MOVE, DG ENER and DG CNECT), as well as the consultant PriceWaterhouseCoopers.	Article 27 of the CEF Regulation lays down a legal requirement to evaluate the policy instrument. Other than the legal requirement, the purpose of the evaluation was to serve as basis for decisions regarding renewal, suspension, or modification of CEF.	Relevance Coherence Effectiveness Efficiency EU added value	Relevance Coherence Effectiveness	**Qualitative:** Review of legislative documents and reports, open public consultation, surveys, targeted stakeholder consultation, case studies. **Quantitative:** Data collection, selection, and analysis
Directive 1992/62 and 2011/76/EU - Eurovignette	The evaluation is a Commission staff working document performed by the European Commission (2013).	The purpose of the evaluation was to analyse whether the directive fulfil its key objectives and to identify possible gaps.	Relevance Coherence Effectiveness Efficiency EU added value	Effectiveness Efficiency	**Qualitative:** The only available information regarding data and methodology is that information was received from member states and from research literature.
Directive 92/106/EEC - Combined Transport of goods between Member States	The evaluation is a Commission staff working document (European Commission, 2016a, 2016b). A Steering Group assisted the evaluation process, including representatives from DG TAXUD, DG ENV, DG GROW, DG CLIMA, and the Secretariat General. DG COMP was also consulted.	The evaluation was performed under the European Commission's regulatory fitness and performance programme (REFIT). The purpose of the evaluation was to assess if the legislations still was relevant, achieved its objectives, and if any inconsistencies or gaps needed to be considered.	Relevance Coherence Effectiveness Efficiency EU added value	Relevance Coherence Effectiveness Efficiency EU added value	**Qualitative:** Stakeholder consultations (public online consultation and workshop), desk research. **Quantitative:** Data gathering and analysis, calculations of external costs, estimating benefits.
EU Regulation 561/2006 - Rest periods on rolling/floating roads and social legislation relating to road transport	The evaluation was performed by Ricardo, Milieu and TRT (Windisch et al., 2016), commissioned by European Commissions Directorate-General for Mobility and Transport.	The purpose was to “provide insight into the actual performance of the three legislative acts and the overall impacts (both intended and unintended).” (Windisch et al., 2016).	Relevance Coherence Effectiveness Efficiency EU added value	Effectiveness	**Qualitative:** Interviews, surveys, case studies.
EU Regulation 913/2010 - European rail network for competitive freight	The report presents the results and analysis from an open public consultation performed by the European Commission (2016c)	Article 23 of the regulation require the Commission to submit a report to the European Parliament and Council examining the application of the regulation. Beyond Article 23, the Commission decided to	Relevance Coherence Effectiveness Efficiency	Relevance Coherence Effectiveness Efficiency	**Qualitative:** Open public consultation

		perform a broader analysis of the regulation's effects.			
European Shortsea Network – (Evaluation for the Norwegian Short Sea Promotion Centre)	Askildsen (2005) at the Department of Transport Economics (TØI) has carried out an evaluation of Short Sea Promotion Center Norway (SPC Norway) on behalf of the Ministry of Trade and Industry (NHD), the Ministry of Transport and Communications (SD) and the Ministry of Fisheries and the Ministry of Coastal Affairs (FKD).	The purpose was to evaluate if the policy had achieved its target and followed its plan.	Relevance Effectiveness	Relevance Effectiveness	**Qualitative:** Interviews, questionnaires, analysing EU-documents.
Marco Polo I and II	Three evaluation reports: 1. Performed by Europe Economics (2011) on behalf of Directorate-General for Mobility and Transport. 2. Performed by European Court of Auditors (2013). 3. Performed by the European Commissions' Innovation and Networks Executive Agency (INEA) (2020).	1. The purpose of the evaluation by Europe Economics (2011) was to assist in the evaluation of the Marco Polo programme covering the period 2003-2010. 2. The purpose of the evaluation performed by the European Court of Auditors (2013) was to assess the effectiveness of the Marco Polo programmes in terms of planning, management, supervision, and target fulfilment of funded projects. 3. INEA (2020) do not mention a specific purpose of the report. However, it is mentioned that the report presents main facts, figures, and an outlook regarding the results from the Marco Polo II programme and includes an outlook on the results achieved.	1. Europe Economics (2011): Relevance Coherence Effectiveness Efficiency 2. European Court of Auditors (2013): Effectiveness 3. INEA (2020) Effectiveness Efficiency	1. Europe Economics (2011): Relevance Coherence Effectiveness Efficiency 2. European Court of Auditors (2013): Effectiveness 3. INEA (2020) Effectiveness Efficiency	1. Europe Economics (2011): **Qualitative:** Stakeholder interviews, survey, review documents, desk research. **Quantitative:** Data analysis, comparing expected and achieved modal shift, estimating effect on externalities. 2. European Court of Auditors (2013): **Qualitative:** Among others: examination of files, interviews, analysis of impact assessments, surveys, review of evaluations of project proposals, on-site verification of the achievements of completed projects. **Quantitative:** Data analysis, comparison between targets and reported achievements. 3. INEA (2020) **Qualitative:** Questionnaire to beneficiaries **Quantitative:** Data analysis, comparing targets with achievements, ex-post calculation of external benefits of the programme.

