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Final report

IMPLICATIONS OF ELECTRIFICATION FOR REGIONAL BIOGAS MUNICIPAL TRANSPORTATION SYSTEMS

Exploring Narratives and Systemic Effects

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Michael Martin[1,2], Sjoerd Herlaar[1], Tomas Lönnqvist[1], Sara Anderson[1], Åsa Romson[1], Anders Hjort[1] and Philip Peck[3]

[1] IVL Swedish Environmental Research Institute

[2] KTH Royal Institute of Technology, Department of Sustainable Development, Environmental Science and Engineering (SEED)

[3] Lund University, International Institute for Industrial Environmental Economics (IIIEE)

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PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 48367-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

The Swedish Energy Agency is a government agency subordinate to the Ministry of Infrastructure. The Swedish Energy Agency is leading the energy transition into a modern and sustainable, fossil free welfare society and supports research on renewable energy sources, the energy system, and future transportation fuels production and use.

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ABBREVIATIONS

CLD	Causal Loop Diagram
EV	Electric Vehicle
dB	Decibels
FTE	Full Time Equivalent (Jobs)
GHG	Greenhouse Gas
LBG	Liquefied Biogas
LNG	Liquefied Natural Gas
Nm3	Normal Cubic Meter
NOx	Nitrous Oxide
PM	Particulate Matter
SDM	System Dynamics Model

SUMMARY

In recent years, and in response to concerns about climate change, ambitious goals have been set in Sweden to develop a fossil-free transportation fleet by 2030. The public road transportation fleet in Sweden is already fueled to a large extent by renewable fuels. Biogas utilization in public bus-based transportation has been an important part of this, and is now intricately linked to Swedish waste management systems, supplying a significant proportion of fuel for municipal bus fleets.

However, recently, the interest in electricity-based drive chains as a core part of fossil-free transportation in urban environments has been steadily increasing, and numerous municipalities have begun to transition from biofuels to electrification in their bus fleets. This has primarily been pursued in inner-city transportation systems thus far, and is apparently accelerating, in turn displacing biogas and other biofuels.This is one area where there has been limited scientific investigation of the potential implications of electrification. Not least because of the potential effects for municipal waste management systems, where there have been very large investments over the past three decades. Thus, there is a need to understand the broader systemic implications of such shifts. In particular, electric transportation systems have been promoted primarily on the basis of positive expectations that focus primarily on the direct local level benefits, while there are few studies that include indirect effects of such a transition.

The aim of this project was to review the context and broader systemic implications of increased electrification of urban public transportation systems. We do this by applying a novel methodology, whereby we study the discourse used to promote the electrification of Swedish bus fleets and the competition between electrification and biogas. This provides a deeper understanding of the beliefs and expectations regarding both technical systems, the potential effects of displacement, and aspects and indicators used to motivate their benefits. This is then used to develop a description of a transition pathway, which in turn supports the creation of a quantitative dynamic model utilized to assess the environmental and socio-economic implications of electrification and the displacement of biogas. In this case, the model is applied for the electrification of Stockholm's inner-city bus fleet.

The discourse analysis, which examined a large collection of media, e.g., news articles, trade journals, reports, governmental propositions, previous studies, and interviews, provided a basis for mapping the themes projected to public audiences. This also supported the description and mapping of a) a general picture of the expectations created for electrification and b) the contemporary view of biogas bus systems and the ongoing role of biogas. The review provided substantial evidence that the general narrative present in public media presents electrification of municipal transportation systems as an inevitable and desirable system for the future. A positive and optimistic picture is presented of the technological systems, their expected advancements in range and reliability, and ongoing innovation within these novel systems. Drivers for uptake are presented primarily based upon the environmental benefits they offer for fossil-free, clean, and quiet transportation, but cost advantages are also presented. While biogas systems in public transportation are also framed as fossil-free, and an important contributor of social value, this is a minor theme and is primarily presented in technical publications. Such themes seldom appear in mainstream media. Displacement of biogas is both explicit and implicit in a deal of material. Some material clearly recognized that up-

take of biogas in other markets is required if the benefits, both environmental and societal, of biogas systems are to be maintained. An electrification scenario, which explicitly includes the displacement of biogas from municipal bus fleets and uptake in new markets was modeled using preconditions derived from the discourse analysis findings.

The results of the modeling aligned well with the expectations and 'possible futures' that were derived from the mapping of the media discourse. The electrification of inner-city municipal transportation led to reduced direct environmental impacts (e.g., reduced GHG emissions, particulate matter, and NOx emissions) in addition to contributing to significant socio-economic cost savings from reduced exposure to these emissions in the inner-city. Noise was found to be reduced, although not at levels as significant as the expectations highlighted in the discourse. While the loss of biogas markets in public transportation as a result of electrification is held to pose a clear threat to the market viability of the Swedish biogas system, this study assumed that the biogas demand could grow in other markets such as maritime and heavy-duty vehicle transport. As such, the implications of replacing fuels such as diesel for heavy-duty vehicles in addition to liquified natural gas and marine diesel in the maritime sector with biogas can result in large positive environmental impact reductions and large associated socio-economic benefits. With the given studied narrative, overall electrification was also found to have a benefit for employment, illustrating an increase in full-time employment possibilities, although this depends largely on the origin of the vehicles and infrastructure employed for this transition. Despite this, the biogas system still provides a large share of employment opportunities through continued use in alternative markets. However, the limitations and scope of the study are important to highlight, and the generalizations may not be applicable for other regions outside the studied system, i.e., Stockholm.

Finally, in addition to the qualitative and quantitative analysis conducted for the electrification-biogas interplay, the study also reviewed the possible barriers and incentives that could be used to displace biogas use to other sectors engaging actors and discussing the policy alternatives, where a policy brief was also produced to address a number of stakeholders to support future biogas development and viability in alternative markets.

SAMMANFATTNING

Sverige har antagit ambitiösa mål om en fossilfri transportsektor 2030 som ett svar på den ökade oron för klimatförändringarna. Den vägbundna kollektivtrafiken drivs i stor utsträckning av förnybara drivmedel. I kollektivtrafiken utgör biogas utgör en stor del av drivmedelsanvändningen och den har varit en viktig del i omställningen till fossilfrihet. Dessutom är biogassystemen sammanlänkade med andra samhällsfunktioner, t.ex. sophanteringssystemet.

På senare tid har intresset för elektrifiering som ett sätt att uppnå fossilfrihet i stadsområden vuxit sig allt starkare. Ett flertal kommuner har inlett omställningen från biodrivmedel till elektrifiering av bussflottan. Det sker framför allt i innerstadsområden och förefaller leda till en undanträngning av biogas och andra biodrivmedel.

Elektrifieringens påverkan på biodrivmedelssystemen är inte något väl utforskat område, men vilka potentiella konsekvenser för sophanteringssystemet det innebär bör beforskas ytterligare. Eftersom det har gjorts stora investeringar i biogassystem och sophantering, är det viktigt att förstå vilka följderna av en ökad elektrifiering och en eventuellt minskad biogasanvändning kan bli för dessa system. Med tanke på att elektrifiering har motiverats med positiva lokala effekter är det särskilt viktigt att utforska de potentiella indirekta effekterna av en sådan utveckling.

I det här projektet har vi utforskat de systemiska konsekvenserna av en ökad elektrifiering av kollektivtrafiken. Det gjordes genom att tillämpa nya metoder som analyserar diskursen kring elektrifieringen och diskursen kring konkurrens mellan elektrifiering och biogasanvändning. Målet är att ge en ökad förståelse för de uppfattningar och förväntningar som finns på de tekniska systemen, vilka potentiella undanträngningseffekter som kan ses, samt vilka aspekter som används för att motivera det ena eller det andra systemet. Detta arbete används sedan för att beskriva en möjlig omställningsväg och för att skapa en kvalitativ och dynamisk modell. Modellen används för att utvärdera miljömässiga och socio-ekonomiska implikationer av en elektrifiering och en undanträngd biogasanvändning. I projektet applicerades modellen på Stockholms innerstadsbusstrafik.

Diskursanalysen inkluderade olika slags media: nyhetsartiklar, branschtidningar, rapporter, riksdagspropositioner och -motioner samt intervjuer. Den gav en översikt över de ämnen som täcks i media och som förmedlas till allmänheten. Detta gav i sin tur en bild av hur de förväntningar som finns på elektrifieringen av bussflottan ser ut, samt de befintliga biogassystemen och biogasens roll.

Analysen visade att media generellt beskriver elektrifiering som både en önskvärd och oundviklig utveckling. En positiv och optimistisk bild målas upp av de tekniska systemen som inkluderar elektrifiering, dess förväntade framsteg gällande räckvidd och tillförlitlighet, och pågående innovationsarbete. De argument för elektrifiering som presenteras är att det möjliggör en fossilfri, ren och tyst transport. Även kostnadsfördelar framhålls. Biogas i kollektivtrafik beskrivs också som fossilfri och som att den genererar sociala fördelar, men detta syns främst i tekniska tidskrifter och inte i vanliga media.

Undanträngning av biogas diskuteras både uttryckligen och underförstått. Vissa artiklar/media säger att biogas måste ges en ny användning (om den ersätts av elektrifiering) för att behålla de sociala och miljömässiga fördelarna.

Resultaten från diskursanalysen innebar att vi i modelleringen även inkluderades ett elektrifieringsscenario där den undanträngda biogasen används på nya marknader. Modelleringsresultaten ligger väl i linje med förväntningarna och de ”möjliga framtiderna” som framkom då mediadiskursen analyserades. Elektrifiering av kollektivtrafiken i innerstaden skulle leda till minskad direkt miljöpåverkan (minskade utsläpp av växthusgaser, partiklar och NO_x), utöver de socio-ekonomiska fördelar av minskad exponering mot dessa utsläpp i innerstaden skulle ge. En elektrifiering skulle vidare leda till minskat buller, men inte i den omfattning som beskrivs i media.

Undanträngningen av biogas från kollektivtrafiken är ett hot mot biogasens överlevnad. I denna studie har vi antagit att biogasen kan växa på nya marknader såsom sjöfart och tunga transporter. Då biogas ersätter diesel i tung transport eller naturgas och diesel i sjöfart, kan det leda till stora miljömässiga och socio-ekonomiska fördelar. Vi fann också att elektrifiering kan ha positiva effekter på arbetstillfällen, men detta beror till stor del på varifrån fordon och infrastruktur kommer. Biogassystemen fortsätter att generera arbetstillfällen om alternativa marknader finns. Det bör dock noteras att dessa slutsatser inte alltid är giltiga utanför fallstudien i projektet, Stockholm.

Slutligen, utöver den kvalitativa och kvantitativa analysen som utförts för samspelet mellan elektrifiering och biogas, så visar arbetet i detta projekt också på möjliga incitament och barriärer för att byta användningsområde för biogasen. Dessa slutsatser är sammanfattade i en policy brief som togs fram efter diskussion med ett antal aktörer och intressenter om olika policyalternativ för att påverka utvecklingen och biogasens bärkraft på olika marknader.

CONTENTS

1 INTRODUCTION

In recent years, and in response to concerns about climate change, ambitious goals have been set to develop a fossil-free transportation fleet by 2030 in Sweden (Government of Sweden, 2010). As such, renewable fuels have received increased attention in the private and public sectors. The transition has been pursued to achieve reductions in greenhouse gas (GHG) emissions while also supporting Swedish biofuel production systems and regional industries (Eklöf et al., 2012; Martin et al., 2017). In Sweden, municipal transportation, i.e., bus fleets, is primarily fueled with renewable fuels in many Swedish municipalities, primarily biofuels (Sveriges Bussföretag, 2018). Furthermore, some regions have already achieved fleets running exclusively on renewable transport fuels, e.g., Stockholm (Stockholm County Council, 2017).

While there is consensus that electrical drive systems for buses deliver clean and low carbon inner-city public transportation – these were also the fundamental drivers for the uptake of biogas (Berglund et al., 2011; Ammenberg et al., 2018; Fallde and Eklund, 2015). A difference is that public transportation fleets provide an important market for biogas from waste. Thus, while one desirable system is being replaced by another – the waste management biogas system and the positive externalities it generates may be threatened by the loss of a foundational market. Electrification of bus fleets displaces more than biogas drive-chains – it also affects other areas of the socio-technical system.

However, the interest in electrification for promoting fossil-free transportation in urban environments has been steadily increasing (Creutzig et al., 2015; Gustafsson et al., 2021; Xylia and Silveira, 2017). A number of municipalities have begun investigations and have plans for the potential transition from biofuels (e.g., biogas) to electrification in inner-city transportation systems; see, e.g., (Stockholms Läns Landsting, 2017 a,b; Xylia and Silveira, 2017; WSP,2016). Nonetheless, there has been limited scientific literature reviewing the potential benefits of electrification of urban public transportation systems. The studies that are available are often limited to reviews of the technical potential of the systems, providing qualitative accounts of the expectations, and are limited to the GHG emission reductions and potential cost savings for the fuels; see e.g., Xylia et al. (2019), Hagberg et al. (2016), Xylia and Silveira (2017), WSP (2016)There is a need to extend these assessments to understand the broader systemic implications of this transition, as electric transportation systems have been promoted primarily with positive expectations. A large share of this focus has been placed on the direct local level implications (e.g. reduced noise and less emissions) with few studies including more indirect effects of a transition, such as the displacement of incumbent biofuel systems.

1.1 AIMS

The overall aim of this project was to review the context and broader systemic implications of increased electrification of urban public transportation systems. To do so, we focus on the replacement and displacement of biogas-based bus fleets in the Stockholm inner-city environments with electric systems.

1.2 LIMITATIONS

The analysis conducted in this study has focused primarily on the implications of electrification of the Stockholm inner-city bus fleet. As such, it should be highlighted that the results from this study are not generalizable to other areas in Sweden where the incumbent systems (such as fuel choice, fleets, and infrastructure, etc.), may be contextually different. Furthermore, while this study provides a review of the environmental and socio-economic implications of dynamic electrification scenarios, the study did not review the investment costs needed for the infrastructure and systems required for a biogas-based bus fleet and electric bus fleet. As such, a techno-economic assessment of the changes was considered outside the scope of this study despite its importance for regional investments.

This report primarily provides a new methodological development for the scientific community and insights for regional actors involved in biogas, municipal transport, and electrification strategies. Assumptions and results should therefore be taken into consideration when attempting to employ the results for other areas or different contexts. The model and results were employed with the purpose of identifying how and what factors contribute to environmental and socio-economic implications in the system when understanding the shift from biogas to electric municipal transportation systems, including dynamic processes and temporal aspects. We did not study the displacement of biogas to other municipal transportation systems (e.g., regional or peri-urban transportation), nor did we include the effects on other biofuels.

Furthermore, while the study is based entirely on Stockholm, further developments and cases are outlined in an ensuing project through the MESAM (Människa, Energisystem och samhället) program, a research program funded by the Swedish Energy Agency (Energimyndigheten), where further developments of the modeling approach and a case study involving a co-digestion system for biogas in Skåne will be developed.

2 METHODOLOGY

To assess the implications of future pathways for electrification, biogas, and surrounding systems, the study developed and employed a novel approach to develop dynamic scenarios to evaluate the environmental and socio-economic implications of alternative future pathways for a biogas-electric municipal transport interplay. This is done by applying qualitative methods, i.e., discourse and content analysis, to provide insights into the dominant narratives, expectations, and implications projected by different stakeholders (Section 2.1). The qualitative information obtained in the discourse and content analysis is then used to develop a causal loop diagram. This process aided in delivering an improved understanding of the potential effects on other systems (both positive and negative) (Section 2.2.). The causal loop diagram and the output from the discourse analysis were then combined with specific aspects of changes in the system, and system dynamics modeling (SDM) was performed. The modeling assessed the dynamic behavior and potential consequences (again both positive and negative) of electrification and displacement of biogas-based municipal transportation (see further details in Section 2.3). Furthermore, the SDM was also influenced by stakeholder input, which was provided through policy lab methodology to improve the understanding of the incentives and barriers for biogas displacement, and emerging (new) markets for biogas due to electrification (Section 2.4). This included a review of the political barriers and opportunities for alternative routes for biogas systems.

For this methodology, we take inspiration from the method of *quantitative story-telling*. Quantitative story-telling takes a neutral stance to inform decision making through a combination of qualitative and quantitative analyses, which according to Renner and Giampietro (2020, pg 2.), aims to "….check the quality of an elected story-telling and related *policy* narratives…..to test the plausibility." While this study does not take policy narratives only into account, but a more general view of the discourse enfolding, we include influences from (and to) other sectors. A depiction of the methodological outline of the project is provided in Figure 1 below, and further details are described in the following sub-sections.

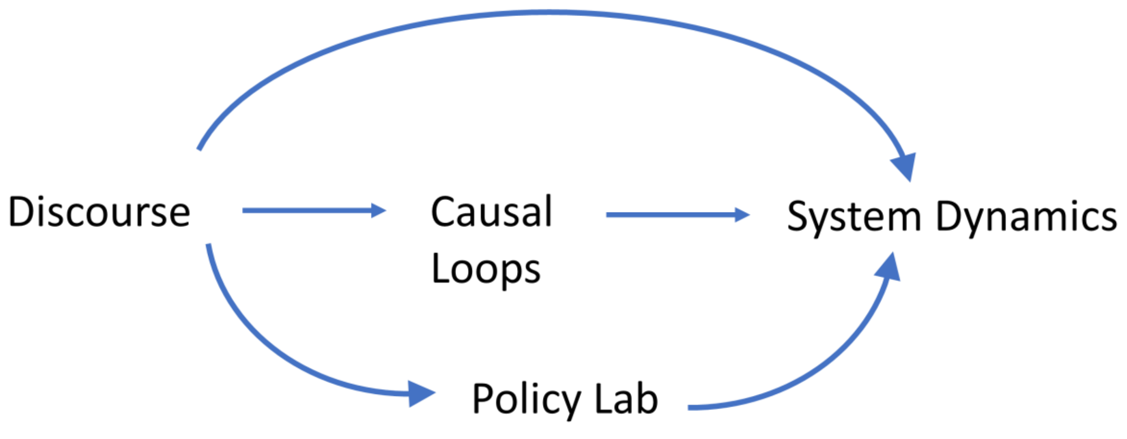

Figure 1: Graphic Representation of the Methodological Approach

2.1 DISCOURSE AND CONTENT ANALYSIS

Discourse analysis is a methodology used to examine the argumentative structure in documents and other written or spoken statements, where discourse is defined as a collection of ideas, concepts, and categories through which meaning is given to social and physical phenomenon, see e.g. Hajer (2006). We used the discourse analysis to identify common themes, futures, and important aspects to motivate biogas and electrification for public transportation systems. In order to address the aim of this study and provide input to the quantitative modeling, the following questions were developed to guide the analysis: 1) What is the role of biogas and electrification in the future?; 2) How are these motivated?

The discourse analysis was conducted by analyzing publicly available media to identify the narratives and expectations created for electrification and the role of biogas in the future by examining text-based, publicly available material. These included:

- News articles in leading newspapers
- Web-available transcripts from Swedish Television (SVT) and Radio Sweden (SR)
- Articles in technical and trade journals/magazines
- Branch organization reports
- Governmental propositions, and
- Previous studies

The latter included complementary documents and material which emerged from the previously outlined information. Articles included in the analysis were identified using the search phrases:

1. El+buss, Elbuss, Elfordon
2. Biogasbuss, biogas + buss + buss* + fordon + trafik
3. Gasbuss gas + buss.

Articles from the period 2015 to 2020 were included in the study. In total (n=231) news articles, (n=83) trade and branch journals, (n=13) independent reports, and (n=3) governmental documents were reviewed. Interviews (n=16) were also conducted with a selection of the biogas, electrification, and municipal transportation authorities from different regions in Sweden. These included e.g., Stockholm, Skåne, and Västra Götaland on the role of biogas and electrification in future transportation systems[1] Thereafter, an additional interview was added to develop further insights on the role of electrification and the future for electric transportation systems from an electrification expert, complementing the 'biogas-dominant' focus of the former interviews and validating many of the inputs for the discourse analysis on the role of electrification. All interviews were recorded and had varying duration (ca. 40-90 minutes).

