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Citation for the original published paper (version of record):
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
http://dx.doi.org/10.1016/j.tranpol.2021.05.021

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

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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

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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
0967-070X/

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.

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