Motorways of the Sea	The evaluation was performed by ICF, the Institute of Shipping Economics and Logistics (ISL), and Trasporti e Territorio (TRT), commissioned by the DG MOVE of the European Commission (ICF et al., 2017).	According to ICF et al. (2017): "The purpose of this contract is to provide the European Commission (EC) with: * An ex-post evaluation of the Motorways of the Sea (MoS) concept, covering the period 2001 to 2013. * An analysis of prospects for the further development of the concept."	Relevance Coherence Effectiveness Efficiency EU added value	Relevance Coherence Effectiveness Efficiency EU added value	**Qualitative:** Consultations with stakeholders and commission officials via semi structured interviews, written consultation to relevant stakeholders, desk-based research and analysis, literature review. **Quantitative:** Data analysis of short sea shipping trends, project data assembly and analysis.
NAIADES - Navigation and Inland Waterway Action and Development in Europe	Two reports: 1. European Commission (2011b) performed a mid-term progress report for NAIADES in 2011. 2. European Court of Auditors (2015) performed a special report regarding IWT in Europe, which include some information regarding NAIADES performance.	1. No specific purpose is mentioned by the European Commission (2011b): "The report gives an overview on the achievements reached so far, the measures still underway or to be tackled and outlines the next steps until 2013". 2. No specific purpose is mentioned by the European Court of Auditors (2015). They examine if IWT strategies have been implemented effectively in the EU, if they contribute to improved conditions and an increased modal share of IWT, as well as if they are coherent and based on relevant and comprehensive analyses.	1. European Commission (2011b): Relevance Coherence Effectiveness 2. European Court of Auditors (2015): Relevance Coherence Effectiveness	1. European Commission (2011b): Relevance Coherence Effectiveness 2. European Court of Auditors (2015): Relevance Coherence Effectiveness	1. European Commission (2011b): **Qualitative** No methodology is mentioned. The report qualitatively summarizes the policies and actions taken on the IWT-area. 2. European Court of Auditors (2015): **Qualitative** On-the-spot audit visits, analysing policy and strategy documents and other available information from the Commission, UNECE and other third parties., **Quantitative:** Data analysis regarding financial, transport and navigability indicators.
National Aid - The Mode Shift Revenue Support- MSRS	Two evaluation reports: 1. Performed by ARUP in 2014 on request by Department for Transport (2014). 2. Performed by Arup, AECOM and Port Centric Logistics Partners (PCLP) consortium, also requested by the Department for Transport (2020a).	The purpose of both reports was to provide updated evidence to support decisions on regarding the prolongation of the support scheme. The evidence should consider the financial need for the grant, which include calculating cost differences between freight transports by road, rail and water. Department for Transport (2020a) also had as purpose to review support levels under the MSRS scheme and analyse how a similar policy instrument could be implemented for coastal shipping.	Department for Transport (2014): Relevance Coherence Effectiveness Efficiency Department for Transport (2020a): Relevance Coherence Effectiveness Efficiency	Department for Transport (2014): Relevance Coherence Effectiveness Efficiency Department for Transport (2020a): Relevance Coherence Effectiveness Efficiency	Department for Transport (2014): **Qualitative:** Stakeholder consultations, interviews with grantees, workshop, model review and development. **Quantitative:** Data collection and analysis, impact assessment, estimating lorry journeys removed and cost benefit ratio. Department for Transport (2020a): **Qualitative:** Stakeholder consultation, workshop, interviews with grantees, discussions at

					conference, email response to “engagement pack” (including background information, excel spreadsheet and questionnaire). **Quantitative:** Data collection and analysis, impact assessment, estimating lorry journeys removed and cost benefit ratio.
National Aid - "The Waterborne Freight Grant Scheme"	Two evaluation reports: 1. Performed by ARUP in 2014 on request by Department for Transport (2014). 2. Performed by Arup, AECOM and Port Centric Logistics Partners (PCLP) consortium, also requested by the Department for Transport (2020a).	The purpose of both reports was to provide updated evidence to support decisions on regarding the prolongation of the support scheme. The evidence should consider the financial need for the grant, which include calculating cost differences between freight transports by road, rail and water. Department for Transport (2020a) also had as purpose to review support levels under the MSRS scheme and analyse how a similar policy instrument could be implemented for coastal shipping.	Department for Transport (2014): Relevance Coherence Effectiveness Efficiency Department for Transport (2020a): Relevance Coherence Effectiveness Efficiency	Department for Transport (2014): Relevance Coherence Effectiveness Efficiency Department for Transport (2020a): Relevance Coherence Effectiveness Efficiency	Department for Transport (2014): **Qualitative:** Stakeholder consultations, interviews with grantees, workshop, model review and development. **Quantitative:** Data collection and analysis, impact assessment, estimating lorry journeys removed and cost benefit ratio. Department for Transport (2020a): **Qualitative:** Stakeholder consultation, workshop, interviews with grantees, discussions at conference, email response to “engagement pack” (including background information, excel spreadsheet and questionnaire). **Quantitative:** Data collection and analysis, impact assessment, estimating lorry journeys removed and cost benefit ratio.
National Aid - Freight Facilities Grant - FFG	Published paper in Transport Reviews by Woodburn (2007).	The purpose of the evaluation paper is expressed by Woodburn (2007) as follows: “The paper has four key objectives: to catalogue the evolution of the rail freight grant funding process in Britain; to identify the schemes that have received Freight Facilities Grants (FFGs) since 1997/98; to assess the extent to which the planned flows resulting from those FFG awards have materialized; and to evaluate	Relevance Coherence Effectiveness Efficiency	Relevance Coherence Effectiveness Efficiency	**Qualitative:** Questionnaire survey to recipients of FFGs between 1997 and 2005. **Quantitative:** Desk based gathering data regarding freight grant funding, comparing freight volumes applied for and volumes achieved.

		the role of rail freight grants in influencing rail freight volumes, particularly in a liberalized rail-operating environment.”			
Shift2Rail	The evaluation report was performed by an expert group on request by European Commission (Fontanel et al., 2017)	Article 11 of the Shift2Rail regulation require an evaluation of the policy instrument with assistance of independent experts (Fontanel et al., 2017). Furthermore, an interim evaluation is also a key requirement in the regulatory framework of Horizon 2020. The purpose of the evaluation, other than fulfilling the requirements, was to assess the progress and mid-term achievements of Shift2Rail over the time period 2014 - 2016.	Relevance Coherence Effectiveness Efficiency EU added value	Relevance Coherence Effectiveness Efficiency EU added value	**Qualitative:** Interviews, stakeholder consultations, analysing documents.
State aid to transfer goods to rail - the Province of Emilia Romagna	The original report was not found. The performance of the aid scheme is summarized in a decision letter from the European Commission regarding the prolongation of the policy instrument (European Commission, 2019a). In the decision letter it is stated that the legislative Council was provided a final report by the Regional government of the Emilia Romagna province, and that an environmental report was drafted by the regional Directorate of the Environment and Territorial Protection.	Prolongation of the state aid.	Relevance Coherence (with EU internal market) Effectiveness Efficiency	Relevance Effectiveness Efficiency	**Quantitative:** Data analysis regarding trends in rail traffic under the scheme, comparing expected and achieved modal shift and savings in emissions, estimating energy savings and costs.
State aid to transfer goods from road to rail "Ferrobonus" (Italy)	The original report was not found. The performance of the aid scheme is summarized in a decision letter from the European Commission regarding the prolongation of the policy instrument (European Commission, 2016d). In the decision letter it is stated that the original evaluation report was provided to the European Commission by “Italian Authorities”.	Prolongation of the state aid.	Relevance Coherence (with EU internal market) Effectiveness	Relevance Effectiveness	**Quantitative:** Data analysis regarding trends in rail traffic under the scheme.