An inductive approach was employed when reviewing the media, guided by the questions above. The written media, reports, and interviews were triangulated to form the main content in the analysis. This was done by highlighting themes and visions presented in the media to analyze the making

[1] The majority of these interviews were performed as semi-structured interviews during 2019 by Agnes Hagstroem in her Master Thesis which was used as a pre-study for this project.

of alternative futures. All material included was coded in the program NVivo version 12. We employed the concept of socio-technical imaginaries[2] to outline potential visions of futures, both contested and imagined, and themes emerging in the discourse analysis and how these are motivated (McNeil et al., 2017). Similar approaches have been conducted by a number of authors in the Science and Technology Studies literature, which helped to guide the analysis (see, e.g. Jasanoff and Kim, 2015; Lazarevic and Valve, 2017; Mutter, 2019a; Trencher and van der Heijden, 2019; Axen and Kurani, 2013; Butler et al., 2015; Rygaug and Toftaker, 2016; Sovacool, 2017; Mutter and Rohracher, 2021). This resulted in a series of major themes (nodes; n=9) generated while examining the collected data. These in turn enfolded subsidiary themes (subnodes; n= 67). A breakdown of the nodes employed in Nvivo is provided in Appendix 1, while further details on the themes are found in the results in subsequent text.

Thereafter, a deductive approach was then applied to identify indicators and aspects for environmental and socio-economic sustainability present in the media. This was done by analyzing the media and interviews highlighted above, primarily in the motivational descriptions of the impacts and benefits of the systems employing content analysis[3]. Similar approaches have been conducted to outline how media addresses sustainability for renewable energy, i.e. biofuels, see e.g. Lazarevic and Martin (2016).

The narratives and themes from the discourse analysis combined with the content analysis were then employed to outline behavior, critical aspects/indicators, and changes in the system over time to guide the subsequent development of causal loops diagrams and build up the quantitative model using system dynamics modeling; see Section 2.2 and 2.3 below for further details.

2.2 CAUSAL LOOP DIAGRAM

Given the emergent themes and future socio-technical imaginaries outlined in the discourse analysis, a causal loop diagram (CLD) was developed to outline potential consequences of changes incurred to a broader number of systems based on changes to the biogas fleet brought about by increased electrification. As such, it outlines the potential effects of this change on other systems or functions. These can be positive or negative in their ‘polarity’ to outline how a particular design or variable is affected by the change in another. Furthermore, changes in one system can also be both reinforcing or balancing between different systems, where reinforcing loops depict how a change in one system may compound in another, and balancing loops, in contrast, counter the changes in one direction with change in the opposite direction; a depiction of these is provided in Figure 2.

CLDs help to depict potential stories and identify the complexity, interrelationships, and structure of these. They provide a visual representation that can be used to develop modeling approaches and

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[2] Socio-technical imaginaries are defined as “…collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology” (Jasanoff and Kim, 2015)

[3] Content analysis is an efficient approach to search for and analyze phenomena that cannot be observed directly, including themes, words, and concepts within texts to understand their presence, relationships, and meaning (Krippendorff 2004; Kassarjian 1977).

communication the understanding of the system with others, in addition to identifying potential unintended direct and indirect environmental consequences of decisions and actions; see further details in Laurenti et al. (2016). The CLDs, which were based on the discourse analysis, aided in outlining affected systems and functions. This includes the variables which directly affect the systems and functions, which are used to outline their influence. As such, we use this as a base for our system dynamics model, where an increased complexity is also represented; see further details below.

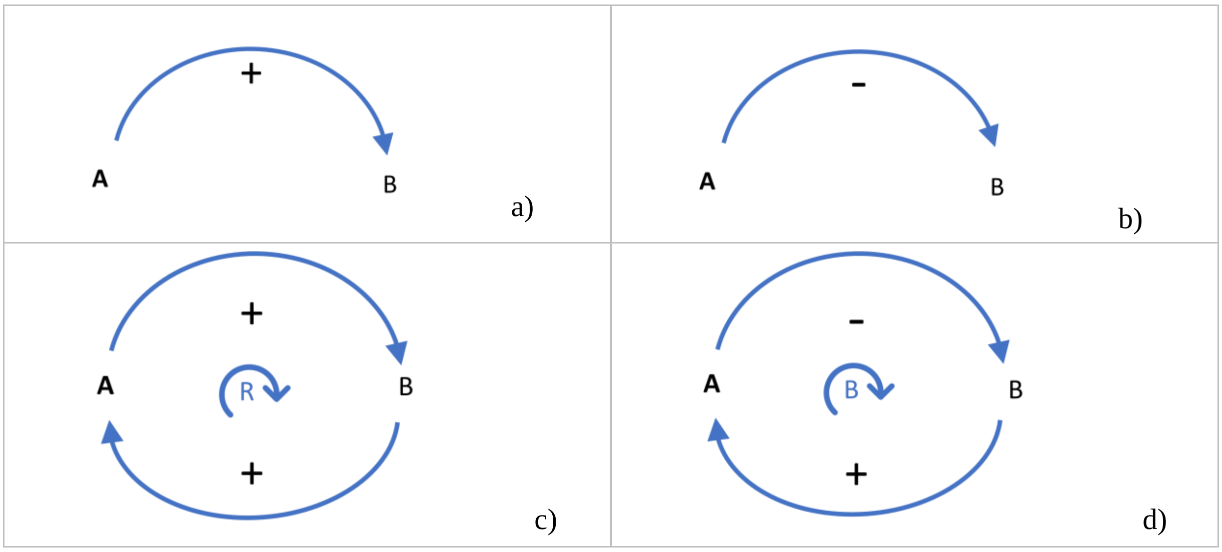


Figure 2: Causal loop overview showing the different polarity of flows and types of loops, including in a) A change in the state of A causes the state of B to change in the same direction; if A increases/ decreases, B increases/decreases; b) A change in the state of A causes the state of B to change in the opposite direction; if A increases/decreases, B decreases/increases; c) Reinforcing (positive) feedback. If the state of A changes, this causes a change in B that feeds back to amplify the change in A.; d) Balancing (negative) feedback. If the state of A changes, this causes a change in B that feeds back to negate or dampen the change in A.

2.3 SYSTEM DYNAMICS MODEL

As the decisions made in each system are not static, the variables are generally modeled as dynamic changes over time and can have implications during a set temporal period. A system dynamics model (SDM) was developed to outline and assess the changes from electrification for regional biogas systems and the resulting environmental and socio-economic implications this may have. This approach was chosen as it can study the non-linear behavior of complex systems over a time period using stocks, flows, feedback loops, and combine different functions and time delays. As such, it is a powerful tool to study potential narratives and changes in systems over time (Ghaffarzadegan et al., 2011; Richardson, 2011).

In order to assess the dynamic changes in the system, the SDM was developed to address several questions related to our aims and objectives. Namely, these questions review both direct and indirect changes to the immediate inner-city area and those affected systems due to changes in the bus fleet. As such, we address questions such as:

- What are the direct implications of electrification for the inner-city (e.g., emissions) (e.g. reviewing the direct change in airborne emissions in the inner-city)?

- How does this affect the current biogas system (e.g. addressing what will happen with the biogas)?
- What are the potential environmental and socio-economic implications of these changes in both direct and indirect terms (both regionally and nationally) (e.g. addressing the resulting change in direct (inner-city) and indirect (regional and national) emissions and socio-economic costs)?

2.3.1 Base Case

The SDM is based on Stockholm's inner-city bus fleet and the implications of electrification. The Stockholm bus fleet consists of 280 buses, using three different types of fuel: 142 biogas buses, one ethanol (ED95) bus, and 140 RME buses. Each vehicle drives an average of roughly 47 850 km per year. As previously outlined, this study is limited to the implications of electrifying and the displacement of the biogas buses only. The biogas buses are assumed to consume an average of 0.74 Nm^3 of biogas per km driven (RS, 2021), despite differences in their size and weights. The public transport system in Stockholm receives biogas from different suppliers, but this project assumes the biogas produced for the fleet originates from one wastewater treatment plant, namely Henriksdal wastewater plant in Stockholm, which produced roughly 126 GWh of raw biogas in 2019 from sewage sludge where it is upgraded for different uses (i.e., (>95% methane). In this study, the production of biogas is assumed to be constant over the period of study, supplying roughly 48 GWh per year[4]. See Table A2-1 in Appendix 2 for further details on the current bus fleet and assumptions based on input from Region Stockholm (RS, 2021)

2.3.2 Modeling Period

The model, which was developed employing Stella Architect 2.0.1 (ISEE, 2020), runs for 30 years (2020-2050) with time increments of one month (i.e. 360 timestamps). Over this period, the biogas bus fleet is phased out and replaced by electric buses. These buses use electricity produced away from the inner-city and thus also shift a share of the environmental impacts. To visualize this, the model makes a distinction between direct emissions (emissions occurring inside the inner-city) and indirect emissions (emissions occurring outside the inner-city). Furthermore, the model quantifies the socio-economic costs (i.e., damage costs due to the exposure) associated with these emissions (both direct and indirect). Other inclusions are noise and job creation (measured in full-time equivalents (FTEs)) dependent on the type of electric bus procured; see further details in subsequent sections.

It is assumed that biogas accumulates over time due to increased electrification, and a corresponding reduction in biogas. Therefore, alternative use for the biogas is assumed to take place once the biogas stock reaches a certain threshold (i.e.100 000 Nm^3 of biogas in stock). At that point, all biogas not consumed by the biogas buses is assumed to be upgraded through liquefaction to produce liquified biogas (LBG), to be used as an alternative to fossil equivalent fuels such as diesel in

[4] While it is not certain that all methane will originate from biogas, or from this one plant, this study makes this assumption for simplification in the model.

trucks and ferries outside the inner-city[5]. Once again, as these are outside the inner-city, the emissions from the trucks and ferries are considered indirect emissions over the thirty-year analysis in the model.

The electric buses are assumed to employ an average of 1.2 kWh/km as stipulated in several sources, e.g., Scania (2020) and Borén (2020) for urban driving. In order to model the implications of electric buses, it is assumed that these buses are primarily internationally sourced in the early years, and steadily increase with more domestically produced buses in later years of the model. The sections below outlined further details. For further details on the datasets employed and references to datasets, please see Appendix 2.

2.3.3 Indicators

The implications of electrification were assessed employing environmental and socio-economic indicators included in the system dynamic model. These included the following environmental indicators: greenhouse gas (GHG) emissions (measured in CO_2-eq), particulate matter (PM2.5), noise (dB), and nitrous oxide emissions (NOx). Socio-Economic indicators included jobs (measured in full-time equivalent jobs (FTE)) and socio-economic costs (SEK). All information and data for the different indicators are obtained from the literature unless otherwise stated. Further details are outlined in the subsequent text.

Environmental Indicators

The system includes multiple environmental indicators to assess the environmental implications from different parts of the system. These indicators are primarily related to life cycle emissions, such as operating the buses, burning of fuels[6], and new infrastructure. The model also tracks impacts due to the Swedish energy mix for electricity. All environmental impacts from different processes were derived from Ecoinvent (2020), other specific data for fuel emissions, both well-to-wheel (WTW) and tank-to-wheel (TTW) emissions, were derived from Hallberg et al. (2018). As previously outlined, these include GHG emissions, particulate matter, and nitrous oxide emissions. Furthermore, noise from vehicle use is also included for inner-city environments to outline the potential reduction in noise levels when comparing biogas and electric buses, with data obtained from Borén (2020) and Turcsany (2019).

Socio-Economic Indicators

Previous studies have outlined the socio-economic costs and benefits of replacing fossil fuels with biogas (Anderson et al., 2018 a,b). However, few studies have studied the socio-economic costs and benefits of electrification. As such, this study reviewed the potential socio-economic costs of this transition focusing on the direct implications in urban areas, in addition to the implications for

[5] It is uncertain if all biogas will be liquified as the biogas plants, of different sizes, may have varying capacity to install such systems. However, in this study, and based on the discourse, we have chosen to use this assumption.

[6] This includes the direct emissions from the combustion of biogas in the vehicles (modeled as direct emissions), and the emissions from other emissions of displaced by the biogas in the indirect impacts.

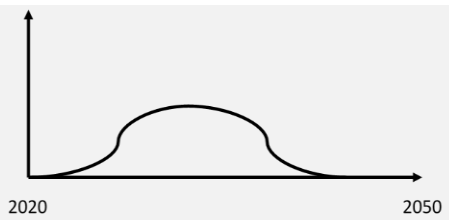
displacement effects of the biogas used in other sectors from expanding electrification, including e.g., displacement of diesel and natural gas use to biogas (LBG) in other sectors.

In order to assess the implications of changes in emissions related to the direct implications of replacing biogas bus traffic with electric buses, the socio-economic costs of the different systems were assessed. All data was taken from the socio-economic effects (i.e., costs) based on the ASEK 7.0 method developed by Trafikverket (2020). In this report, the negative impact of carbon dioxide and other air-borne emissions are outlined with resulting socio-economic costs. For airborne emissions, the logic behind these economic figures are that there are implications of exposure to emissions to humans and the environment. These result in responses to these emissions, i.e., damages to both humans and the environment, which result in associated costs measured in economic value. Further details are outlined in Trafikverket (2020)[7]. Indicators for exposure to the noise created by buses are also outlined, where the socio-economic effects of noise are also outlined, based on input from EcoTraffic (2015) and Trafikverket (2020). Data from emissions from the buses and burning of other fuels were used in the socio-economic indicators to calculate the damage costs. PM10 emissions were assumed to be similar between the biogas and electric buses, as also outlined in the ASEK 7.0 method; see Trafikverket (2020). Employment data to assess the FTE jobs was obtained from a number of sources, including Peck (2017) for biogas systems, EkoGen (2010), and WWF (2020) for bus-related employment, and related to renewable energy jobs (Kloos, 2020; Blyth et al., 2014).

2.3.4 Behavior and Functions

Behavior models for different variables were included to assess how they may dynamically change over the period modeled. These were, in some cases, constant, linear, or others representing different specific changes. For example, the increase in electric buses was not linear but was a direct result of procurement periods for biogas buses, resulting in a steady increase (step-wise) in electric buses with each procurement period. As this study was influenced heavily by the discourse, we used this information to develop the causal loops and the behavior of the different variables employed in the model. Through direct contact with different experts, input from workshops, and presenting initial results to the reference group, several of these were validated. Further details are outlined in Table 1 below, and further details are provided in Appendix 2.

Table A: Variables employed for the buses in the model and their dynamic behavior. Further behavior and variables employed in the model are available in Appendix 2.

Variable	Behavior	Description
Bus Procurement		The Bus Procurement is assumed to be a bell-structure. The procurement happens per month, since this is the timestep of the model.

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[7] Notably, the ASEK7.0 model has steadily increasing socio-economic costs for the emissions of these substances between 2017 and 2040 which were also included in our model. This is due primarily to inflation.

2.3.5 General Overview of the System Dynamic Model

Three building blocks make up the main tools used in system dynamics modeling. These tools are 1) stocks, 2) flows, and 3) converters, as illustrated in Figure 3. Each of these tools serves a specific function in the model, and a combination of these three can build intricate systems. Stocks can be seen as containers that collect a certain variable that flows into them, depicted as boxes in the subsequent figure. Flows fill or drain a stock, with the arrow showing whether the flow is going to or from, the stock. Converters hold constants or functions used in equations to convert variables since keeping unit consistency is of vital importance to the functioning of the model; depicted as a circle in the subsequent figure. All these building blocks are connected with connecters, i.e., arrows that indicate that certain stocks, flows, and converters have a relationship with each other (ISEE, 2020). A depiction of the 'main' stock-flow diagram used to model the direct impacts (which is vital for other indirect implication models) is depicted in Figure 3. A depiction of other models connected to the direct the main stock-flow diagram are included in Appendix 2.

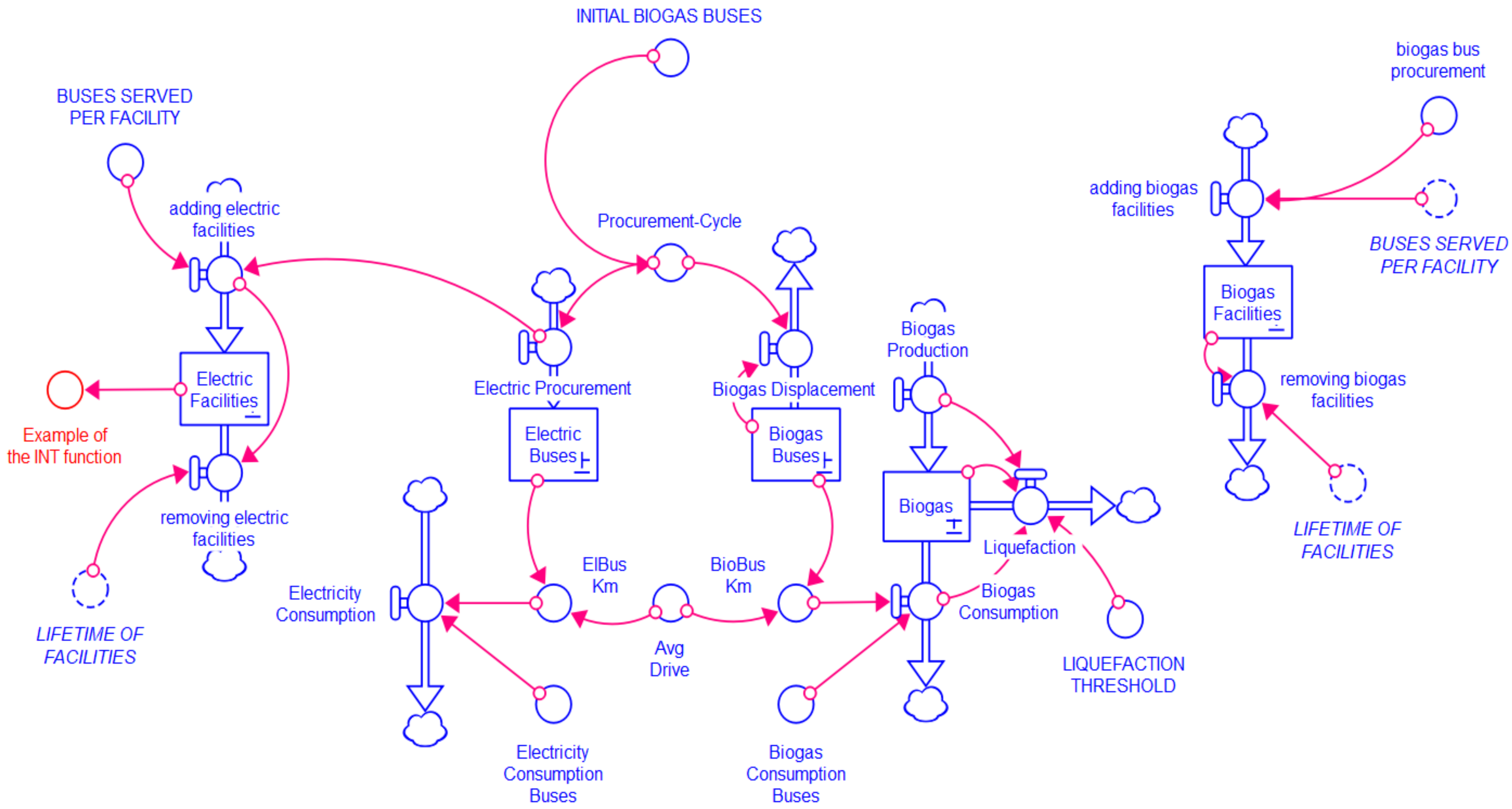

Figure 3: Inner-City Implications Model in the System Dynamics Model.

2.4 POLICY LAB

The project also focused on identifying the primary barriers and incentives that could be used to displace biogas use to other sectors, engaging actors, and discussing the policy alternatives. The Policy Lab methodology was employed, which is a co-creative development process where actors with different competencies develop and test ideas about new policies or rules to solve societal problems (Hinrichs-Krapels et al., 2020). Policy Lab is also used as a tool for innovation when problems require knowledge and perspectives from different angles and where solutions include policy changes. The focus, purpose, and methods within Policy Lab methodology are user-centered but can vary and be adapted to the problem area.

For the Policy Lab, we used a model inspired by design-thinking theory[8] which has been applied in internal projects at IVL (2020). The primary steps include, 1) Empathize with users (i.e., learning about the audience), 2) Define the problem (identifying the users' needs, 3) Ideate (generating ideas for design), 4) Prototype (turn ideas into concrete examples) and finally 5) Test (evaluating the design). A depiction of the steps in this method are shown below in Figure 4.

Figure 4: Depiction of Design-thinking methodology

In the Policy Lab for this case, we set a work-flow according to the model above:

1. Identification of relevant actors and key aspects (empathize)
2. Identification of the relevant documents to compile and analyze through a literature review (define)

[8] Cognitive scientist and Nobel Prize laureate Herbert A. Simon was the first to mention design thinking as a way of thinking in his 1969 book, *The Sciences of the Artificial*. Design-thinking combines the human, technological and strategic needs of our times and has progressively developed over the past decades to become the leading innovation methodology it is today.

3. Carry out a stakeholder workshop where the findings are discussed. In the workshop, all actors identified in Step 1 are invited to formulate their views (ideate)
4. Compile proposals and design communication to decision-makers, a 'Policy Brief' (prototype - implement)
5. Let the actors from the workshop react to the proposed Policy Brief, adjust it, and send it out to identified policy actors (test -evaluate)

For the study, a workshop was held including five persons from national policy actors, six persons from regional authorities, four persons from gas producers/suppliers or customers, and five researchers specializing in energy systems, systems analysis, and transportation; see Appendix 3 for more information on the stakeholders and individuals included in the workshop.

The results from the workshop and collected literature and information were developed into a policy brief. This was circulated with participants from the workshop for validation. The policy brief is outlined in the results section below and is a separate output of the project (also included in Appendix 3). Furthermore, it should also be noted that information and insights from the policy lab were also vital for the validation of a number of inputs to the modeling previously described.

3 RESULTS

The following sections outline the main results of the project. These include 1) outlining the main findings from the discourse analysis, 2) the development of the causal loop diagram, 3) the systems dynamic model, 4) outlining the direct and indirect implications of electrification, and 5) highlighting results from the policy lab on the political incentives and barriers for biogas displacement.

3.1 DISCOURSE AND CONTENT ANALYSIS

The analysis outlined several emerging themes and narratives being developed on the role of biogas and electrification. The following sections outline these converging and diverging narratives, providing an account of the different socio-technical imaginaries and expectations, themes, and indicators employed in the discourse on the interplay between biogas and electrification.

3.1.1 Emerging Socio-Technical Imaginaries

While subsequent sections outline different themes and details emerging in the discourse, firstly, this section provides an account of the socio-technical imaginaries outlined in the analyzed material as an overarching analysis of the imaginaries. These imaginaries included different 'potential futures' developed by stakeholders, both converging and diverging in their scope for the role of both biogas and electrification. These have been titled 1) 'Electrification of all inner-city fleets,' 2) 'Biogas and other clean-fuels in peri-urban and regional traffic,' 3) 'Biogas and Electric synergies,' and finally, 4) 'A continued role for biogas in the Swedish energy mix.' More information on these are outlined below.

Based on the narratives outlined above, and as the scope of the study was to assess the implications of electrification, the first narrative 'Electrification of all inner-city fleets,' was used as a base for further analysis below; also being most prevalent in the material reviewed. We also took into account the role of a continuous production and use of biogas, with displacement effects happening, as much of the material points to this option. Further details are outlined in the system causal loop diagram and system dynamic model methodology sections below.

Electrification of all inner-city fleets

Above all, our analysis points to the emerging socio-technical imaginary narrative of electrification of inner-city municipal transport systems as an ideal system for the future. In this narrative, the electrification of inner-city bus fleets is inevitable and will progress extensively nationwide. With this comes significant advancements in technology and large investments in municipal bus fleets. This was motivated by many stakeholders by the potential for electrification to reduce climate impacts, increase energy efficiency, contribute to less noise and cleaner inner-city environments, etc. Similar results have been highlighted in previous studies by Mutter (2019a, b). This prevalent theme in the media was also validated in the workshop held for the policy lab, despite an underlying apprehension amongst biogas proponents. There is less discussion in the material on the role of biogas in this future and what the effects are for incumbent systems, although displacement is often highlighted[9].

Biogas and other clean fuels in peri-urban and regional traffic

Another less prevalent theme is the role of internal combustion vehicles in regional (or peri-urban) traffic. Here, continued support for other renewables, e.g., biodiesel and biogas, are highlighted. However, many of these suggest ending fossil fuels, e.g., diesel, in these systems. As such, while electrification will develop inner-city areas, the focus for peri-urban and rural transport should increase the share of renewable and clean fuels.

Biogas-Electrification synergies

Despite the expectations created for electrification, a subtle yet more inclusive narrative was also present, where a role for biogas and electrification were seen to be partly complementary; see e.g., assertions in Energigas Sverige (2020). Furthermore, in this narrative, some of the media outlined a continued role for biogas as a viable option for waste management systems, with biogas playing a crucial role in nutrient recovery for an emerging circular economy. There was also mention of potential synergies that could be developed between biogas and electric infrastructure. This was highlighted as co-located charging infrastructure, integrating electric charging infrastructure with gas infrastructure during the transition to allow for biogas displacement to take place and ensure the societal benefits of biogas production continue.

A Continued Role for Biogas

It was also found in a number of reviewed media that there is a narrative on the future, with continued support, for biogas in Sweden's energy mix. Currently, there is a demand for biogas that exceeds its production. In this narrative, this demand will continue, and Swedish biogas producers will continue to reach the (now theoretical) potential of biogas production from different residual streams. Biogas will find a role, if not in inner-city transport, in other areas and continue providing inputs for future sustainable regions.

3.1.2 Emerging Themes

In addition the the narratives on 'potential futures' outlined above, roughly nine main themes emerged in the discourse analysis. These were developed into parent 'nodes' in the analysis software Nvivo and included a number of sub-nodes to highlight important aspects. Further details are provided in Appendix 1 on the coding. The main themes included Environmental Benefits, Socio-Economic Policy, Competition and Displacement, Societal Infrastructure, Scientific and Technical Achievement, Proponents, Systems and Components, Responsible Stewardship, and Justification, see Figure 5.

[9] In the system dynamic modeling, biogas systems are assumed to remain intact, and the biogas is displaced to other markets.

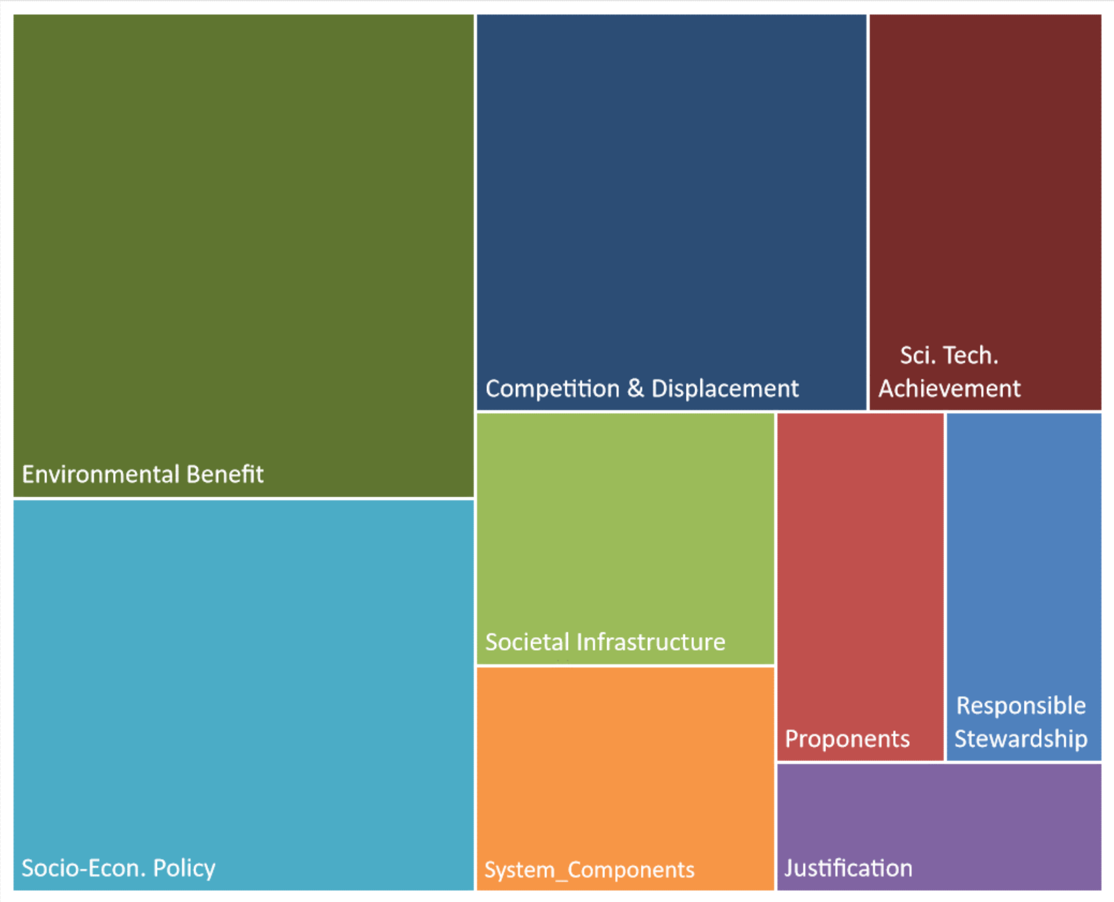

Figure 5: Treemap highlighting the main thematic areas from the discourse analysis to discuss the benefits of electrification, biogas or both. The size of the box indicates the relative proportion of the total.

From the analysis, it was found that many of the codes employed overlapped between these main themes. Therefore, in the subsections below, we outline thematic areas represented in the different themes above. These include 1) Competitive Framing of Electrification and Justification, 2) Expectations and Challenges, and further analysis to identify the indicators employed to address sustainability in 3) Sustainability and Indicators.

Competitive Framing and Justification

From the analysis, it was found that proponents of both systems use narratives to promote their benefits and competitive advantages. Often these are done by comparing to a counterfactual reference case, i.e., a fossil-fuel-based bus fleet, to motivate the technology. However, the incumbent systems are often renewable systems, e.g., in Stockholm where the majority of fuel for municipal transport is from renewable sources. These comparisons are often done by suggesting superior sustainability and benefits for society, e.g., reduced dependence on fossil fuels, reduced emissions, less noise, comfort, contributions to local and regional development, and the circular economy; see further stipulations in subsequent sections.

Electrification is primarily motivated by its contribution to reaching goals and targets for reduced emissions, clean and fossil-free transportation. Many of the articles included interviews with local politicians who motivated their choices and developments of municipal transportation systems in this direction. Many news articles highlight the developments as being the ‘largest’ and with information on the investment costs to add further emphasis on its importance. Furthermore, often the word ‘cool’ is used to promote the future developments and electrification of fleets. Additionally, investments in electric fleets was also suggested to lead to increased competition and job creation from Swedish vehicle producers and OEMs compared to current systems in place.

Different actors, primarily biogas proponents, have been more wary and vocal of electrification due in part to a direct threat on their market base. The potential limitations of electrification are often outlined, often pointing out the electricity mix as an important part in the fossil-free claims and carbon-neutrality of electrification; see e.g., recent assertions questioning the electrification imaginary by Eklund (2021) and also similar findings in Mutter (2019a).

There are also a large material base proposing the benefits and value of biogas systems. Biogas systems are often suggested to provide large socio-economic benefits, though many of the stakeholders outlining these also recognized the difficulty in assessing these benefits through qualitative and quantitative methods. A number of studies and material outline the benefits of biogas compared to fossil fuels, but rarely are these systems compared to electrification other than stating that inherent benefits may be lost from the competition with electrification systems.

Expectations and Challenges

Included in a number of the main themes coded, and also highlighted in the socio-technical imaginaries outlined above, are a number of expectations and challenges on the development, both new and current systems, for both electrification and biogas systems. As previously highlighted, the discourse employed for electrification is primarily positive, outlining many expectations of an electrified municipal transport system. Expectations generally revolve around technological developments and steady improvements. Much optimism is provided in the discourse on the potential for electrification, both now and in the future. However, some criticism has also been raised by a number of stakeholders, both in academic and public settings. A number of studies identify the challenges for developing charging stations, and above all, meeting electric capacity challenges, which are currently becoming increasingly problematic. An important aspect to consider is the driving range of the electric buses, which is a major obstacle to overcome, highlighted by a number of proponents and critics of electrification. Electric systems are highlighted as being sensitive to the electric mix employed. Furthermore, inner-city buses serve large numbers of travelers, and in many bus routes, this will require larger articulated busses which are only recently coming to the market.

A large number of studies also indicate the potential of biogas from different residual streams in order to valorize organic wastes further. It is expected that biogas markets will continue to increase, despite electrification by a number of sources. Stockholm was often pointed out as having a less than optimal food waste handling system, being one of the worst in Sweden. This was framed both as a challenge and an opportunity to develop systems to handle this large share of food waste (e.g., in the Högdalen biogas plant), creating a large new market for biogas. Furthermore, in several cases, electrification proponents were optimistic of the synergies with biogas, suggesting the displacement of biogas to regional transport, industry, and heavy-duty vehicles. This was found to be important in the development of more fossil-free industries, with many of the ‘fossil-free roadmaps’ outlining biogas as an important addition to reduce fossil fuel consumption. Notable areas for its use are in industry, sea transport, and heavy-duty vehicles to replace natural gas and diesel as energy carriers. However, in the Stockholm system, and despite the general optimism created for electrification, local political documents outline the transition from biogas to electrification through new procurements to take place in the coming years. As such, the contracts for biogas buses will end, successively affecting small fleets of biogas buses in a step-wise function in the coming years (i.e., after 2024); also analyzed in the system dynamics model.

Sustainability Indicators for Motivating Systems

As also previously highlighted, a number of sustainable future imaginaries are highlighted and implied for biogas and electrification systems. From further analysis of the content, we identified several aspects and indicators employed as motivations for these sustainable future imaginaries and comparisons of electrification with incumbent and fossil-fuel transportation systems. These gave input to the assessments in the system dynamic model to understand the potential direct and indirect implications often discussed but infrequently assessed.

A large number of environmental indicators are employed to highlight the benefits of electrification and biogas systems. These include indicators such as clean/particle-free environments, noise, carbon dioxide or GHG emissions, energy efficiency, the degree of fossil-free energy, indirect benefits, and challenges; respectively, in that order, see also Figure 6. While primarily environmental indicators were outlined, few socio-economic indicators were discussed. Those studies which did outline socio-economic implications were related mainly to the waste management system benefits of biogas systems. Furthermore, comfort and traveler experience were also discussed in several articles to provide a positive attribute for electric buses. In several of the articles reviewed in the material, the negative environmental and social impacts of battery production were discussed, highlighting the upstream consequences of cobalt extraction. Finally, as a number of studies outlined, while biogas is often highlighted to contribute to many regional resource-efficiency and ancillary benefits, these are rarely highlighted and often not quantified.

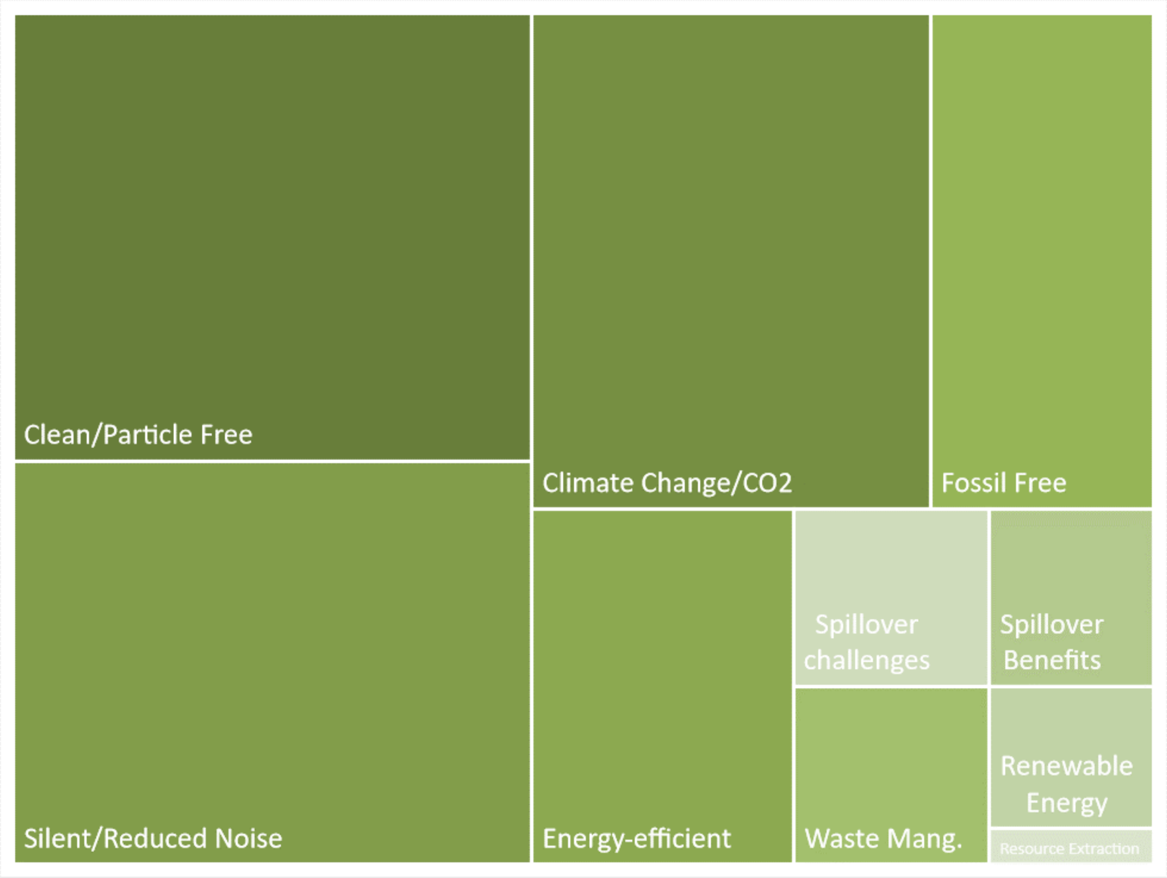

Figure 6: Treemap highlighting the indicators identified in the discourse analysis (Environmental benefit node) to discuss the benefits of electrification, biogas or both. The size of the box indicates the relative proportion of the total.

3.2 CAUSAL LOOP

In order to aid in the development of the system dynamics model, the cause-effects related to increased electrification were mapped. This included how the electrification of inner-city buses would impact other systems. We limited the causal loop to direct and indirect consequences due to changes in the increase in electrification and changes to the use of biogas in the municipal transportation sector, i.e., primarily related to the first narrative described above (*Electrification of all inner-city fleets*). The system dynamics model below is also limited to studying the aforementioned narrative with displacement effects for biogas. While further scenarios could have been included, once again, this was chosen due to the prevalence of this narrative in the discourse.

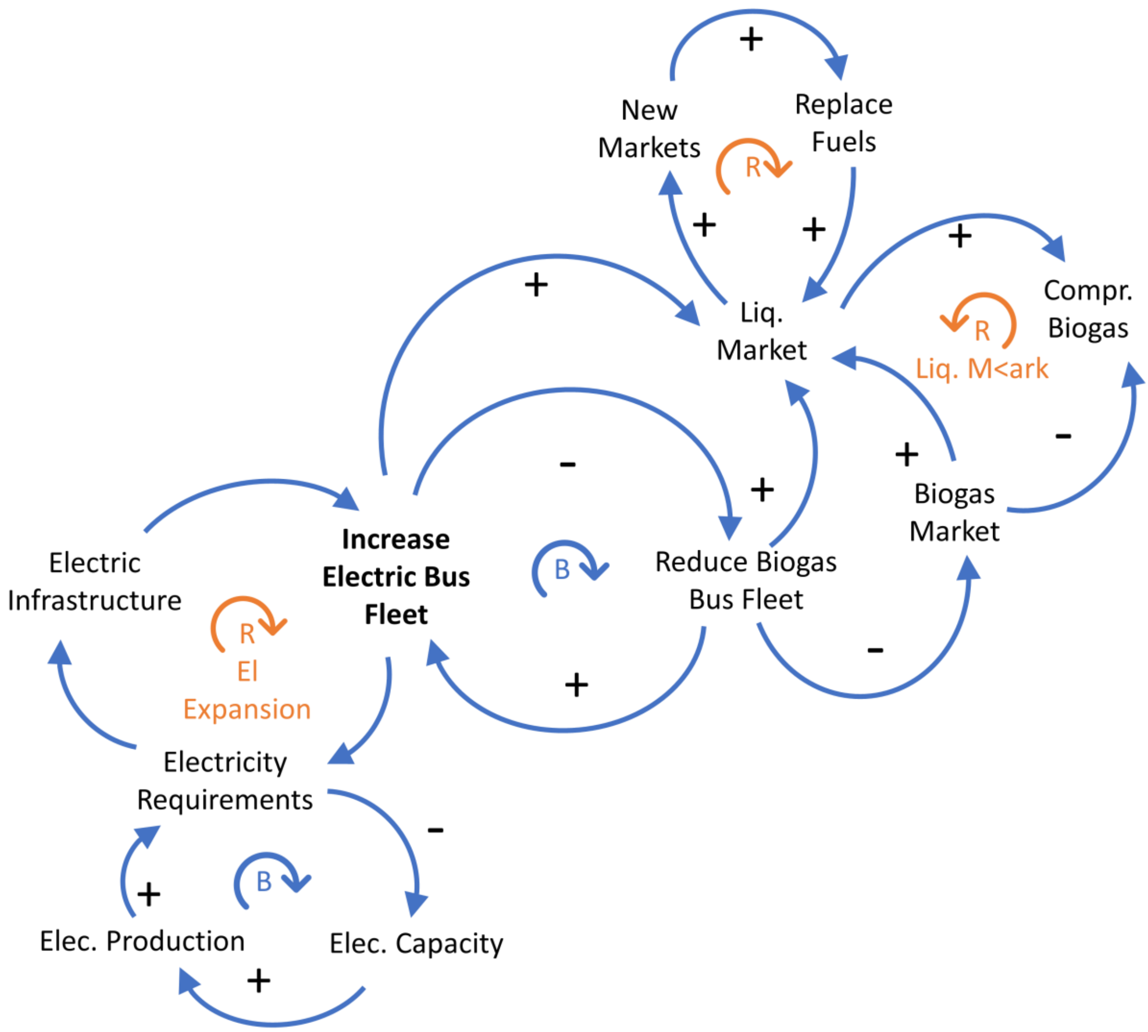

Figure 7: Causal Loop Diagram for Changes due to Increased Electrification. R-Refers to reinforcing loops, and B-refers to balancing loops.