State Aid - to transfer goods from road to rail "Nuovo Ferrobonus" (Italy)	The original report was not found. The performance of the aid scheme is summarized in a decision letter from the European Commission regarding the prolongation of the policy instrument (European Commission, 2019b). In the decision letter it is stated that the original evaluation report was provided to the European Commission by “Italian Authorities”.	Prolongation of the state aid	Relevance Coherence (with EU internal market) Effectiveness	Relevance Effectiveness	**Quantitative:** Data analysis regarding trends in rail traffic under the scheme
State Aid - to transfer goods from road to water "Ecobonus" (Italy)	1. The performance of the aid scheme is summarized in a decision letter from the European Commission regarding the prolongation of the policy instrument (European Commission, 2012a). In the decision letter it is stated that the original evaluation report was provided to the European Commission by “Italian Authorities”. However, the original report was not found. 2. RAM S.p.a (2019) present some state of the art regarding best practices in the Croatian and Italian territories regarding modal shift policy instruments in a report for the project “Capitalization and Harmonization of the Adriatic Region Gate of Europe (CHARGE)”. Among others, they present information regarding the Ecobonus performance. However, they do not mention how they have gathered the information and where it comes from.	1. European Commission, 2012a): Prolongation of the state aid. 2. RAM S.p.a (2019): The report aims to analyse policy instruments and best practices for promoting intermodality in the Italian and Croatian territories.	1. European Commission, 2012a): Relevance Coherence (with EU internal market) Effectiveness 2. RAM S.p.a (2019): Effectiveness Efficiency	1. European Commission, 2012a): Relevance Effectiveness 2. RAM S.p.a (2019): Effectiveness Efficiency	1. European Commission, 2012a): **Quantitative:** Data analysis, estimating number of journeys on subsidized routes. 2. RAM S.p.a (2019): **Quantitative:** It is not mentioned if the information presented in the report comes from already published work, or if the presented Ecobonus results have been estimated within the RAM S.p.a (2019) study. However, the presented results are of a quantitative nature and include estimations of cost-benefit ratios and number of journeys on subsidized routes.
State Aid - to transfer goods from road to rail "Miljökompensation" (Sweden)	The policy was evaluated in 2020 by the Swedish Transport Administration (2020).	Article 15 of the regulation for the environmental compensation require the Swedish Transport Administration to follow up the	Relevance Coherence (with EU internal market) Effectiveness	Relevance Effectiveness	**Qualitative:** Interviews with grantees, discussion regarding how the

		policy instruments performance and ensure that the purpose of the policy instrument is met.			funding was split between different actors.
State Aid - Financial support for rail operations (Austria)	The performance of the aid scheme is summarized in a decision letter from the European Commission regarding the prolongation of the policy instrument (European Commission, 2017b). In the decision letter it is stated that the original evaluation report was performed by the Austrian state-owned company SchiGmbH. However, the original report was not found.	Prolongation of the state aid	Relevance Coherence (with EU internal market) Effectiveness Efficiency	Relevance Effectiveness Efficiency	**Quantitative:** Data analysis, estimations of modal shift, externalities, and cost benefit ratio.
Trans European Transport Network (TEN-T)	A midterm evaluation report of TEN-T was prepared for the European Commission in 2011 by the consultant firm Steer Davis Gleave (2011). Furthermore, a review of the TEN-T programme was planned to be published by the end of 2020 but have still not been published by April 2021.	The objective of the evaluation was to evaluate the methods and impacts of TEN-T projects, and to provide conclusions and recommendations on the implementation of the TEN-T programme.	Relevance Effectiveness Efficiency	Relevance Effectiveness	**Qualitative:** Stakeholder interviews, desk research. **Quantitative:** Analyzing statistical data on the different calls and work programs.

Annex C: Performance of evaluated policy instruments

Name of the Public Policy Instrument	**Brief description and policy objectives/targets**	**Effectiveness**	**Efficiency**
Connecting Europe Facility (CEF)	Connecting Europe Facility (CEF) for Transport is an EU funding instrument aiming at realising European transport infrastructure policy by supporting the upgrading of existing infrastructure and investment in new infrastructure (European Commission, 2021c). There are several general objectives for CEF, and specific objectives for CEF Transport, including among other things: removing bottlenecks, enhancing rail interoperability, bridging missing links, improving cross-border sections, ensuring sustainable and efficient transport systems, optimising the integration and interconnection of transport modes, as well as enhancing the interoperability of transport services, while ensuring the accessibility of transport infrastructures.	The evaluation does not quantify any effects on modal shift or associated externalities, but rather describe what type of projects that CEF supports, how the funding is allocated between these projects, and how the program is managed and communicated. According to European Commission (2021c), the lack of a proper ex-post analysis comparing the performance of the program with the policy objectives (targets), is a result of the policy lacking relevant, well-defined, and robust key performance indicators as well as well-defined targets. The existing key performance indicators focus on effects in the longer term, such as number of multimodal logistic platforms, including inland and maritime ports and airports connected to the railway network. As these types of projects require a certain amount of time to be realised, the current key performance indicators lack the ability to provide information in a timely manner regarding necessary improvements and corrections of the programme. According to the evaluation, the projects selected between 2014 and 2016 will contribute to transport modes being better integrated by 2020 by an investment of EUR 287 million (EUR 91 million from CEF) connecting 5 inland ports, 9 maritime ports, and improving 7 rail-road terminals. It is stated that CEF Transport is contributing to EU modal shift targets (stated in the 2011 White Paper) and the decarbonisation of the transport sector by allocating about 81% of the currently allocated funding to rail and IWT. When it comes to CEF's effectiveness in achieving operational objectives, it is stated that the programme triggers additional investments that would not have been kicked off without the EU support (for example infrastructure investments with lifespans of 30-50 years). CEF is however criticized in the evaluation for not reaching its objectives of promoting synergies at project level, which is explained by a rigidity of the legal and budgetary framework regarding eligibility of projects and costs. When it comes to information and outreach of the program, it is concluded that the program effectively manages to reach the relevant participants. The majority (74%) of the stakeholders have a positive view of the programmes activities for raising	Efficiency is not discussed in terms of the policy instruments' effects on modal shift and negative externalities. Instead, efficiency is discussed from a perspective of project selection, implementation, and management of CEF. According to the evaluation, heavy calls oversubscription has resulted in a competitive process, where the best project proposals are selected based on relevance, maturity, quality of applications, and highest EU added value. For CEF Transport, the assessment of the funding gap based on cost benefit analysis submitted by the applicants has been improved since the implementation of CEF but could still be reinforced. The management of the program is considered efficient, according to the evaluation. However, it is stated that the administrative burden imposes disproportionate costs on smaller projects and could be better adapted.