From our analyses in the discourse analysis, as outlined in the aforementioned text, it was found that electrification of buses in the inner-city could have a number of consequences that may affect the bus fleet, energy carriers employed, and have indirect effects on their capacity as illustrated in the causal loop diagram in Figure 7. First off, increasing the inner-city electric bus fleet would negatively affect the biogas bus fleet (shown with a balancing loop). This would also lead to increased demand for electricity and electric charging infrastructure and capacity. Increasing electrification was found to influence the compressed biogas market locally negatively. This would potentially lead to displacing the biogas to other markets, which was suggested to lead to increased liquefication of the biogas (LBG) to reach other markets. This, although not outlined above, can include LBG used for heavy-duty vehicles, industry, and ferries. The causal loop diagram does not show all indirect changes and influential factors which may affect the uptake or use of electrification and biogas, respectively, e.g., political decisions, pricing of competing fuels, etc. However, some influential factors, such as procurement milestones, are included in the system dynamics model.

3.3 SYSTEM DYNAMICS OF THE BIOGAS-ELECTRICITY INTERPLAY

The following sub-sections outline the overall dynamics in the model for important parameters such as the number of buses, biogas, and electricity employment, and after that outline the environmental and socio-economic implications.

3.3.1 Illustrating Dynamic Changes

Figure 8 below shows the procurement cycle implemented in this model over the course of 30 years.

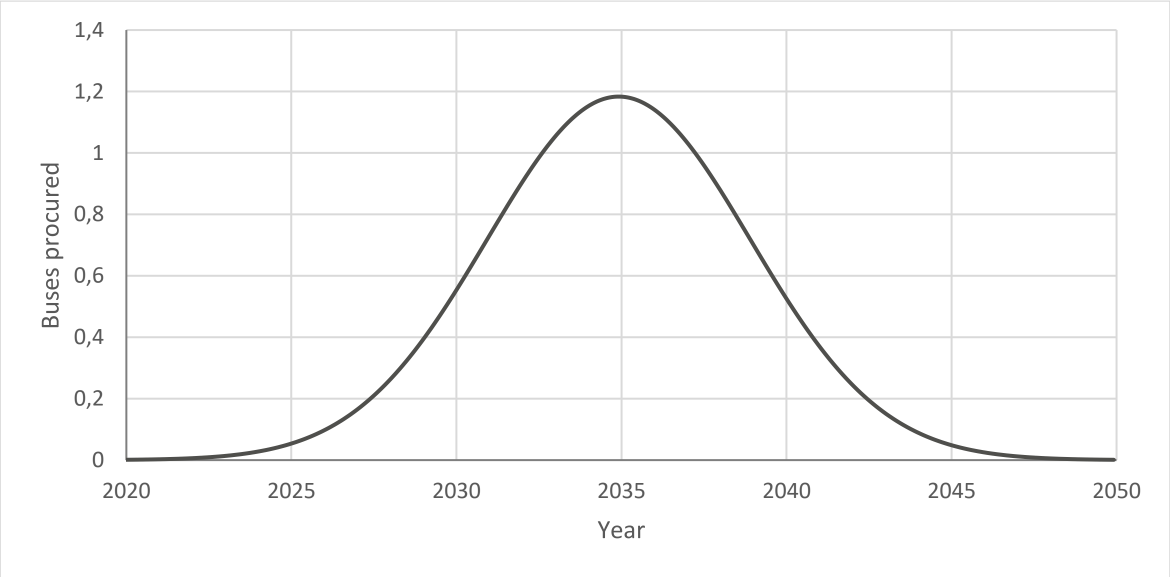

Figure 8: Procurement of electric buses during the studied period.

The procurement of electric buses and subsequent replacement of biogas buses was modeled as a bell curve, where procurement is slowly ramped up towards 2035, after which it decreases until all biogas buses are replaced. While this is also introduced in the method section above, it is important to note as many of the parameters in this study are dependent upon the share of electric and biogas buses. As such, Figure 9 illustrates how the procurement cycle influences the bus fleet over time[10].

[10] The total size of the bus fleet is kept the same over time at roughly 140 buses.

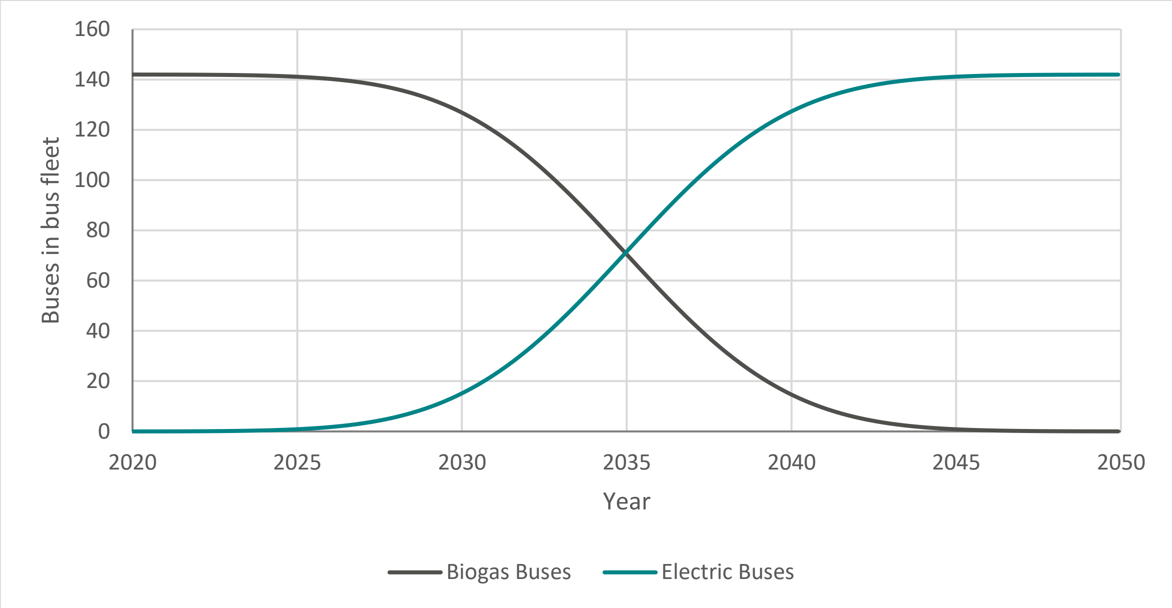

Figure 9: Biogas and electric buses in total numbers during the studied period.

With the change in bus fleet, a decrease in biogas consumption by the bus fleet ensues. As a consequence, an introduction of electric buses and slow increase in their numbers will lead to an increase of electricity consumption as depicted in Figure 10.

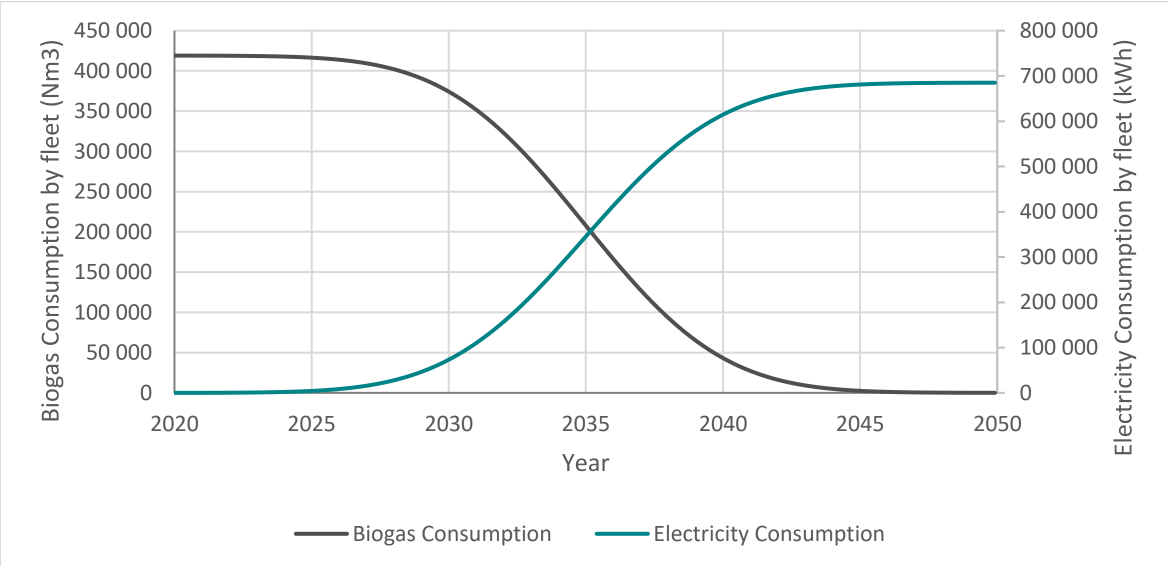

Figure 10: Comparison of inner-city fleet consumption of biogas and electricity during the studied period, showing Nm3 of biogas consumed and kWh of electricity employed.

3.3.2 Environmental Implications

The model includes CO_2-eq, NO_x, and PM2.5 emissions for direct emissions (i.e., inner-city emissions), in addition to indirect implications of the displacement of fuels used in vehicles outside the inner-city (e.g. diesel in heavy-duty vehicles and LNG and Marine Diesel in the maritime sector). Noise is also outlined for inner-city environments but was not quantified for indirect implications.

GHG emissions

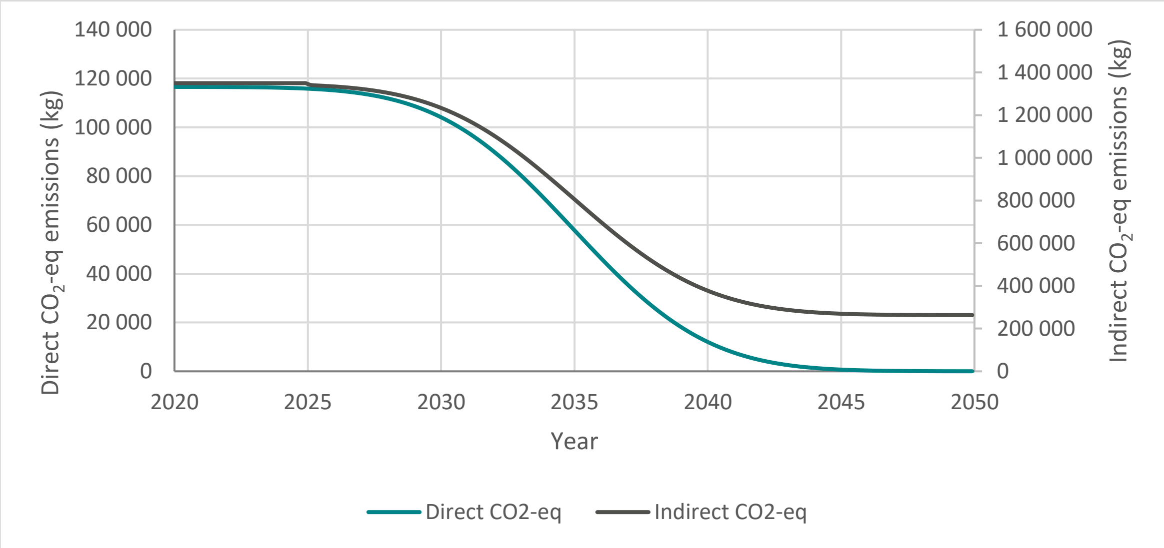

Figure 11: Comparison of Direct and Indirect GHG emissions. Direct GHG emissions uses the left y-axis, while Indirect GHG emissions are shown on the right y-axis. All emissions are measured in kg of CO_2-eq.

Figure 11 illustrates the direct and indirect emissions of greenhouse gases (GHG) (i.e., CO_2-eq). The left axis tracks inner-city emissions, while the right axis tracks indirect emissions in equivalent kilograms of CO_2-eq. Again, direct refers to CO_2-eq emissions produced within the inner-city (e.g., by direct emissions from buses), while indirect refers to CO_2-eq emissions in peri-urban and rural areas (e.g., the combustion of fuels in regional heavy-duty vehicles). As illustrated, a decrease in both direct and indirect GHG emissions can be seen. For the direct emissions, this is due primarily to the fact that the electric buses produce no CO_2-eq in the inner-city, where this is reduced to zero. The displaced biogas is converted to LBG and used to displace diesel, which has significantly higher CO_2-eq/kWh emissions than LBG, resulting in a decrease outside the inner-city, as illustrated in the reduction in indirect emissions. There is a slight increase of CO_2-eq due to increased electricity production, but given the order of magnitude of the indirect GHG emissions, this is not visible in the figure. It must be noted that the direct and indirect GHG emissions share the same graph to demonstrate the similar curve, but that the two curves use different axes: the left y-axis for direct emissions and the right y-axis for indirect emissions. The indirect emissions are roughly ten-fold that of the direct GHG emissions.

Fine Particles (PM2.5)

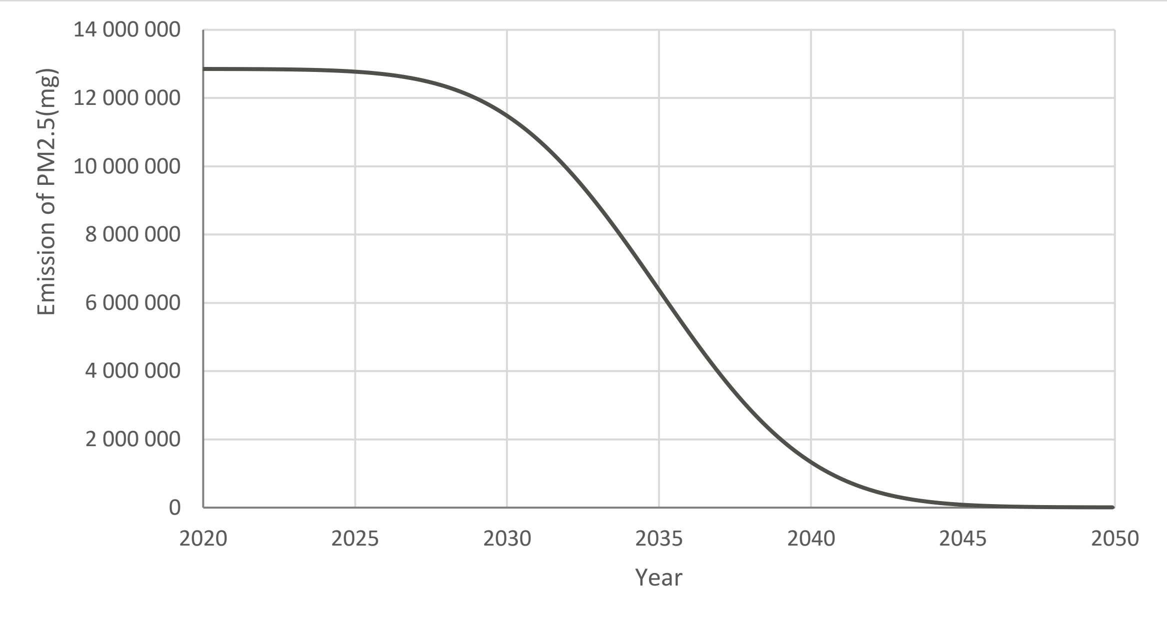

Figure 12: PM2.5 emissions within the inner-city (measured in mg of PM2.5)

Figure 12 shows a clear decline of PM2.5 emissions in the inner-city due to an increase in electric buses and less biogas combusted. It is important to note that the model only includes tailpipe PM2.5 emissions and does not include PM10 emissions, i.e., particulate matter from tires, brakes, and any other moving parts which remain in both vehicles but may vary slightly.

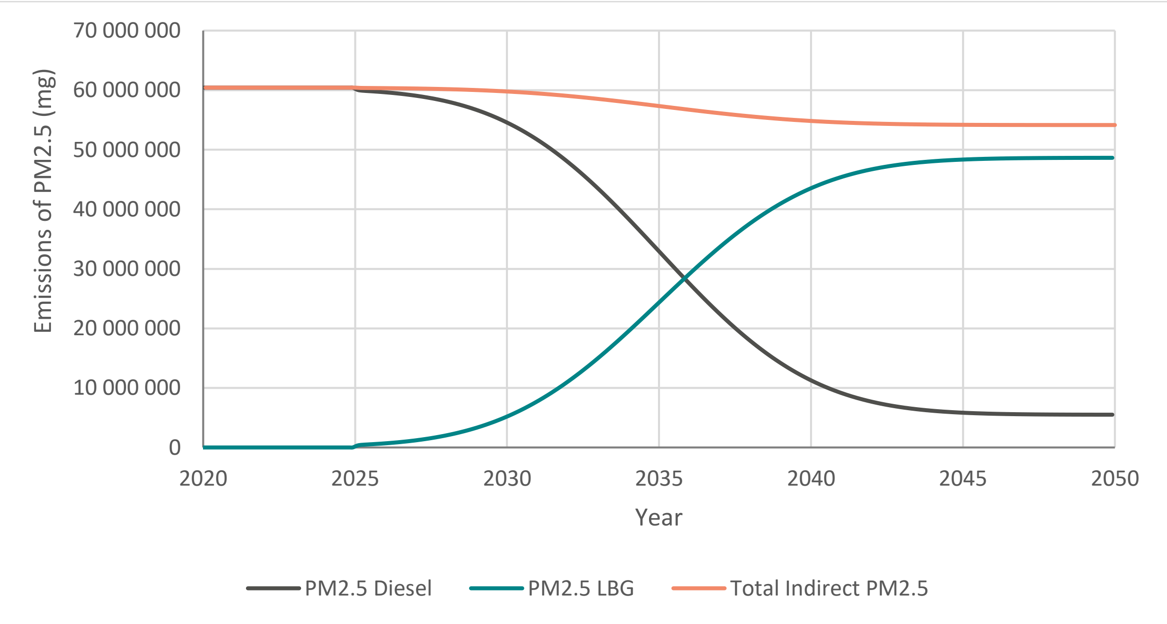

Figure 13: Indirect PM2.5 emissions

Furthermore, the indirect PM2.5 emissions show a similar trend, i.e., a reduction, primarily through LBG displacing diesel. As illustrated, the PM2.5 emissions for diesel combustion versus LBG show an overall trend toward reduction over time. As such, the total PM2.5 emissions reduce slightly, i.e., by roughly 11%.

Nitrous Oxide Emissions (NOx)

Figure 14 below shows the NO_x emissions in the inner-city over time due to biogas displacement and an increase in electric buses. As illustrated, these slowly go toward zero as more electric buses are included in the city.