		awareness and promoting the programme. Improvements are however suggested, such as giving feedback on rejected project proposals, further efforts in promoting CEF as a climate policy, as well as further efforts in promoting CEF to smaller stakeholders and to the public.	
Directive 1992/62 and 2011/76/EU - Eurovignette	The internalization of external costs for road transports could potentially lead to a modal shift of freight to rail and/or water as road transports become more expensive. The Eurovignette directive provides a legal framework which allows the member states to charge freight transports by truck in accordance with their impact on infrastructure, environment, air quality and noise levels. However, the directive does not obligate the member states to introduce charging schemes, but only provide the possibility to do so. The objective of the directive is to “encourage differentiated charging based on external costs as a means towards sustainable transport” (Directive 2011/76/EU).	According to the evaluation, statistics on freight transports show some potential evidence of a modal shift to rail in Germany and Austria due to the distance-based system. However, it is difficult to prove the causality between the modal shift and the introduction of the tolls and to isolate the effects from other policy instruments and effects on the transport sector. Charging levels and systems vary a lot between the member states, and there is a wide range of price signals within the union. In some countries, the road charging systems are time-based vignettes (e.g. in Sweden, Denmark, Netherlands, and Luxembourg) while other countries (e.g Germany and Austria) apply distance based tolls. Some of the systems are electronic, while other systems include physical barriers. Thus, the directive fails to contribute to a fully integrated internal market.	According to the evaluation, distance-based toll systems are more efficient than time-based vignettes as they can internalize the external costs in a more efficient way (user pays principle). Time-based vignettes and tolls that only apply to specific roads are not considered very efficient in changing behaviour compared to network-wide integrated tolling systems. The wide range of charging systems in the member states and the wide range of technologies applied within the systems impose unnecessarily high administrative costs to haulers.
Directive 92/106/EEC - Combined Transport of goods between Member States	The Combined Transport Directive is an EU policy instrument promoting modal shift. As stated in the evaluation, the objective of the directive is to “better utilise the existing transport infrastructure and resources and to reduce negative externalities of road transport to the environment by incentivising the use of other means of transport.” (European Commission, 2016a). Furthermore, the numerical modal shift target stated in the 2011 white paper (30% of freight over 300km by 2030 and 50% by 2050) constitutes a new objective for the Combined Transport Directive. To achieve the objectives, the policy instrument aims at eliminating quantitative restrictions and authorisation procedures for combined transports, clarifying the non-application of road cabotage restrictions on road legs, and providing financial support to some combined transport operations.	According to the evaluation, the policy has been effective in terms that it has contributed to combined transport operations that had not been possible without the directive. However, the modal shift has been slower than expected and, and the growth of the share of combined transport operations (estimated to 4.2% on average) will not be sufficient to reach the targets set out in the 2011 White Paper. According to the evaluation, the most effective parts of the policy are the liberalisation of combined transport road legs from quotas and authorisations (in Article 2), as well as the elimination of compulsory tariffs (in Article 8). The fiscal incentives within the policy could be effective in theory but have not been so in practice due to methodologies not leading to the support translating into price reductions for the users of combined transports. The tax- and reimbursement levels vary between countries and give, in many cases, too small incentives to be able to counterbalance the price disadvantages of combined transports compared to pure road transports. Furthermore, the definition of combined transport has been interpreted differently between member states, leading to delays and fines for combined transport operations in some countries.	Both qualitative methods such as stakeholder consultations, and quantitative methods were used for analysing the performance of the policy. However, there are some limitations in the quantitative analysis due to difficulties in finding relevant data for several of the evaluated years. Still, according to the evaluation, the Combined Transport Directive has resulted in reduced externalities (accidents, noise, congestion, air pollution, climate change) from road transport, representing benefits to society of €2.1 billion annually. The costs of the policy have not been possible to quantify in the evaluation due to lack of data. However, as an example of costs it is mentioned that the annual cost for tax reimbursements and exemptions in Germany amounts to €2 million annually. The qualitative consultation says that stakeholders do not think that the benefits could have been achieved to lower costs, but they argue that some things should be done electronically instead of paper and stamps.

EU Regulation 561/2006 - Rest periods on rolling/floating roads and social legislation relating to road transport	The EU regulation (EC) No. 561/2006 establish rules for, among other things, how often and how long professional drivers must rest. Article 9 in this regulation covers the rest periods for rolling and floating roads (road transports which have a part of the route on railway or water). According to the regulation, this part of the transport is allowed to be counted as rest time, favouring the use of multimodal transports. As stated in Regulation (EC) No 561/2006: "This Regulation lays down rules on driving times, breaks and rest periods for drivers engaged in the carriage of goods and passengers by road in order to harmonise the conditions of competition between modes of inland transport, especially with regard to the road sector, and to improve working conditions and road safety. This Regulation also aims to promote improved monitoring and enforcement practices by Member States and improved working practices in the road transport industry."	Article 9 of the regulation is not evaluated in terms of modal shift or negative externalities. However, it is evaluated according to its enforcement in the member states. According to the evaluation, there are still some uncertainties regarding when the drivers are allowed to rest or not. Some drivers have for example been issued with penalties in France because the authorities did not understand how to enforce the rest periods. Thus, the enforcement of the policy is not uniform in all countries, and it need to be further harmonized and remove uncertainties.	
EU Regulation 913/2010 - European rail network for competitive freight	Regulation (EU) No 913/2010 concerning a European rail network for competitive freight set the rules for the establishment, organisation, and management of international Rail Freight Corridors. The policy aims at boosting rail freight and achieving the modal shift objectives in the White Paper on Transport. Among other things, it aims at promoting intermodality between rail and other transport modes by integrating terminals into the corridor management and development. As stated in Regulation (EU) No 913/2010: "The aim of this Regulation is to improve the efficiency of rail freight transport relative to other modes of transport. Coordination should be ensured between Member States and infrastructure managers in order to guarantee the most efficient functioning of freight corridors. To allow this, operational measures should be taken in parallel with investments in infrastructure and in technical equipment such as ERTMS that should aim at increasing rail freight capacity and efficiency."	The evaluation does not specifically evaluate the policy in terms of modal shift, but rather consider opinions regarding the policy. Most stakeholders seem to believe that the regulation is effective, even though member states and advisory groups are only considered somewhat effective in promoting the implementation of the rail freight corridors according to several respondents. Some respondents said that the Regulation focuses on establishing (as opposed to operating) the rail freight corridors, which the stakeholders do not consider sufficient to achieve the policy objectives. Most respondents believe that it would be beneficial to have specific targets to monitor the effectiveness.	Several stakeholders considered the policy as efficient but meant that the benefits will start to be felt only in the medium or long term.
European Shortsea Network – (Evaluation for the Norwegian Short Sea Promotion Centre)	European Shortsea Network is a network which connects all the Shortsea promotion centres in Europe. The purpose is to be a platform for exchanging ideas and to be the main source of information for the transport mode. The shortsea promotion centres aim is to contribute to a modal shift by providing information about the transport mode.	Even though the European Shortsea Network has not been evaluated as a whole, there is an evaluation of the Norwegian Shortsea Promotion Centre (Askildsen, 2005). According to the evaluation, the shortsea promotion centre has not been effective. Existing data show that no modal shift has been achieved and there are no success-examples at all. They argue that the policy has not at all fulfilled its aims.	

Marco Polo I and II	The Marco Polo programmes aimed at promoting a modal shift of freight transports by providing grant to greener transport modes such as rail, IWT and maritime transport (European Court of Auditors., 2013). According to INEA (2020), the objective of the Marco Polo I programme (2003 to 2006) was to contribute to maintaining the modal split of freight transport between the transport modes at 1998 levels by shifting the expected increases in road freight to other transport modes. The overall target established for the program was a modal shift of 48 billion tkm, and the expected modal shift by the selected actions were 47.7 billion tkm. The available budget was €102 million. The target of the Marco Polo II programme (2007-2013) was to shift 143.5 billion tkm of freight transport from road to other transport modes. The available budget amounted to €435 million and was available for following actions: modal shift; catalyst; common learning; motorways of the sea, and traffic avoidance.	According to Europe Economics (2011) there has been a significant underachievement of the Marco Polo I programme. The achieved modal shift has been far below expected levels. The European Court of Auditors (2013) also find the Marco Polo Programmes ineffective due to several factors. For example, even though the reported modal shift (for Marco Polo I) equal to 22,1 billion tkm of freight, only 46% of the expected modal shift was achieved according to the evaluation. Furthermore, there have been few relevant project proposals, the sustainability of the projects have been limited, and the program has come with heavy administrative burdens. Moreover, several of the funded projects would have started without support from the scheme. However, in a reply to the European Court of Auditors (2013) by the European Commission, it is mentioned that the European Commission considers the objectives as very ambitious, and that deciding the effectiveness based on target fulfilment may lead to the Marco Polo programmes being considered less effective than they are. According to the Commission, the modal shift under the Marco Polo Programmes is substantial. Between 2003 and 2012, more than 4 million trucks were shifted away from road, resulting in estimated benefits of avoiding above 4.5 million tonnes of CO_2 emissions, reducing traffic jams by about 64,000 kilometres, and saving more than 75 lives. Furthermore, the European Commission also argue that the performance of the Marco Polo Programmes should be seen in the light of the economic crisis. In the final report on the Marco Polo II programme, INEA (2020) discuss the effectiveness of both Marco Polo programmes, but with focus on Marco Polo II. According to INEA (2020), Marco Polo I had available €102 million. Grant agreements were signed for €73.8 million. But by the end of the programme only €41.8 million were paid, representing 41% of the initial available funding. The funded actions resulted in a modal shift of 21.9 billion tkm, representing 46% of the overall modal shift target. The target for Marco Polo II of shifting 20.5 billion tkm per year (143.5 billion tkm during the entire programme) was set up in accordance with the expected increases of EU freight transport over the same time period (INEA, 2020). However, due to the financial crisis, the EU freight market decreased by 8.33% representing 302 billion tkm. This made the economic context less favourable for reaching the target. Out of the total budget of €435, an initial funding of €315.5 was awarded to actions with an expected modal shift of 113.9 billion tkm. However, by the end of the program only €130.9 were paid and resulted in the shift of 41.9 billion tkm. Thus, there was a	According to Europe Economics (2011) the achieved efficiency for Marco Polo I projects were 326 tkm per EUR of subsidy when measured in terms of committed funds. This is way below the expected efficiency of 741 tkm per € of subsidy on average. However, some projects achieved more modal shift than expected but were not able to receive more funding than was specified in the Grant Agreement. According to INEA (2020) the Marco Polo II programme resulted in the avoidance of 3.5 billion tonnes of CO_2-emissions. The external cost reduction of the programme resulting from the achieved modal shift range between €385.4 million and €408.8. As the total amount of grants provided were €131 million, the program generated € 2.9-3.1 of environmental benefits (including air quality, noise, climate change, accidents and congestion) for every euro spent.