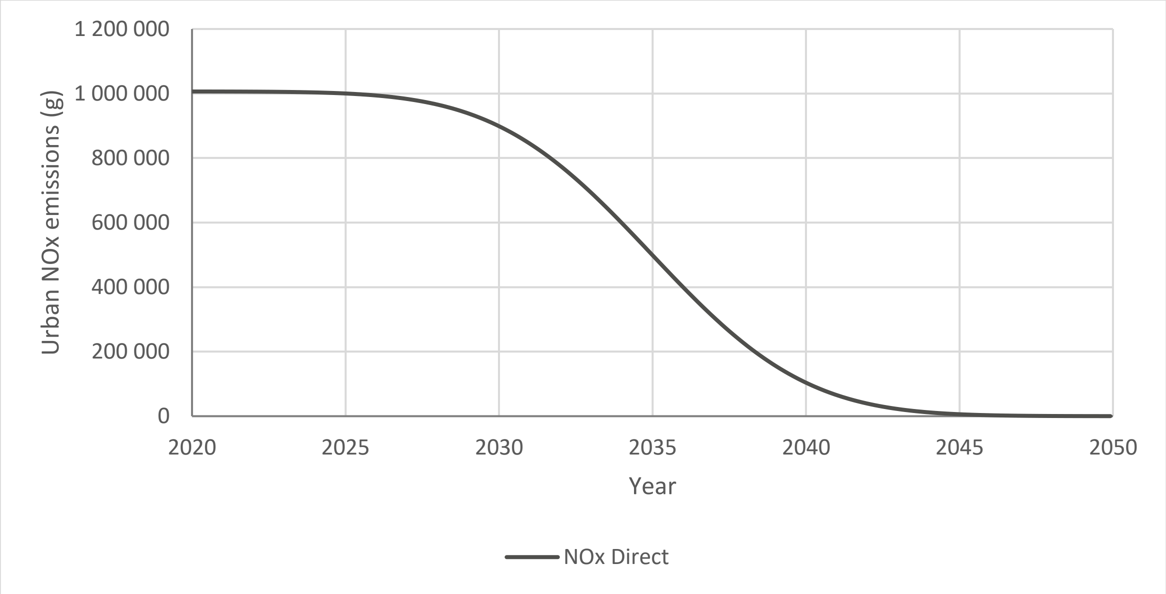

Figure 14: NOx emissions in the inner city over time (measured in g NOx)

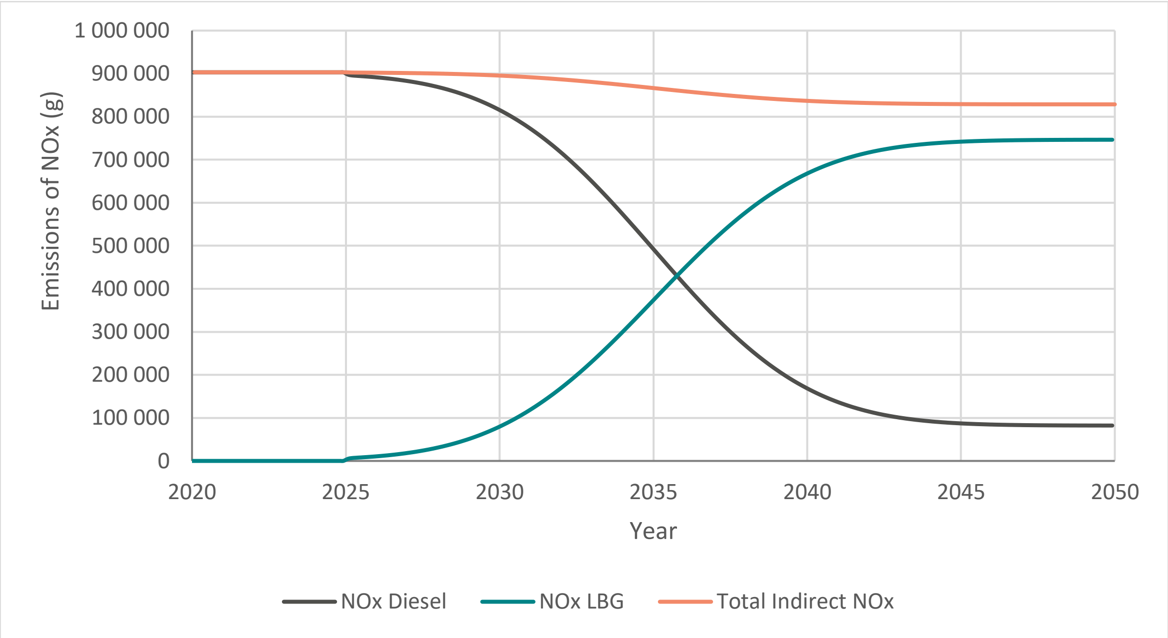

Figure 15: Indirect NOx emissions from fuels (measured in g NOx)

Indirect emissions of NOx also show a similar trend, where displacement of diesel by LBG reduces the overall NOx production, reducing NOx emissions over time through the use of LBG by roughly 9% compared to the original value, see Figure 15.

Noise

As Figure 16 illustrates, the average noise produced by a bus at a given point in the inner-city does not have a large effect. Due to the lack of a combustion engine, the electric buses show a slight decrease in noise pollution, though the difference is small, where a decrease of roughly 6 dB for electric buses are seen.

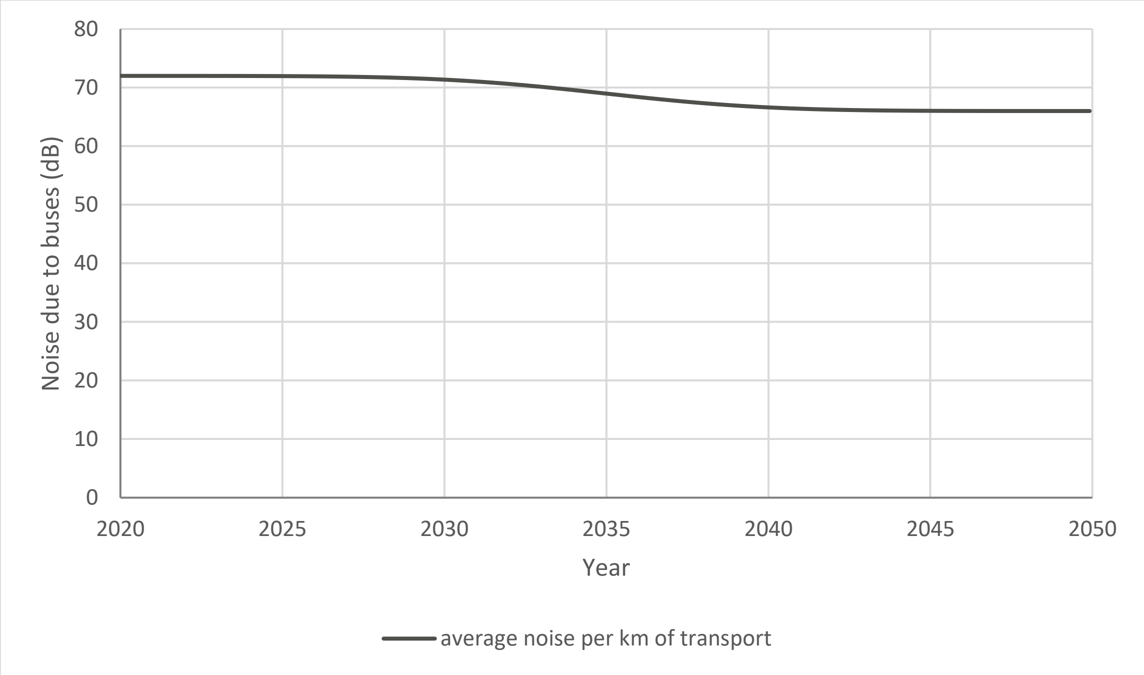

Figure 16: Average noise per km during the period of study (measured in decibels per km).

3.3.3 Socio-economic impacts

The socio-economic costs rely heavily upon the modeled emissions of NOx, PM2.5, GHG emissions and noise. Figure 17 shows that the societal costs mainly result from the direct PM2.5 and CO_2 emissions. All direct emissions decrease over time, with CO_2-eq and PM2.5 and showing the largest change. Once again, it should be noted that these are tailpipe emissions only and that the study excludes other forms of particulate matter, e.g., PM10, which would remain for electric buses regardless of the fuel.

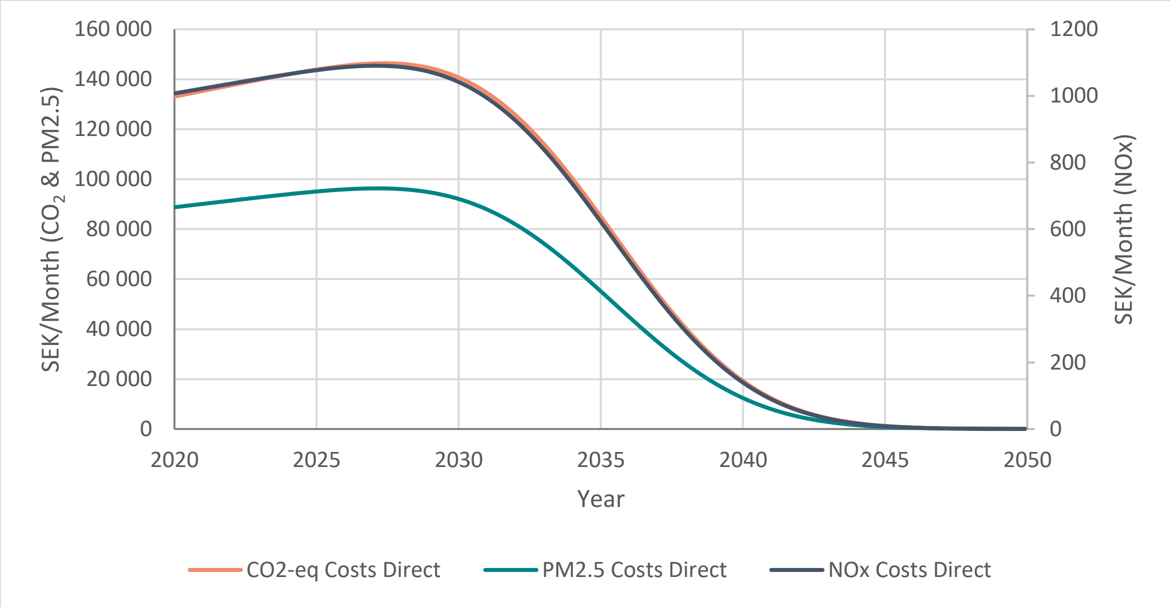

Figure 17: Socio-economic costs per month from direct PM2.5 and CO_2-eq emissions as a result of biogas displacement.

The indirect costs show a different set of curves, with NO_x and PM2.5 showing an increase in costs and CO_2-eq showing a decrease at the time the LBG displaces the diesel; see Figure 18. At the start and the end of the timeframe, however, there is an increase in costs related to GHG emissions (CO_2-eq). This is due to an increase in electricity production for the bus fleet in the urban center. Furthermore, the model includes the extrapolation of costs due to emissions as a result of inflation. For this reason, costs go up by around 0.12% and 0.14% per month. Further details on the modeled increase can be found in Appendix 2, which includes all functions and equations through which the costs per type of emission increases over the period.

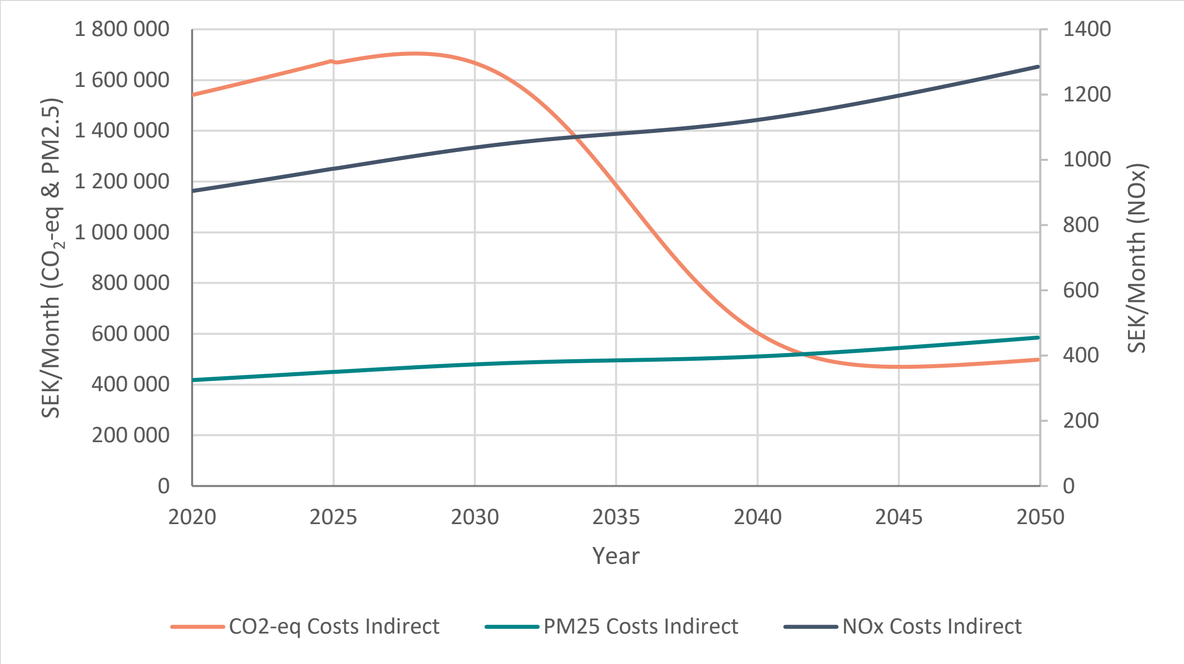

Figure 18: Socio-economic costs per month as a result of biogas displacement (NO_x Costs included on the right y-axis).

Employment (FTE)

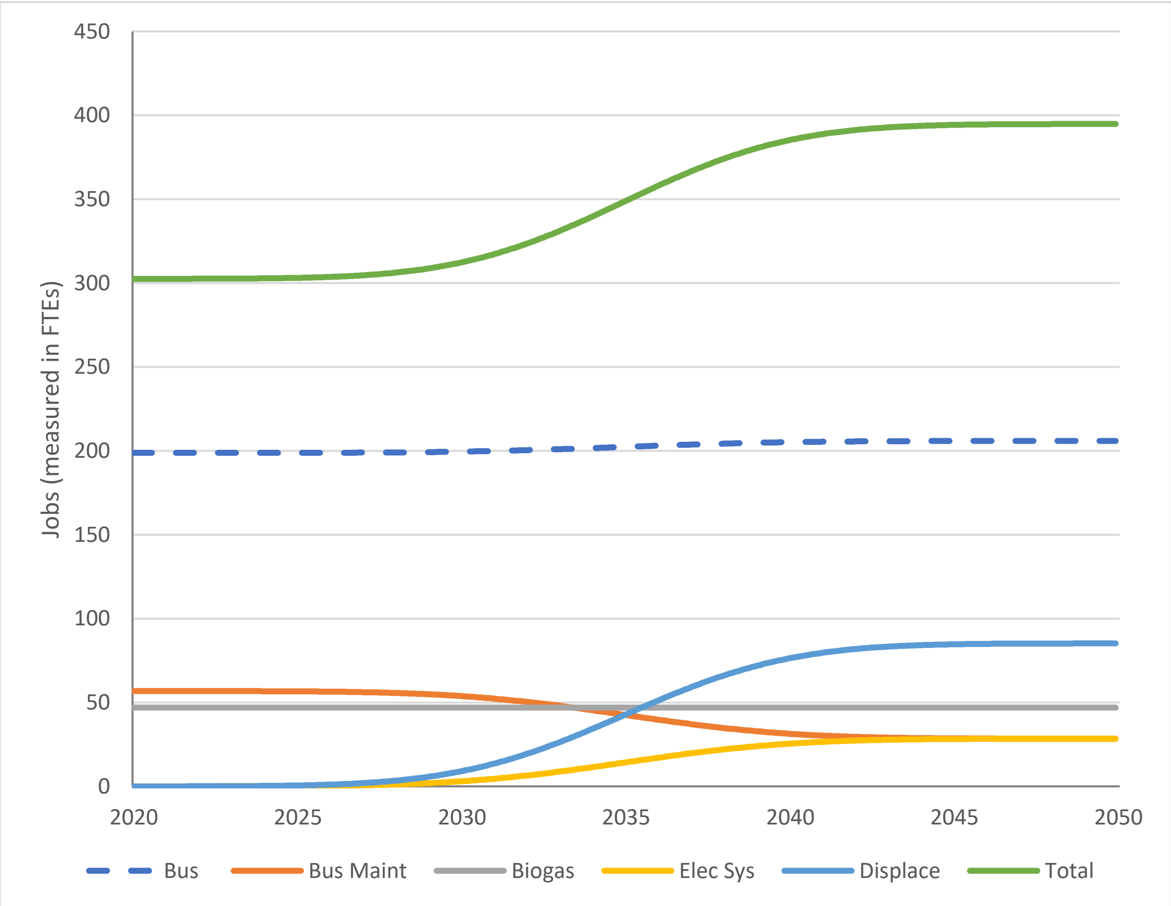

Figure 19: Implications on employment in the biogas and electrification sectors during the studied period (shown in FTEs) during the 30 years.

Figure 19 illustrates the implications of electrification on employment within the biogas and electrification sectors. Figure 20 provides further details, reviewing how, e.g., the maintenance and other bus-related jobs, for employment change with a shift from biogas to electric buses. As the results suggest, the overall jobs within the studied system increase over the period. Of note, and as outlined in Appendix 2, it is assumed that the jobs associated with producing roughly 48 GWh of biogas remain the same throughout the period. However, as the biogas is shifted to other sectors, the number of FTE jobs may increase for heavy-duty vehicles (with new vehicles employing LBG), in addition for electric buses and electric capacity. This is assumed to take place in the renewables market as Sweden transitions to a fossil-free energy system. The results also illustrate that the FTEs may change for the different buses, as biogas buses (being ICE engines) require more maintenance, while the maintenance of electric buses have lower FTE jobs. Furthermore, and as outlined, while the total employment is expected to grow, this is dampened by the fact that it is assumed that not all vehicles will be procured from domestic producers.

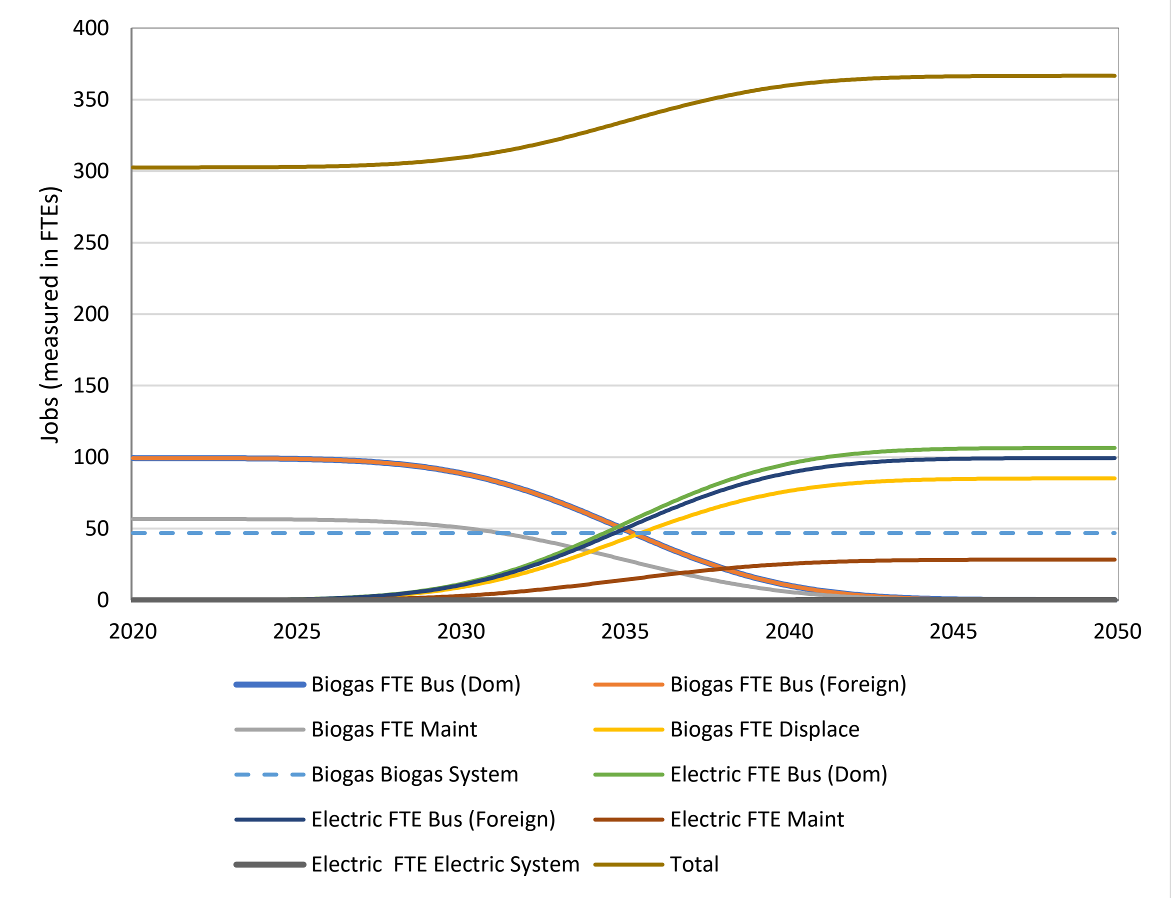

Figure 20: Details on the shift in jobs for biogas and electric related segments (shown in FTEs) during the 30 year period, illustrating further details to complement Figure 19.