		significant underachievement of several actions supported under the programme. Closed actions on average achieved 50% of their initial targets. However, the level of target achievement for the MarcoPolo II actions differed depending on transport mode, with rail actions having the highest level of achievement. Rail actions represented 46.5% of the programmes total achieved modal shift followed by maritime transport (35.3%), traffic avoidance actions (8.6%), mixed actions (7.9%), and IWT (1.7%). The lower level of success for IWT actions was mainly explained by stronger competition from road transport at shorter distances, unstable water levels and infrastructure limitations. Even though there were several efforts from Marco Polo II to facilitate a wider participation of the programme, the responsiveness to the calls for proposals was low. There were also several applicants that withdrew their proposals during the grant preparations. The INEA (2020) report highlights a set of problems that complicated the achievements of the targets: overestimation of demand in the applications, infrastructure limitations, lack of interoperability and cooperation, changing market conditions, and the persistent attractiveness of road transport.	
Motorways of the Sea (MoS)	The maritime pillar of TEN-T is called Motorways of the Sea (MoS), which is a policy for promoting the maritime transport sector as an alternative to road freight transport. Since its implementation, the MoS concept has been financed through several other EU funding programs such as CEF, TEN-T and the Marco Polo I and II programmes (2003-2013). According to Decision no 884/2004/EC: “The trans-European network of motorways of the sea is intended to concentrate flows of freight on sea-based logistical routes in such a way as to improve existing maritime links or to establish new viable, regular and frequent maritime links for the transport of goods between Member States so as to reduce road congestion and/or improve access to peripheral and island regions and States.” MoS has however evolved over times with changing objectives and do now also include environmental concerns, integration of maritime transport in logistic chains, maritime safety, traffic management, and training (ICF et al., 2017).	A frequently mentioned comment by stakeholders was that the policy is lacking clarity regarding overall goals and objectives (ICF et al., 2017). This also leads to difficulties in evaluating the policy instrument in terms of target achievement. Furthermore, a lack of data makes it difficult to quantify the effects of the policy instrument. The measurable performance has been mixed. Some modal shift from road to shipping have been encouraged by the policy instrument but there has not been a significant improvement of shortsea shipping compared to road transport under the programme. The qualitative evidence shows that reductions in road congestion seem to be minimal. There is however evidence that MoS has contributed to innovation and technological advancements. Most of the quantified targets within MoS are those set up for the Marco Polo Programs. Therefore, the results regarding effectiveness overlap with the results for the Marco Polo Programs and are not considered very effective in terms of target achievement. However, the evaluation highlights the importance of the economic crisis and its effects on the sector.	According to ICF et al. (2017) MoS has mainly relied on grants instead of financial instruments, which can often tackle market imperfections more efficiently. They argue that there are therefore possibilities to further improve efficiency by developing MoS financial infrastructure.

NAIADES - Navigation and Inland Waterway Action and Development in Europe	The NAIADES action programme is an overarching strategy of the European Commission to strengthen the position of IWT as part of intermodal freight solutions. According to the European Commission (2011b), the overall objectives of the NAIADES program is: “Competitiveness, intermodal integration, awareness raising; energy-efficiency and environmentally friendliness of the fleet; removal of infrastructure bottlenecks; research and technological development; technology and innovation transfer into the sector and last but not least employment, education and training and working conditions.”	According to the (European Commission, 2011b) NAIADES contributed to valuable and tangible results. However, the lack of dedicated resources to the action programme, as well as the financial crisis has been a disadvantage for the implementation of the programme. According to the European Court of Auditors (2015), the modal share of IWT grew after 2006 when NAIADES was implemented (and when financial support to TEN-T increased). However, at the aggregate level the Court considers the European IWT strategies to not have been effectively implemented, as the policy objective of shifting freight transport from roads to IWT has not been achieved and overall navigability conditions have not improved. Furthermore, it is mentioned that the policy lacks precise objectives regarding IWT.	
National Aid - "The Mode Shift Revenue Support- MSRS	The Mode Shift Revenue Support (MSRS) is an aid system in Great Britain promoting a modal shift of freight transport to rail and IWT. The MSRS exist in two versions: MSRS intermodal and MSRS bulk and waterways. MSRS intermodal provides a standardized support for which the grant level differs depending on if the modal shift is achieved in port or other terminals. The MSRS bulk and waterways grant level is decided individually and depends on the expected environmental benefits. According to the European Commission (2014c), the objective of the MSRS is to shift freight transports from road to rail or IWT in order to reach environmental benefits. By covering some of the extra costs of rail and IWT compared to road, the policy instrument aim to allocate available funds to those transport services which offer the greatest environmental benefits for the money.	In the evaluation report from 2014, interviews with stakeholders show that there is a general agreement that the MSRS intermodal has played an important role in achieving a modal shift to rail, with around 700.000 containers moved annually under MSRS support (Department for Transport, 2014). The MSRS bulk and waterways is considered effective for rail transports. However, the uptake of awarded grants to IWT is low. According to the water industry, this reflects the difficulties of moving IWT in the United Kingdom. According to the evaluation report performed in 2020, the most likely outcome if tampering or withdrawing the grant is that transport flows performed by rail or IWT will shift back to road or cease altogether (Department for Transport, 2020a). Both evaluation reports suggest some improvements to the MSRS. For example, reviewing the application process and undertaking a communications program to encourage a wider range of applicants to the MSRS is suggested by the Department for Transport (2020a). Furthermore, interviews with the water industry expressed a wish for the standardized intermodal rail grant to also be available for waterborne transports on an equal basis, as they believe this could induce more industry interest and create a level playing field between rail and water (Department for Transport, 2014).	Even though the uptake of IWT grants is low, a benefit to cost ratio of 4.27:1 for every £1 of grant expenditure was estimated for the MSRS scheme (including both intermodal and bulk and waterways) in 2014 (Department for Transport, 2014). Furthermore, when the MSRS was prolonged in 2020 it was estimated that the impact of ending the scheme would result in a net worsening for society of up to £57.9 million per annum (Department for Transport, 2020a).
National Aid - "The Waterborne Freight Grant Scheme"	The Waterborne Freight Grant (WFG) is an aid system in Great Britain which aims at promoting the development of coastal and short sea shipping transport in the United Kingdom, and thereby reducing the environmental, health and social impact of road traffic (European Commission, 2020a).	According to the Department for Transport (2014), the WFG had a very low uptake with only 4 awarded WFG:s at the time of the evaluation. When prolonged again in 2020 no more grant supports had been awarded between 2015 and 2019 (Department for Transport, 2020a). It is expressed a wish to increase the grant period to more than 3 years as well as to	Even though the uptake of the WFG has been low, the granted projects has effectively achieved a modal shift, and resulted in reduced externalities from road transports. According to the Department for Transport (2014), the support scheme has generated a benefit to cost ratio of approximately 4.66:1 for every £1 grant.

	WFG assist companies for up to 3 years with the operating costs associated with costal and short sea shipping flows compared to road transport (Department for Transport, 2020b). The grant level is decided depending on the expected environmental benefits and financial needs associated with the modal shift, but the maximum grant is 30% of the total operating costs or €2 000 000.	promote a more active engagement between grant fund managers and the industry in order to increase the uptake of the policy.	
National Aid - Freight Facilities Grant - FFG	The Freight Facilities Grant (FFG) has existed in Great Britain since 1974 in different versions. Today, it only exists in Wales and Scotland. The objective of the FFG scheme is to encourage a modal shift away from road freight transports, by helping companies invest in new rail or water-based handling facilities, where the absence of the grant would lead to the companies choosing road transports over less environmentally damaging transport modes (European Commission, 2012b).	Woodburn (2007) evaluate the performance of the policy between 1997/98 to 2005/06 by comparing the freight volume achieved with the volume applied for, as well as a questionnaire survey with recipients of FFG. Out of the 36 granted awards, 23 had achieved their planned volume or more, resulting in an aggregate impact in line with predictions. For the granted awards that did not reach the expected volumes, rail service problems such as lacking network capacity, reliability, and costs, were mentioned as main causes. Overall, the study considers the FFG as effective.	During the period 1997/98 to 2005/2008 an additional £0.50 of private sector money has been invested in rail freight facilities for every £1.00 of grant funding. However, recipient companies expressed a felt that the grant decision-making process is complex and time-consuming and that the scheme can be improved by simpler, more flexible and user-friendly procedures.
Shift2Rail	The Shift2Rail Joint Undertaking is a public-private company under the Horizon 2020 EU policy instrument. Shift2Rail aims at coordinating research and innovation within the railway sector and to contribute to a more integrated, sustainable, competitive, and effective railway sector within the EU. The major objectives of the Shift2Rail Joint Undertaking is to support the achievement of the Single European Railway Area, increase the attractiveness and competitiveness of the European railway system in order to promote a modal shift, and help the European rail industry to keep its position as leader on the global market for rail products and services (Fontanel et al., 2017). These objectives will be achieved through coordinated research and development within the railway sector.	The objective of the evaluation was to assess progress and mid-term achievements of the policy for the time period 2014-2016 (Fontanel et al., 2017). There were however no completed projects by the time of the evaluation, and therefore it is mainly a focus on the functioning of the administration of the programme in the evaluation. According to the evaluation, Shift2Rail is a well-functioning program that has resulted in increased visibility of rail research and improved the coordination of many technical aspects. However, some concern regarding multimodality is expressed by some of the interviewed stakeholders. When all rail research is organized by the rail sector there is a focus on rail only and less focus on multimodal solutions and innovation. Another identified problem for the policy is that the project applications are unevenly distributed between the EU member countries and that it is mainly larger actors that dominate the projects, while small and medium enterprises are less represented.	Only operational efficiency is discussed in the evaluation report due to the lack of completed projects by the time of the evaluation. Overall, the management of Shift2Rail is considered efficient.
State aid to transfer goods to rail - the Province of Emilia Romagna	The Emilia Romagna Region in Italy provides an aid scheme for the promotion of rail transports. The aid is paid in the form of a subsidy to logistics companies and railway undertakings and corresponds to the difference in external costs between rail and alternative modes of transport. The support is set at € 0.007 per tkm and is only paid to new rail transports. However, the subsidy is limited to the kilometres within the region and with a maximum amount of € 150,000 to each actor. The objective of the subsidy is to reduce environmental pollution and improve road safety and security by rebalancing	When prolonged in 2014 and later in 2019, the performance of the subsidy was evaluated (European Commission, 2014a, 2019a). According to the Regional government and regional Directorate of the Environment and Territorial Protection, rail freight has increased steadily since the introduction of the subsidy. Over the three year period 2014-2016, the subsidy has resulted in the removal of 140 931 heavy trucks from the regions roads, exceeding the removal of 80,000 heavy trucks which was expected (European Commission, 2019a). Most of the subsidized services either has their origin or destination at a port (European Commission, 2019a).	According to the evaluation, the modal shift subsidized under the scheme contributed to 70% more emission savings than expected (assuming a full road scenario without the subsidy). The report estimates that the subsidy has resulted in energy savings by approximately 60 %, about 86.4 GWh. Given a price of electricity of EUR 0.176/kWh, they estimate that total savings resulting from the subsidy exceeds EUR 15.2 million, compared to the state aid expenditure of approximately EUR 1.9 million.