3.3.4 Alternative Displacement

In order to examine alternative forms of displacement, the data for emissions per kWh for the displaced biogas to other markets includes displaced diesel (heavy-duty vehicles) or marine diesel and LNG (shipping).

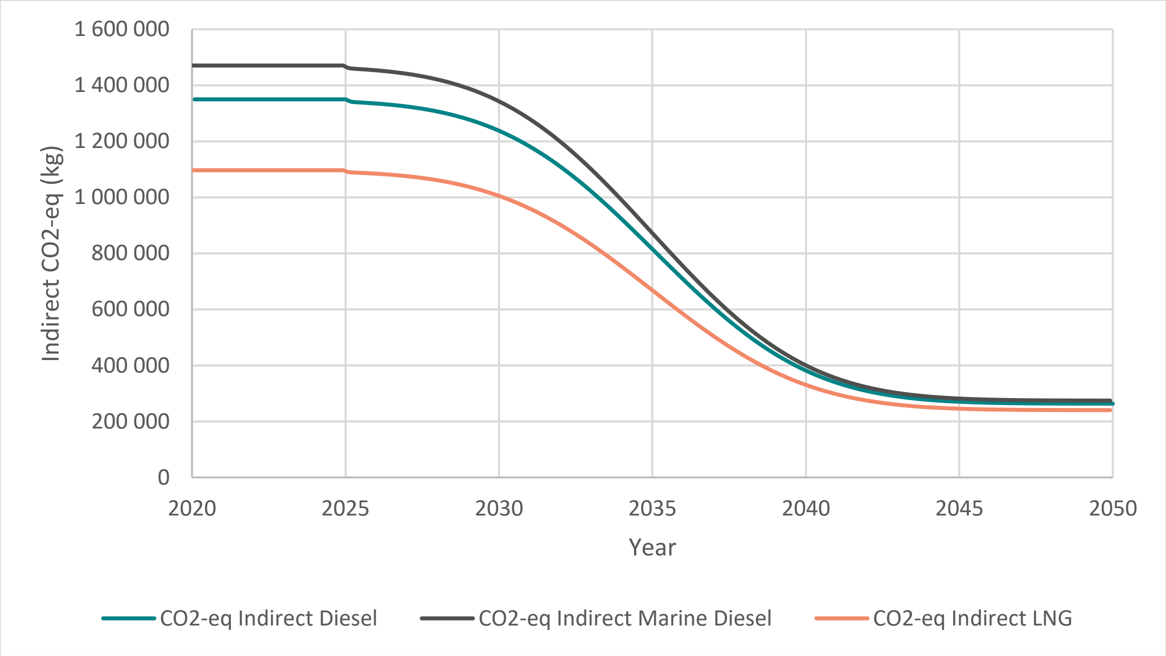

Figure 21: Comparison of GHG emissions (measured in kg CO2-eq) due to displacement of various fuels with biogas.

Figure 21 shows the difference in CO_2-eq emissions for these three fuels due to replacement by LBG. As illustrated, all displaced fuels assessed show similar reductions in emissions during the studied period. However, marine diesel was found to have the largest change, being the fuel that shows the largest difference between the start and the end of the modeled period. Furthermore, Figure 22 illustrates the difference in PM2.5 emissions between the different displacement scenarios. As illustrated, the largest reductions can be seen for displacing LBG to replace marine diesel fuel. Figure 22 does not show the results for diesel as the results for PM2.5 emissions marine diesel and diesel were similar and thus overlap; as such, diesel is excluded from the figure.

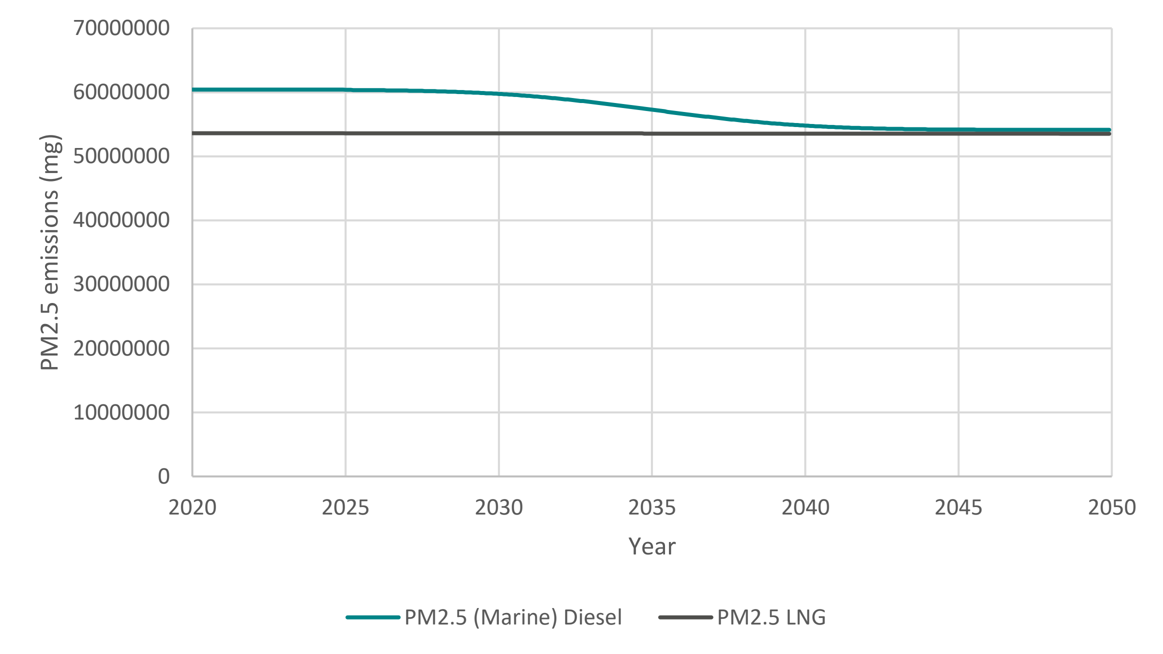

Figure 22: PM2.5 emissions in two different displacement scenarios during the studied 30 year period (measured in mg PM2.5 emissions)political drivers and barriers to 'new' biogas markets.

3.4 POLICY LAB

The main output from the Policy Lab was the development of a Policy Brief. This document (in Swedish) provides recommendations on policy incentives that could displace biogas to sectors where there is under-usage and potential for expansion. These recommendations include a more focused view on the role of biogas and how to support potential displacement to ensure it remains a viable solution. The policy brief included the following main points (see also Appendix 3).

1) **It is important that the EU regulations are set with biogas in mind so that climate benefits are rewarded and that the broad benefits of biogas can be taken into account,** e.g., climate regulations for heavy-duty vehicles should not only take into account what comes out of the exhaust pipe (so-called tail pipe emissions) but also take into account to the climate benefits from a life cycle perspective for the fuel. Furthermore, it is also important that future rules regarding the so-called taxonomy steer towards the broad benefits of biogas being able to be credited.

2) **Create incentives for benefits other than climate.** Incentives are needed for the efficient management of resources from waste and for the return of nutrients through the use of biofertilizers. Incentives can be created by developing targets or requirements for the use of biofertilizer in combination with taxes and subsidies that favor disposal and cycles or make it more difficult and expensive with non-resource efficient flows, for example, by compensating for recycled plant nutrients returned to productive land and taxes on fertilizers.

3) **Allow use of biogas when incentives are developed for negative climate emissions.** If 'green' carbon dioxide is collected at biogas upgrading plants, this could be of interest for storage or other use that produces negative climate emissions. Biogas production is also an important tool for disposing of methane that would otherwise leak into the air from, for example, storage and handling of manure.

4) **Supplementary incentives are needed for more markets to develop for biogas.** Through liquefaction of biogas, the market for biogas in heavy-duty vehicle transportand shipping is expanded, but also towards industry. The development of electrification and hydrogen is ongoing at the same time. To enable more markets for biogas, both road transport and shipping should be seen as areas where biogas can play a significant role in the future. Biogas is also interesting for industry as an alternative to fossil-based gas. However, additional incentives are needed for the willingness to pay in international shipping and industry to match the biogas' production costs.

5) **Private and public customers' demand for freight transport using biogas should be stimulated** as part of the support currently provided for, among other things, the production and distribution of liquefied biogas (LBG). This can be supported by targeted procurement support and help to spread knowledge among private and public transport buyers, for example, through information on the definition of "environmental truck" in the regulation on the climate premium for certain vehicles.

6) **Coordinate reforms to support a transition to new markets without major declines in demand.** New markets for biogas should be developed before the public transport market shrinks to avoid stagnation. Biogas players need to receive adequate notice in order to be able to adjust and adapt infrastructure.

7) **National government needs to be prepared to act on the basis of the development of imports and exports of biogas.** It is important that national government and authorities closely monitor how support systems are used for the production and use of biogas in neighboring countries and promote biogas' societal benefits in Sweden while maintaining healthy competition.

8) **National government should pay attention to regional biogas development.** Government should therefore request that all regional development plans include analyses of the development of biogas in the region and a plan for the development of competitive regional biogas systems in order to take advantage of the production potential. This would be an important basis for the Swedish Energy Agency's work in following up a possible national production target for biogas, which was proposed by the ‘biogasmarknadsutredningen.’

4 DISCUSSION

4.1 ENVIRONMENTAL IMPLICATIONS OF ELECTRIFICATION

The overall results of this study suggest that there are direct environmental benefits for the inner-city in transitioning to an electric municipal transportation fleet. As shown, inner-city emissions of NOx and PM can be significantly reduced. Similar conclusions were reached by Borén (2020), Magnusson et al. (2020), and WSP (2016) by removing the emissions from internal combustion engines in the inner-city environment.

Moreover, the results of this study also suggest that indirect implications of biogas displacement have many benefits. This can be attributed primarily to reducing the use of diesel in heavy-vehicle transport with LBG. Nonetheless, these indirect environmental effects of electrification are rarely addressed. In a recent study by Magnusson et al. (2020), through scenarios with combined electrification and displacement of biogas to new markets, the GHG emissions reduction potential is explored. However, as the contribution of electrification to this share compared to the displacement effects is not outlined, it is difficult to assess the role electrification and displacement have (i.e., for direct and indirect implications). Despite this, from their scenario modeling, it is apparent that electrification and the displacement of biogas to other alternative markets are both beneficial. In particular, they show that biogas has more benefit in replacing fossil-equivalent fuels in heavy-duty vehicles, i.e., diesel, as opposed to displacing natural gas in the industry; once again, similar to results in this study. Displacement effects have also been partially covered in a study by Profu (2016), reviewing the climate benefits of busses in inner cities powered by biogas, electricity, FAME, and HVO. The results suggested significant changes in climate impacts, or benefits, between the different fuels depending on the system boundaries and type of fuel, making it important to understand and review the different fuels. Further studies, such as those by Lantz et al. (2019), suggest similar findings for the replacement of fossil fuels with biogas. However, the study employed dissimilar environmental impact and emission data for biogas and diesel. For example, the figures for diesel GHG emissions are slightly higher, while the impacts for biogas were found to be much lower per kWh. Thus, it is important to address that the results in this study, as with any quantitative assessments, are sensitive to the data employed. Additionally, the results are based on data from available information, e.g., emissions of vehicles, etc. Due to this, the study may underestimate the advances in technological development in a number of systems, i.e. overestimate the environmental impacts. This can be represented by e.g., the changing capacity of the electricity mix and the associated impacts of a bus kilometer with technological advances in the vehicles and systems in the SDM in future revions.

While the methodology applied in this study can be contextualized in other areas, the results of this are not meant to be generalizable for other biogas systems and contexts nationwide. As the biogas supply for Stockholm, mainly based on WWTP is unique, further research should be conducted for regions with more prominent co-digestion plants fueling their municipal transportation system as the results for the applied context may be quite different. In those cases, there may be substantially more value to the biogas system for the regional development and societal values created as there are more links to municipal waste handling, agriculture, etc. (Martin and Parsapour, 2012; Mutter, 2019a; Ammenberg et al., 2018). As previously mentioned, the methodology and SDM model from this study will be utilized to study the implications of electrification for the biogas system in the Skåne region.

4.2 SOCIO-ECONOMIC IMPLICATIONS

As aforementioned, the results suggest that the societal costs of electrification, which resulted in reduced socio-economic damages, can be improved through electrification and biogas displacement. While there are a number of studies that have reviewed the socio-economic costs of displacing fossil fuels with e.g., biogas (Anderson et al., 2018; Lantz et al., 2019; WSP, 2016), few have studied the effects of electrification. However, the aforementioned studies are relevant when reviewing the displacement effects of biogas to other markets, which may displace fossil fuels. For example, in the study by Lantz et al. (2019), societal costs (i.e., reduced societal costs) are compared between biogas and fossil fuels. The results are similar to our indirect effects for the displacement of fossil fuels with biogas/LBG, although the values used are based on a previous version of the ASEK model. In this study we employ a more recent version of the ASEK model, and take into account increasing societal costs for exposure to emissions as stipulated in the ASEK7.0 method, consequently leading to stagnation and increases over time for e.g. NOx; see Figure 18.

A large number of media reviewed in the discourse also discussed the socio-economic benefits of biogas, often suggesting that biogas is ‘important for societal waste management, though few provided further tangible indicators (quantitative or qualitative). As applied in this study, the socio-economic costs from so-called damages were outlined in addition to employment indicators. Similar assertions are also provided in Peck (2018) to review the benefits of biofuels in comparison to fossil counterparts. Nonetheless, it should be recognized that the development of the incumbent biogas systems in municipalities has taken ample time to develop (Fallde and Eklund 2015; Berglund et al., 2011) and are deeply embedded in local and regional systems (including infrastructure, industry, agriculture, etc.). Several previous f3 studies have also illustrated the extensive societal and local benefits from regional biofuel production and use (Martin et al., 2017; Peck et al., 2018; Lönnqvist et al. 2019; Ammenberg et al. 2018)) and for promoting circular and bio-based development regionally (Hagman and Eklund, 2016; Martin and Parsapour, 2012). These benefits are not always valued, and risk being lost if biogas is only evaluated as a renewable transportation fuel.

Although a large share of the material suggests extensive societal benefits from electrification, there are few assessments or studies available of the potential socio-economic benefits of electrification. One such largely positive aspect is the noise. While this was found to be relatively minor in the actual noise category, this may be important to address the socio-economic damage, especially in inner cities where ICEs can cause extensive noise at specific locations.

While this study suggests that electrification of the municipal sector can lead to an increase in the number of FTE jobs in society, this is rarely outlined as an aspect in the material reviewed in the discourse analysis. Instead, the focus has been primarily on positive expectations on the potential of electrification for the promotion of Swedish producers and OEMs of electric vehicles and components to increase employment. Nonetheless, this study also assumes that a large share of electric buses will be procured from abroad, as is currently the case in a number of municipalities. As such, job creation may be an issue for expanding electrification, despite the availability of domestic producers of electric buses. It is assumed that half, although potentially more, of the electric buses are procured from foreign producers, despite several domestic producers of buses and vehicles in

Sweden. Given that public procurement continues to put a high priority on price, it is hoped that new procurement legislation can, and will, take into account life cycle implications and review the costs (Ryding et al., 2019, as Swedish (or Nordic) produced goods often perform better than their foreign counterparts (Martin et al., 2021; Hertwich and Peters, 2009). Furthermore, while the values employed have been obtained from the literature, they may be both over or underestimations of the FTE jobs related to electrification and biogas development. Despite this, it should be noted that a range of studies has found that renewables often have larger employment shares compared to fossil equivalents (IRENA, 2020). As such, further studies on the potential job creation from increased electrification are welcome in the literature.

4.3 SOCIO-TECHNICAL IMAGINARIES

This discourse and content analysis employed was a valuable approach to understand the general picture of the electrification and biogas socio-technical imaginaries and discourse used to promote or defend their position in society. As highlighted in the results, we found that a positive picture of electrification was outlined by a majority of the material reviewed. Biogas was also framed as a critical societal function, though under threat from an increase in electrification.

As Mutter (2019a, b) suggests, the context of the incumbent systems often dictates the resistance to change and validation of current systems. While the previous studies found increased friction with the incumbent biogas systems in Linköping and Malmö, the Stockholm system is again unique. The wastewater treatment-based system in Stockholm may not be as linked to the regional identity in addition to other materiality and societal functions as inherent in other areas, such as those in e.g., Linköping and Malmö (Mutter and Rohracher, 2021). As such, there may be less resistance to electrification in Stockholm. As Mutter (2019a; pg 2) suggests, "*Each technology is also linked with specific material realities of the future mobility system. This materiality includes the substantial challenge of developing sufficient infrastructure to support renewable mobility systems including an extensive network of fueling or charging stations.*" This highlights that imaginaries may be contested and divergent at different geographic locations.

While many popular science reports and media platforms generally present positive views regarding this development, the academic literature is nascent with studies reviewing the consequences of such transitions for incumbent regional renewable energy systems in Sweden; although some studies on Swedish municipalities have been outlined, see Xylia et al. (2019) and Borén (2020). Biogas systems are an important example of such. Implications for biogas systems of electrification conceivably include a number of displacement effects within the regional economic system. While this study, according to the discourse, suggests that the biogas will continue to have a market, the reality may be different. In a previous study WSP (2016) the effects of electrification were assumed to reduce the market for biogas, thus affecting its competitiveness and economic viability. As such, and while this study did not review this, it is important to highlight that for incumbent biogas systems which are being increasingly being 'threatened' this may be a reality. Also, the biogas market has long been one of uncertainty and relying heavily on 'incentives' to sustain its viability and continued investment (Martin, 2015; Lönnqvist, 2017). However, in this study, once again it was assumed that the biogas would continue to have a market, as biogas production and use has continued to expand in a number of markets with significant room for expansion (SOU 2019; Lönnqvist 2017; Martin et al., 2017), despite the potential reduction in municipal transportation systems.

Indicators found to be important in the media, interviews, etc., were relatively convergent. Reducing carbon emissions (i.e., GHG emissions) was found in the majority of documents to support both electrification and biogas. This can partly be explained by the prominence of climate-based policy-making and the use of GHG to proxy sustainability in the bioenergy industry, i.e., a so-called 'carbon vision'; see Lazarevic and Martin (2016, 2018). The quantitative results do validate some of the discourse available, but only for direct inner-city implications. Once again, extended implications of changes from a broader systemic perspective are often less apparent in such discourse and in the literature (Martin et al., 2017).

4.4 IMPLICATIONS OF A NARROW FOCUS

In the face of increasing policy examples to develop and support electrification, the general focus and motivations provided have primarily been on reducing fossil dependence and climate impacts. Several researchers have previously suggested that such a narrow focus is often unwarranted and that the science-policy framework may lead to this narrow 'vision,' which may also risk potential unforeseen consequences, see, e.g., stipulations in Laurent et al. (2016) and Lazarevic and Martin (2016, 2018). As Mutter (2019a, pg 2) suggests, decision-making is complicated and that the *"...perceived advantage of these technologies goes beyond the environmental benefits they offer and includes a complex understanding of the desirable future society."* Furthermore, as outlined in Eklöf (2011, pg 1), promotion of systems based on limited sustainability motivation *"...one needs to ask which science is relevant for which policy choice, to be aware that lack of scientific certainty carries different weight in different political situations and to recognise that high decision-stakes entail value plurality, also within scientific circles."*

This study focused specifically on the implications of replacing an incumbent biogas system. While other biofuels are also prevalent in the bus fleets in other areas, and in the peri-urban fleets, their rapid expansion, and due to the fact that they are primarily imported fuels, replacement may not, therefore, generate as many significant long-term consequences as that seen for biogas production.

Electrification has been shown to have many positive effects for inner-city environments and also indirect benefits from biogas displacing other fuels. While the impacts of the electricity itself play a minor role in the overall environmental impacts of the system, the effects of an increased electric capacity are, however, not trivial. The study assumes that much of the electricity will come from renewables in the future despite a reduction in nuclear. Renewable energy continues to be a contested and controversial subject, especially related to the framing of renewable electricity in the future (Lilliestam and Hanger, 2016; Djerf-Piere et al., 2016). Previous studies have shown that the electricity mix is an influential factor in the environmental impacts of electricity in Sweden (Gustavsson et al., 2021).

Despite the positive results outlined for the displacement of biogas to new markets from the electrification of municipal transportation, the effects on the biogas system are yet to have real effects studied. Electrification of municipal transport, on a large scale, is a recent phenomenon. As such, the academic literature has been absent of studies exploring the enfolding effects, despite some prospective qualitative and quantitative examples; see again stipulations in Mutter (2019 a,b) and Magnusson et al. (2020).

4.5 LIMITATIONS AND POSSIBILITIES OF THE APPROACH EMPLOYED

This study developed and applied a new methodology for developing dynamic modeling based on discourse to highlight and develop a future narrative to model quantitatively, testing the implications of this future narrative. While the approach provides an interesting method to developing and quantifying a future scenario, with a number of strengths, it has some challenges and limitations for the modeling and comparison to other studies.

Of utmost importance with such modeling is the scope of the study. While we could have included a number of influential factors, the complexity of the system would ultimately increase substantially. We found early that it is important to ensure that a central question (or questions) drives the model to identify changes to the system. One such central question is how and when to model these changes, making the temporal aspect of the study, i.e., the timeframe of the assessment, important.

While the modeling was already a complex endeavor, following our methodology narrowed the scope of the study. This made it difficult for other factors to be included, such as input coming in from meetings and general comments from participants in the study on other ‘potential effects or realities’ that ‘could or should’ be included (but may not have been highlighted in the discourse). As such, the model may have a narrow focus based on the realities seen by a narrow group of stakeholders. One way to improve this is to include a broader set of material for the discourse, including, e.g., more scientific material to provide more academic input.

However, one strength is that, due to its broad scope, the approach allows for a large number of behavioral parameters to be included to explore their influence on the results. For example, this could include an increasing number of combined policy implications. While a number of variables were used to outline the dynamic changes and influence on the results over time, the study does not take into account other critical variables and factors that may affect the system besides the direct changes from potential public procurement changes for the bus fleet, fuel mandates, etc. As such, the model will continue to be developed and can be extended to address and assess the potential changes and dynamic influence between different sectors modeled from political incentives, factors, etc. These were, however, outside the scope of this study, although they may have a major influence. Once again, we would like to highlight that this study will continue in an ‘add-on’ project funded by the Swedish Energy Agency through the MESAM program to study and include more implications for incumbent biogas systems with different inherent properties; where we will review the implications in Skåne. As such, further developments will provide more information for models based on co-digestion, and the implications of changes, as the Stockholm example was unique.

It should be recognized that the model also has substantial uncertainty inherent in this time horizon (i.e., 30 years). As such, models similar to this cannot provide an accurate forecast of the future, but the results may be useful in decision-making (Forrester, 2007). Similar assertions have long been recognized for modeling, such as Box (1980) quote, “*All models are wrong, but some are useful.*” Thus, while the results of this study cannot model the future systems accurately, it can provide some indication of the dynamics and potential implications of electrification for inner-city environments and the resultant indirect impacts for other systems through biogas displacement, targeting when and where to support or provide input to generate the largest societal value.

5 CONCLUDING REMARKS

This study aimed to review the context and broader systemic implications of increased electrification of urban public transportation systems, with a particular focus on the interplay between biogas and electrification. In order to do so, a novel methodology to develop an approach for quantitatively assessing the electrification narrative through discourse analysis and system dynamics modeling was conducted.

The overall results, and message, from the discourse analysis highlighted that a generally positive picture of electrification is seen in much of the material reviewed. This was further addressed in the most prominent socio-technical imaginary outlined, i.e., that the electrification of bus fleets is an ideal system for the future, often motivated by the potential to improve urban air quality through reduced emissions, fossil-free energy, and less noise. Other socio-technical imaginaries were also outlined, where incumbent renewable systems, such as biogas can, and should be displaced to other markets where their benefits can continue to be realized. We also identified a number of themes emerging in the material, where importance is placed through discourse on environmental benefits, socio-economic aspects, competition with current systems and technologies, highlighting the novelty of electrification, boasting of the investments and potential, and finally justifying and motivating the development of electric transportation systems. As the discourse analysis was conducted during the Fall of 2019 through 2020, reviewing media and information on the biogas-electrification interplay, the results may be influenced by the discourse and developments during this period. Electrification is a rapidly expanding area, and as such, discourse emerging in more recent articles which may be more proactive to highlight the potential threats of electrification for incumbent systems are not included. While this is important to show, we have not included temporal aspects in the analysis of the discourse, or themes and trends developing over the period, which may be valuable in future studies.

The results of the quantitative assessments highlighted the potential for electrification to reduce inner-city environmental impacts, also resulting in sizeable socio-economic cost reductions. Large reductions in GHG emissions addition to reductions in NOx and PM2.5 emissions are seen in the inner-city. However, indirect benefits were also highlighted. Above all, biogas displacement was shown to positively influence the environmental impacts of new markets by displacing fossil fuels, e.g. by using LBG in place of diesel and natural gas. Once again, this also led to a significant reduction in socio-economic costs due to reduced exposure to NOx, PM2.5, CO_2, and other GHG emissions. Employment was also studied, where electrification led to an overall increase in jobs. However, these are shifted and replaced in a number of contexts, where, e.g., electrification requires fewer jobs, e.g., maintenance of the vehicles but may have more employment opportunities for vehicle and infrastructure development. Nevertheless, the results are dependent on the context of the study, and generalizations for other biogas systems, even within Sweden, should not be made as the context of the studied system (i.e. Stockholm) is unique.

Testing the novel methodology also led to a number of conclusions. The method and model developed have inherent strengths and weaknesses. Above all, the scope and questions addressed should be outlined, as such models can tend to grow in complexity. Following the discourse and having a focused scope was found to be beneficial for this study. This also suggests that such methods may be limited by the material reviewed, which may require a larger set of material, specifically academic literature to encompass further variables and parameters to explore their influence on the results. It may also be possible to allow for additional validation from stakeholders to develop a set of parameters that may more be more encompassing of their insights. Overall, it was found that using this approach can provide a powerful system to validate and provide quantitative figures to investigate the implications (both environmental and socio-economic) of narratives. We recommend that assessments of further indirect implications are extended to include aspects not covered within the scope of this study. As such, further studies on the implications of electrification are welcomed in the literature to provide new contexts.

Finally, the study also provides insights and input for promoting incentives and removing barriers to the displacement of biogas to alternative markets. This includes accounting for the benefits of biogas by providing incentives for benefits other than climate impact reductions in addition to supporting, stimulating, and coordinating approaches for new markets for biogas to grow.

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APPENDIX 1. DISCOURSE ANALYSIS

CODING

Table A1-1. Coding Employed in the Discourse Analysis.

Node/Code	Description
Competition & Displacement	Statements or information that relate to competition between El systems and Biogas Systems, displacement effects, etc. Includes the division of markets - e.g., bio-gas in the countryside, el in the inner cities.
100% Electric Busfleet Goals	
biogas & El synergy	
biogas for suburbs &or regional traffic	
competition with other public transport	
demand issues for biogas	
Elec for innercity	
investment shift from biogas to el	
Majority electric Demands	
Market shift from biogas to el	
New markets for Biogas	
Outcompete Biogas	
Replace Biogas	
Shift from Biodiesel/Diesel to biogas	
Shift from biodiesel_diesel to Electricity	
Environmental Benefit	Statements related to the environmental benefits of the tech system.
Silent/Noise	
Clean/Particles	
GHG, Carbon Emissions	
Energy efficient	
Fossil-Free	
Renewable Energy	
Spillover Benefits	
Spillover challenges	
Waste Management	
Justification	Statements, opinions, references that seem related to actors justifying the investments, justifying their in-volvement. Include statements that indicate 'personal preference' or 'feel good' emotions related to the technical system. E.g., "this is the most important issue we face"
Business & Competition for Swedish OEMs & Operators	
Cooperation Triple Helix	
Actions	
Innovations	
Investments	
Policy Interventions	
Views	
Personal emotional (subjective) justification	
Traveler satisfaction	
Proponents of Systems	Content that is produced by actors that seem to be 'pushing a system' or demonstrably acting as a sup-porter of the development of a new system for propul-sion of public transport fleets This category should in-clude evidence of special consideration of a technol-ogy system in fiscal incentive systems, or 'särställning'
Biogas production systems	
Biogas utilisation systems	
Electrical Vehicle systems	
Electrification of bus systems	

Responsible Stewardship developmental_social outcomes Economic outcomes Positive environmental outcomes Principles for Green Gas	Content that reflects back on the motivation for change … in such a way that it indicates that decision makers are acting in a way that can be considered to be 'responsible stewardship'
Scientific Technical Achievement Being the first Biggest and best Boom Breakthrough Green Wave Significant Investment Toward the Future	Content that has tone of "innovative systems" that are an achievement of note … For example such will pre-sent achievements in a way that stresses 'forward thinking" or newness - a general tone of portraying the "way of the future"
Societal Infrastructure Displacement of other services (e.g., parking) investment requirements Technical complexity challenges Technical development (rapid) waste management system & biogas	Content surrounding the challenges or needs related to the building or management of societal level infra-structure that enfolds biogas or electrical systems for public transport
Socio-environmental Policy Carbon neutrality Energy Security environmental policy goals National Policy goals for Biogas & system National policy goals for transport electrification policy goal achievement (pursuit of) policy problems_policy conflicts social development policy Technology neutrality_energy carrier neutrality	Content related to the formation of environmental/ social policy goals and/or their attainment - in the sphere enfolding energy carriers or drive systems re-lated to municipal transport fleets
System and Component Issues Cost Issues Lock-Ins Operational System Developments Risks SWOT - biogas-system SWOT - E-system	Content related to the potential barriers, risks, strengths and opportunities related to the systems and components required for electrification and biogas system developments

APPENDIX 2. SYSTEM DYNAMICS MODEL AND ASSUMPTIONS

ASSUMPTIONS AND DATA

Table A2-1. Biogas and electric busses in Stockholm (as of March 2021). Source: Email communication with SLL Johan Böhlin 2021-03-19 and John Gustaf Almquist 2021-03-21.

Area	**Inner city + Lidingö (innanför tull + Lidingö)**
Organization	SLL (Stockholm public transport company)
Number of buses in the inner city	280
Vehicle kilometers per inner city bus	47 846 km/year
Current vehicle / fuel mix in inner city buses	Vehicle gas 142 busses Ethanol (ED95) 1 buss RME 140 busses There are no electric busses in the inner city. The first 15 -30 will arrive by mid 2022. Currently there are totally 14 electric busses in Norrtälje, Märsta and Barkarbystaden
Fuel consumption per km for gas bus	0.74 Nm3/km
Fuel consumption per km for electric bus	1.2 kWh/km (Scania, 2020; Borén, 2020)
Responsibility of infrastructure	SL guarantees a certain electric capacity to the bus depot. The operator is responsible for the charging infrastructure at the depot.
Charging infrastructure	For the operator: cables within the depot and also charging boxes.
Bus owner	The operator owns all the busses. However, the biogas and ethanol busses are financed through SL´s financing company.
Brand / origin	The 14 electric busses are BYF from China. Gas busses are generally European.
Requirements in SL procurement that may affect the operator's choice of electric bus	SL includes electric busses in public procurement considering which trajectories that can handle the daily traffic with mostly nighttime charging at the depot (and some limited additional charging during the daytime during low traffic hours). The demands are “technology neutral” in the sense that the operator could choose fuel cell busses. Every electric bus must replace a combustion engine bus, since the depots are already full.
Choice of Electric buses/operator	The operator must adjust the number of electric busses so that they can be charged with the electric capacity that SL provides at the depot.

Table A2-2. Assumptions for FTEs.

Data	Comment
Bus Related Employment	1.4 FTE for Biogas Bus, 1.5 for Electric Bus (WWF, 2020)
Maintenance for Buses	0.4 FTE Biogas 0.2 FTE Electric
Biogas System	1 FTE/GWh produced (Peck, 2017)
Additional Electricity Demand	0,5 FTE/GWh (Kloos, 2020; Bltyh et al., 2014)
Buses from Domestic and Foreign Producers	50% in both cases

SYSTEM DYNAMIC MODEL DETAILS

Table A2-3. Functions and Variables Employed in System Dynamic Model.

Variable	Equation	Properties	Units	Documentation	Annotation
		Top-Level Model:			
Biogas(t)	Biogas(t - dt) + (Biogas_Production - Biogas_Consumption - Liquefaction) * dt	INIT Biogas = 1000	Cubic Meter	Stock for biogas consumed by biogas buses, and liquifying gas. receives constant inflow through "Biogas Production", representing the inflow of biogas into the system	
Biogas_Buses(t)	Biogas_Buses(t - dt) + (- Biogas_Displacement) * dt	INIT Biogas_Buses = INITIAL_BIOGAS_BUSES	Buses	Stock of Biogas buses	
Biogas_Facilities (t)	Biogas_Facilities(t - dt) + (adding_biogas_facilities - removing_biogas_facilities) * dt	INIT Biogas_Facilities = INITIAL_BIOGAS_BUSES/ BUSES_SERVED_PER_FACILITY	Facilities	Amount of biogas facilities in operation.	
Electric_Buses (t)	Electric_Buses(t - dt) + (Electric_Procurement) * dt	INIT Electric_Buses = INITIAL_ELECTRIC_BUSES	Buses	Stock of Elbuses	
Electric_Facilities(t)	Electric_Facilities(t - dt) + (adding_electric_facilities - removing_electric_facilities) * dt	INIT Electric_Facilities = INITIAL_ELECTRICITY_FACILITIES	Facilities	stock that represents total amount of electric facilities	
LBG(t)	LBG(t - dt) + (LBG_production - "LBG_T/F") * dt	INIT LBG = INITIAL_LBG	kWh	Stock for LBG	
Total_Direct_Costs(t)	Total_Direct_Costs(t - dt) + ("CO_2-eq_Costs_Direct" + PM25_Costs_Direct + NOx_Costs_Direct) * dt	INIT Total_Direct_Costs = 0	SEK	Total direct costs stock	
Total_Indirect_Costs(t)	Total_Indirect_Costs(t - dt) + ("CO_2-eq_Costs_Indirect" + PM25_Costs_Indirect + NOx_Costs_Indirect) * dt	INIT Total_Indirect_Costs = 0	SEK	Stock for Indirect costs	
adding_biogas_facilities	biogas_bus_procurement/ BUSES_SERVED_PER_FACILITY		Facilities/Months	Addtion inflow of biogas facilities	UNIFLOW
adding_electric_facilities	Electric_Procurement/ BUSES_SERVED_PER_FACILITY		Facilities/Months	Inflow of facilities for electric buses	UNIFLOW

Biogas_Consumption	BioBus_Km*Biogas_Consumption_Buses		Cubic Meter/ Months	biogas consumption as a function of km covered by biogas buses and consumption per km	UNIFLOW
Biogas_Displacement	MIN(PULSE("Procurement-Cycle", 1, 1), Biogas_Buses/DT)		Buses/Months	Amounts of biogas buses displaced from the system, based only on "Procurement-Cycle	UNIFLOW
Biogas_Production	420000		Cubic Meter/ Months	Inflow of biogas into the system. Since this is considered outside the scope, it is modeled as a static inflow.	UNIFLOW
Chinese_ElBus_Procurement	Electric_Procurement*(1-"%_Swedish_Buses")		Buses/Months	Chinese Bus Procurement	UNIFLOW
"CO2-eq_Costs_Direct"	"Direct_CO2-eq"*"SEK/Kg_CO_2"		SEK/Month	Flow for direct costs of CO_2-eq emissions	UNIFLOW
"CO2-eq_Costs_Indirect"	"Indirect_CO2-eq"*"SEK/Kg_CO_2_1"		SEK/Month	Flow for indirect costs of CO_2-eq emissions	UNIFLOW
"CO2-eq_Diesel"	"Diesel_T/F"*"CO_2/kWh_Diesel"		kg CO_2/month	CO_2-eq production by diesel use	UNIFLOW
"CO2-eq_LBG"	"LBG_T/F"*"CO_2/kWh_LGB"		kg CO_2/month	CO_2-eq emitted through LBG use	UNIFLOW
"Diesel_T/F"	"Total_T/F_Consumption"-"LBG_T/F"		kWh/Months	Diesel or LNG use to be displaced	UNIFLOW
"Direct_CO2-eq"	Biogas_Consumption*"Biogas_CO_2-eq"		kg CO_2/Month	CO_2 released into the air throughout the direct system.	UNIFLOW
Electric_Procurement	PULSE("Procurement-Cycle", 1, 1)		Buses/Months	Amounts of electric buses added to the system, based only on "Procurement-Cycle	UNIFLOW
Electricity_Consumption	ElBus_Km*Electricity_Consumption_Buses		kWh/Months	Electricity consumed by electric buses. Directly feeds into CO_2 production module	UNIFLOW
"Indirect_CO2-eq"	Electricity_Consumption*Electricity_CO_2_intensity+LBG_production*Energy_Cost_Liquefaction* Electricity_CO_2_intensity+"CO_2-eq_LBG"+" CO_2-eq_Diesel"		Kg CO_2/Month	Indirect CO_2-eq production from 1. electricity production 2. diesel use 3. LBG use 4. Liquefaction of biogas	UNIFLOW
Km_Driven	ElBus_Km+BioBus_Km		km/Months	km driven by buses	UNIFLOW

LBG_production	Liquefaction*"kWh/Nm³_of_Biogas"		kWh/Months	LBG production through liquefaction	UNIFLOW
"LBG_T/F"	MIN("Total_T/F_Consumption", LBG)		kWh/Months	LBG use by trucks and ferries instead of fossil fuels	UNIFLOW
Liquefaction	IF Biogas < LIQUEFACTION_THRESHOLD THEN 0 ELSE Biogas_Production-Biogas_Consumption		Cubic Meter/ Months	Outflow towards the liquefaction process, will kick in at a given threshld given by LIQUEFACTION THRESHOLD	UNIFLOW
NOx_Costs_Direct	NOx_Direct*"SEK/g_NOx_1"		SEK/Month	Flow for direct costs of NOx emissions	UNIFLOW
NOx_Costs_Indirect	NOx_Diesel*"SEK/g_NOx_2"+NOx_LBG*"SEK/ g_NOx_2"		SEK/Month	Flow for indirect costs of NOx emissions	UNIFLOW
NOx_Diesel	"Diesel_T/F"*"NOx/kWh_Diesel"		g/month	NOx emissions from Diesel use	UNIFLOW
NOx_Direct	("ElBus_NOx/Km"*ElBus_Km)+("BioBus_NOx/Km"*BioBus_Km)		g/Month	NOx produced in the inner city. Data taken from Boren.	UNIFLOW
NOx_LBG	"LBG_T/F"*"NOX/kWh_LBG"		g/month	NOx emitted through LBG use	UNIFLOW
PM10_Diesel	"Diesel_T/F"*"PM10/kWh_Diesel"		g/month	PM10 emission from Diesel	UNIFLOW
PM10_LBG	"LBG_T/F"*"PM10/kWh_LBG"		g/month	PM10 emitted through LBG use	UNIFLOW
PM25	(ElBus_Km*PM_ElBus)+(BioBus_Km*PM_BioBus)		mg/Months	Production of PM25 due to buses, locally	UNIFLOW
PM25_Costs_Direct	"SEK/PM2.5"*PM25*mg2kg		SEK/Month	Flow for direct costs of PM2.5 emissions	UNIFLOW
PM25_Costs_Indirect	"SEK/PM2.5_1"*PM25_Diesel*mg2kg_1+"SEK/ PM2.5_1"*PM25_LBG*mg2kg_1		SEK/Month	Flow for indirect costs of PM25 emissions	UNIFLOW
PM25_Diesel	"Diesel_T/F"*"PM25/kWh_Diesel"		mg/month	PM2.5 emission from Diesel	UNIFLOW
PM25_LBG	"LBG_T/F"*"PM25/kWh_LGB"		mg/month	PM2.5 emitted through LBG use	UNIFLOW
removing_biogas_facilities	Biogas_Facilities/LIFETIME_OF_FACILITIES		Facilities/Months	outflow of biogas facilities, to be used for electric facilities	UNIFLOW
removing_electric_facilities	DELAY(adding_electric_facilities, LIFETIME_OF_FACILITIES)		Facilities/Months	End of life for facilities	UNIFLOW
Swedish_ElBus_Procurement	Electric_Procurement*"%_Swedish_Buses"		Buses/Months	Swedish Bus Procurement	UNIFLOW