	the division of freight transport in the region and to promote a modal shift to rail (European Commission, 2019a).		
State aid to transfer goods from road to rail "Ferrobonus" (Italy)	The Ferrobonus Scheme was first implemented in Italy in 2010 and have been prolonged several times since then (European Commission, 2020b, 2016d, 2011c). The aim of the aid scheme is to address structural imbalances between road and rail freight transportation, to strengthen the intermodal transport chain, and contribute to a modal shift to rail. The ultimate objective is to reduce the environmental, health and social impact of road freight transports (European Commission, 2016d). The Ferrobonus provides subsidies to companies using rail transport services which commission multimodal transport or transhipment services on the Italian territory (European Commission, 2016d). To achieve the subsidy at least 80% of the freight volume had to be maintained the following year when introduced in 2010. The Ferrobonus have been re-approved up to 2021 with a maximum subsidy level of EUR 2.5 per train kilometre (European Commission, 2020b).	According to Italian Authorities the Ferrobonus led to an increase in intermodal traffic of 17.3% when it was first initiated (European Commission, 2016d). The end of the aid scheme coincided with a decrease in rail freight, but was recovered by the time of a new provision of the incentive during 2015 (Marzano et al., 2018). The aid that was effectively paid under the scheme amounted to EUR 1,05 per train kilometre compared to the expected grant level of EUR 2 per train kilometre, which was lowered due to budgetary constraints.	
State Aid - to transfer goods from road to rail "Nuovo Ferrobonus" (Italy)	The rail support was introduced in Italy in 2015 and targets railway undertakings. The aim is to promote a modal shift from road to rail by providing a subsidy based on external costs and infrastructure access charges (European Commission, 2019b). The aid is paid in the form of a discount of the infrastructure access charge that need to be paid to the rail infrastructure manager. When it was introduced, it specifically targeted the south of Italy but was then extended to cover the entire country, however with different subsidy levels (Marzano et al., 2018).	In the prolongation letter by the European Commission (2019b) it is observed that rail freight increased with about 13,7 % in the southern regions of Italy and the islands compared to about 7.9% in the rest of the country over the period 2014-2018. This illustrates positive impacts of the policy in promoting modal shift. However, this positive trend in freight transport by rail then slowed down from 2017.	
State Aid - to transfer goods from road to water "Ecobonus" (Italy)	The Ecobonus scheme in Italy provided support to road haulage companies making use of maritime routes instead of road transport between 2007 and 2010. The aim of the Ecobonus was to facilitate a modal shift from road to sea (European Commission, 2012). The subsidy was decided on a basis of reduced external costs, maritime distance, and land distance avoided. According to the model deciding external costs, 100 km shifted from heavy trucks to sea contributed to €133 of positive externalities (RAM S.p.a, 2019). A maximum of 30% of the RoRo fares charged to truckers were paid with a minimum requirement of 80 trips per year on the subsidized route. The transport volumes had to be maintained for three years after the end of the subsidy.	According to European Commission (2012) there was a steady increase in the frequency of the number of journeys on national routes during 2007-2010 under the Ecobonus scheme. However, there were less accepted grants than expected and a decrease in EU trips, which is explained by the economic crisis in 2008. According to Ram S.p.a (2019) the Ecobonus-induced modal shift of 3.184 thousand tons on RoRo routes between Italy and Spain.	According to Ram S.p.a (2019), the modal shift induced by the scheme generated environmental and socio-economic benefits of approximately €1.1 or up to €5.81 per Euro invested, depending on the assumptions.

State Aid - to transfer goods from road to rail "Miljökompensation" (Sweden)	In Sweden, an environmental compensation is paid retroactively for already performed transports to operators that perform or organize transport services at the Swedish railway network. The objective of the environmental compensation is to strengthen the competitive position of rail and support rail as the more environmentally friendly mode of transport, thereby encouraging a modal shift from road to rail (European Commission, 2021d).	According to the evaluation, the policy has rather prevented a modal backshift from rail to road, than promoting an actual modal shift to rail. The policy instrument is criticized in the evaluation for lacking continuity, predictability and a long-term perspective. According to the EU state aid rules, prices should be adjusted so that transport buyers benefit from the environmental compensation. However, according to the evaluation the prices has not been lowered according to the expectations of the transport buyers, which can partly be explained by the lack of predictability of the policy. The compensation scheme is also criticised in the evaluation for including all freight transport on rail. This has resulted in about 22 % of the total funds in 2018 and 2019 going to the company LKAB (mining company) for transports of ore, where rail already is the dominating transport mode and where competition from road transports already is weak.	
State Aid - Financial support for rail operations (Austria)	Austria provides a non-repayable direct grant to rail carriers in Austria that offers or plan to offer freight transport services. The aim of the policy instrument is to encourage a modal shift of freight transports from road to rail and to avoid a modal backshift, and thereby reduce the negative external costs related to freight transports by road (European Commission, 2017b).	When prolonged in 2017, the policy was evaluated by the Austrian state-owned company SchiGmbH (European Commission, 2017b). According to the evaluation, the initial scheme resulted in transport services increasing by 2,8% in tkm for the supported production forms (rail transport services in the forms of single wagonload traffic, unaccompanied combined transport and accompanied combined transport) between 2013 and 2015.	A benefit cost ratio of EUR 3,41 to 1 during 2013-2015 and EUR 3,39 to 1 in 2016 is estimated for the scheme (European Commission, 2017b).
Trans European Transport Network (TEN-T)	The Trans European Transport Network (TEN-T) programme is an EU policy aiming at developing and implementing a Europe wide transport network covering all transport modes (European Commission, 2019c). The ultimate objective of the policy instrument is to close gaps, remove bottlenecks, remove technical barriers, and to strengthen social, economic, and territorial cohesion in the EU (European Commission, 2019c).	As TEN-T is not only a modal-shift policy instrument, it has not been evaluated in terms of achieving a modal shift, even though some aspects concerning co-modality and interoperability between modes are discussed. In the mid-term evaluation performed in 2011, Steer Davis Gleave (2011) mentions several positive effects of TEN-T, such as contributing to key pieces of transport infrastructure in Europe, increased mobility for citizens and goods, and contributing to more focused transport investments in Europe and thereby a more structured transport network. However, several aspects of TEN-T need to be improved. For example, the TEN-T objectives are very broad and defined at a general level. This makes it impossible to meet all objectives, but also very difficult to perform an ex-post evaluation. Even though broad objectives offer flexibility, they lack focus and do not define what TEN-T is trying to achieve. Steer Davis Gleave (2011) therefore suggest that the objectives of TEN-T need to be redefined, clarified as well as prioritised for the program to achieve desired outputs. When it comes to multimodality, Steer Davis Gleave (2011) mention that rail receives most of the TEN-T funding, but that few projects have aimed at integrating rail with other transport modes. The lack of investment in projects focusing on multimodality seem to be a	

		problem within TEN-T as there are several projects which are not meeting their full potential due to a lack of investment in other parts of the transport system, which lead to less possibilities for interoperability and intermodality.	