Swedish_FTEs	(Swedish_ElBus_Procurement*FTE_per_Swedish_bus)+(Chinese_ElBus_Procurement*FTE_per_Chinese_bus)+(FTE_maintenance*(Electric_Buses+Biogas_Buses))		Swedish FTEs/ Months		UNIFLOW
"SEK/PM2.5_1"	6900*(1.001245665^INT(TIME))		SEK/kg	Cost of PM2.5 per mg/km	
"SEK/PM2.5"	6900*(1.001245665^INT(TIME))		SEK/kg	Cost of PM2.5 per mg/km (direct)	
"%_Swedish_Buses"	1		Dimensionless	Percentage of Swedish buses and Chinese buses. 1 will be 100% Swedish, 0 will be 100% Chinese.	
average_noise_per_km_of_transport	((Electric_Noise*ElBus_Km)+(Biogas_Noise*BioBus_Km))/Km_Driven		Decibel/km	Average noise by buses on a km stretch	
Avg_Drive	47846/12		km/Buses/months	Average Drive per bus per month as mentioned by SL.	
BioBus_Km	Biogas_Buses*Avg_Drive		Km/Months	Total km per month covered by biogas buses	
"BioBus_NOx/Km"	1.777471223		g/cubic meter		
biogas_bus_procurement	0		Buses/month	Biogas bus procurement (set at 0)	
"Biogas_CO_2-eq"	0.2782733813		kg CO_2/ Cubic Meter	Boren table 7 for 27.4 g/km (divided by 1000 for kg)	
Biogas_Consumption_Buses	0.74		Cubic Meter/km	Consumption of biogas buses per km. According to SL, this is 0,74 Nm3/km for their buses According to Borén (2020), this is 0,57 Nm3/km (taken from Ecotraffic, 2015)	
Biogas_Noise	72		Decibel/km	(Borén, 2020, Table 8)	
BUSES_SERVED_PER_FACILITY	10		Buses/Facilities	amount of buses served per facility	
"CO_2/kWh_Diesel"	0.3021582734		Kg CO_2/kWh	CO_2/kWh rate for Diesel	
"CO2/kWh_LGB"	0.0345323741		Kg CO_2/kWh	CO2/kWh rate for LBG	

"CO2/MW_Mix"	Heat_CO_2*Heat_%+Nuclear_CO2*Nuclear_%+ Wind_CO2*Wind_%+Hydro_CO2*Hydro_%		kg CO_2/MW	Combination of CO_2 production of each share, and share of production in energy mix	
ElBus_Km	Electric_Buses*Avg_Drive		km/Months	Total km per month covered by electric buses	
"ElBus_NOx/Km"	0		g/km	NOx per km of electric bus (From Boren)	
Electric_CO2	2.3/1000		kg CO_2/kWh		
Electric_Noise	66		Decibel/km	(Borén, 2020), Table 8	
Electricity_CO_2_intensity	"CO_2/MW_Mix"*"MW/kWh"		kg CO_2/kWh	Intensity of electricity production	
Electricity_Consumption_Buses	1.21		kWh/Km	Consumption of buses per km. The values from Borén (2020,p.5) are as follows: Västerås: 1.87 kWh/km Ängelholm: 1.34 kWh/km Gothenburg: 1.21 kWh/km	
Energy_Cost_Liquefaction	0.5		kWh/Liter	kWh/Nm^3 discussed on p.21 of Börjesson et al.(2016)[11] Ranges between 0.2 to 1 kWh/Nm^3. Took 0.5 now, representing a small scale liquefaction plant	
Example_of_the_INT_function	INT(Electric_Facilities)		Facilities		
FTE_maintenance	0.4		FTE	FTEs due to maintenance of buses	
FTE_per_Chinese_bus	0.4		Swedish FTEs/buses	FTE Produced due to the procurement of a Chinese bus	

[11] Börjesson et al., 2016. Methane as vehicle fuel –A well-to-wheel analysis(MetDriv).Report No2016:06,f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden, available at www.f3centre.se.

FTE_per_Swedish_bus	1.6		Swedish FTEs/buses	FTEs due to the procurement of a Swedish bus	
Heat_%	0.39		Dimensionless	Percentage heat from 2019 as documented by Energimyndigheten	
Heat_CO2	0.16		kg CO_2/MW	Based on EcoInvent data (3.5 cut-off)	
Hydro_%	0.1		Dimensionless	Percentage hydro from 2019 as documented by Energimyndigheten	
Hydro_CO2	0.02224		kg CO_2/MW	Based on EcoInvent data (3.5 cut-off)	
INITIAL_BIOGAS_BUSES	142		Buses	initial amount of biogas buses	
INITIAL_ELECTRIC_BUSES	0		Buses	initial amount of electric buses	
INITIAL_ELECTRICITY_FACILITIES	1		Facilities	Initial amount of electric facilities	
INITIAL_LBG	0		kWh	Amount of initial LBG	
"kWh/Nm3_of_Biogas"	9.67		kWh/Cubic Meter	SGC (2012)[12]	
LIFETIME_OF_FACILITIES	180		Month	time after which facilities need to be replaced	
LIQUEFACTION_THRESHOLD	100000		Cubic Meter	Threshold from on which point forward the liquefaction will take place.	
mg2kg	1*10^-6		kg/mg	mg to kg converter	
mg2kg_1	1*10^-6		kg/mg	mg to kg converter	
"MW/kWh"	0.001		MW/kWh	MW to kWh	
"NOx/kWh_Diesel"	0.202158273		g/kWh	NOx/kWh for Diesel	
"NOX/kWh_LBG"	0.18381295		g/kWh	NOx/kWh rate for LBG	
Nuclear_%	0.41		Dimensionless	Percentage nuclear from 2019 as documented by Energimyndigheten	
Nuclear_CO2	0.0036		kg CO2/MW	Based on EcoInvent data (3.5 cut-off)	

[12] SGC, 2012., Basic Data on Biogas. Swedish Gas Technology Centre Ltd (SGC).

PM_BioBus	22.7		mg/km	(Borén, 2020, Table 7) PM2.5 production of biogas buses (tailpipe only)	
PM_ElBus	0.01		mg/km	(Borén, 2020, Table 7). PM25 production of electric buses (tailpipe only)	
"PM10/kWh_Diesel"	0		g/kWh	PM10/kWh for Diesel	
"PM10/kWh_LBG"	0		g/kWh	PM10/kWh rate for LBG	
"PM25/kWh_Diesel"	13.52518		Milligrams/kWh	PM2.5/kWh for Diesel	
"PM25/kWh_LGB"	11.978417		Milligrams/kWh	PM2.5/kWh rate for LBG	
"Procurement-Cycle"	(INITIAL_BIOGAS_BUSES/120)*EXP(-PI*((TIME-180)/120)^2)		Buses	Assumed. Based on bell-structure of which the intergral is equal to the total busfleet. (INITIAL_BIOGAS_BUSES/120)*EXP(-PI*((TIME-180)/120)^2)	
"SEK/g_NOx_1"	1/1000*(1.001219846^INT(TIME))		SEK/g	Cost per g of NOx emitted	
"SEK/g_NOx_2"	1/1000*(1.001219846^INT(TIME))		SEK/g	Indirect costs of NOx emissions per kg	
"SEK/Kg_CO_2"	1.14*(1.0014059^INT(TIME))		SEK/kg CO_2	Cost per kg of CO_2-eq emitted	
"SEK/Kg_CO_2_1"	1.14*(1.0014059^INT(TIME))		SEK/kg CO_2	Indirect costs of CO_2-eq emissions per kg	
Total_Costs	Total_Direct_Costs+Total_Indirect_Costs		SEK		
"Total_T/F_Consumption"	4467540		kWh/ Months	Total amount of displacable fossil fuels	
Wind_%	0.1		Dimensionless	Percentage wind from 2019 as documented by Energimyndigheten	
Wind_CO_2	0.006968884		kg CO_2/MW	Based on EcoInvent data (3.5 cut-off)	

Table A2-4. Information on Variables and Arrays.

Total	Count	Including Array Elements
Variables	102	102
Sectors	9	
Stocks	8	8
Flows	35	35
Converters	59	59
Constants	46	46
Equations	48	48
Graphicals	0	0

Table A2-5. Run-Specifications of Model.

Run Specs	
Start Time	1
Stop Time	360
DT	1/32
Fractional DT	True
Save Interval	0.03125
Sim Duration	36
Time Units	Months
Pause Interval	0
Integration Method	Euler
Keep all variable results	True
Run By	Run
Calculate loop dominance information	False

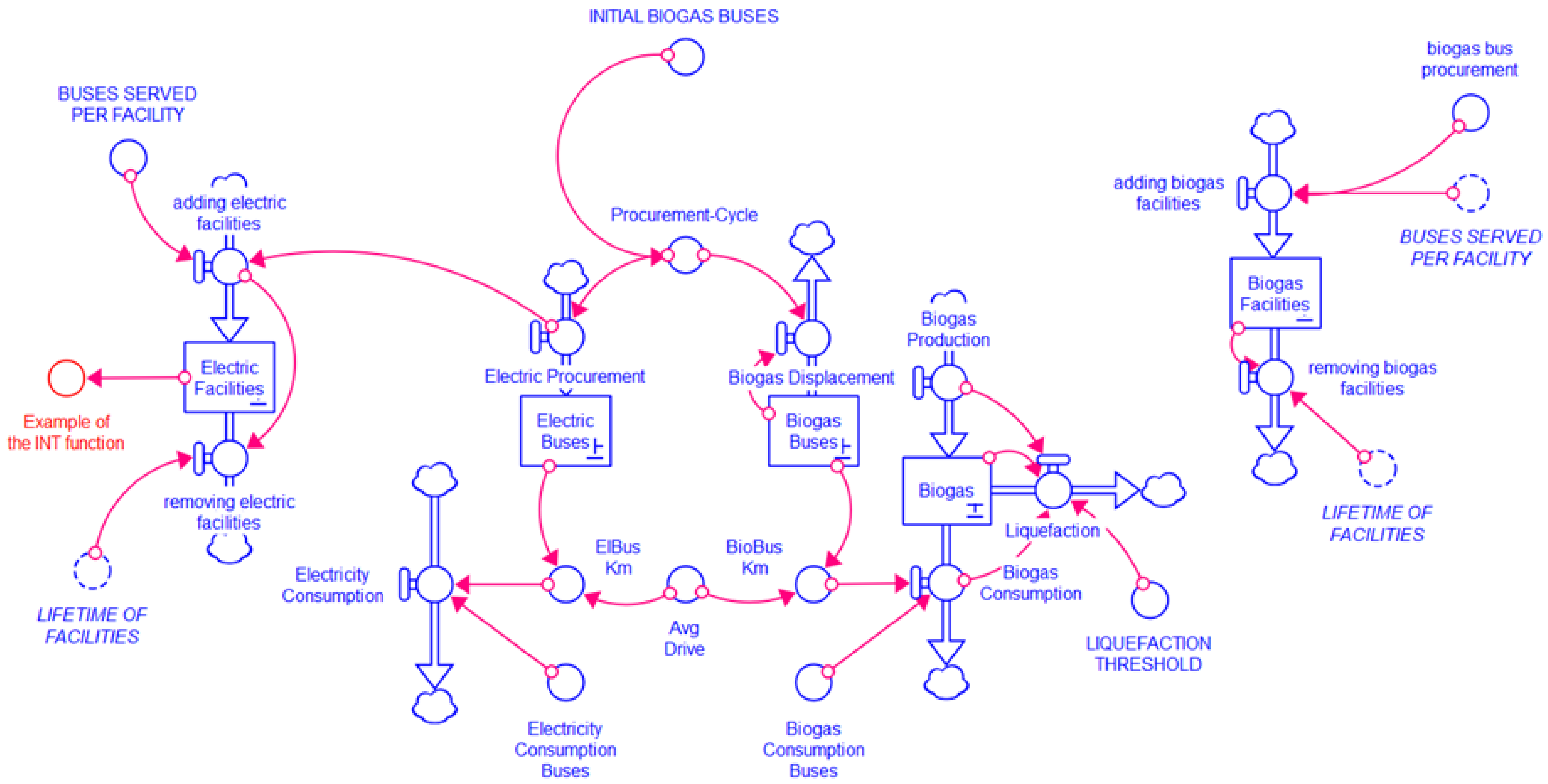

Figure A2-1. Top-Level Model.

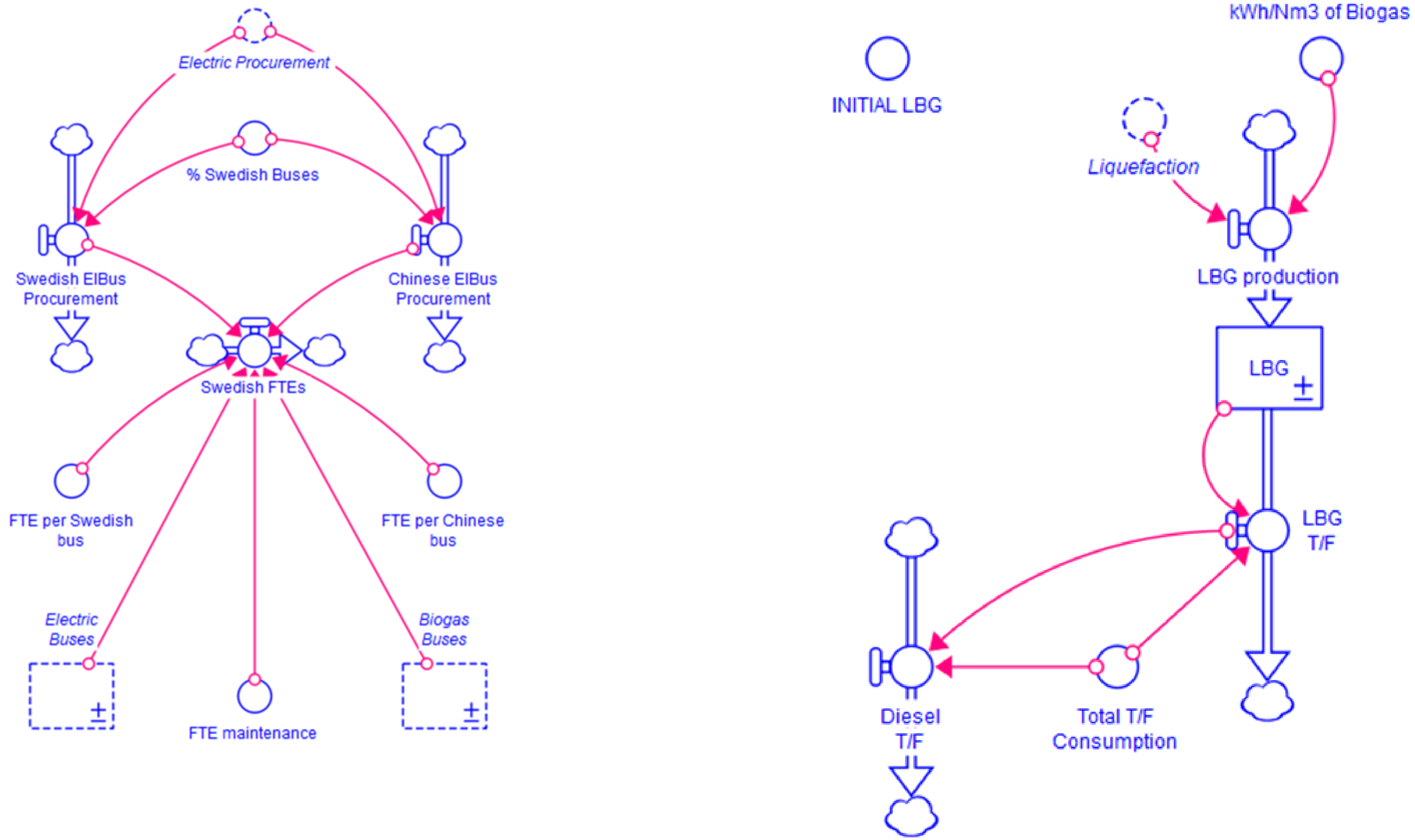

Figure A2-2. Procurement and Liquefaction Module.

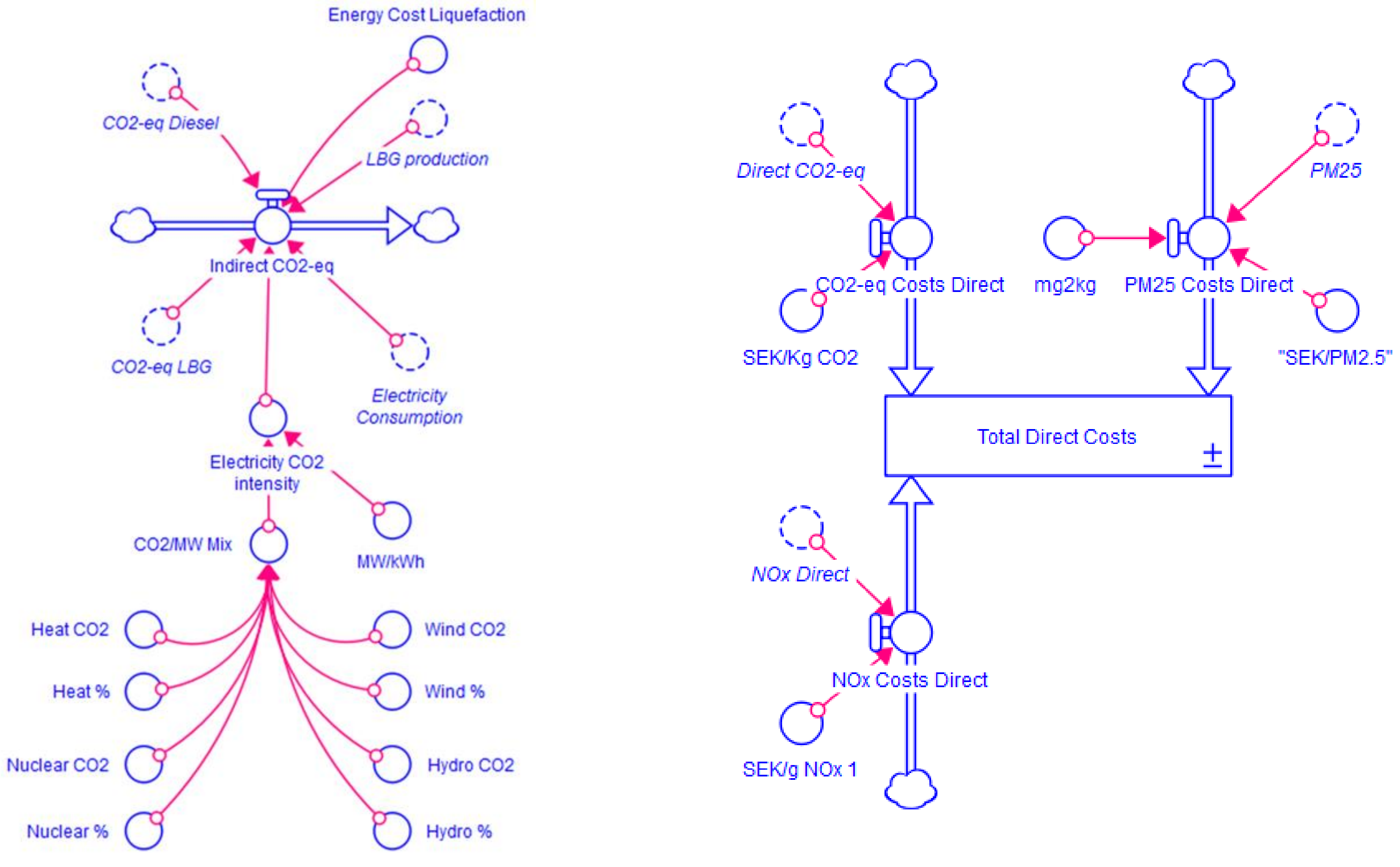

Figure A2-3 Procurement and Liquefaction Modules.

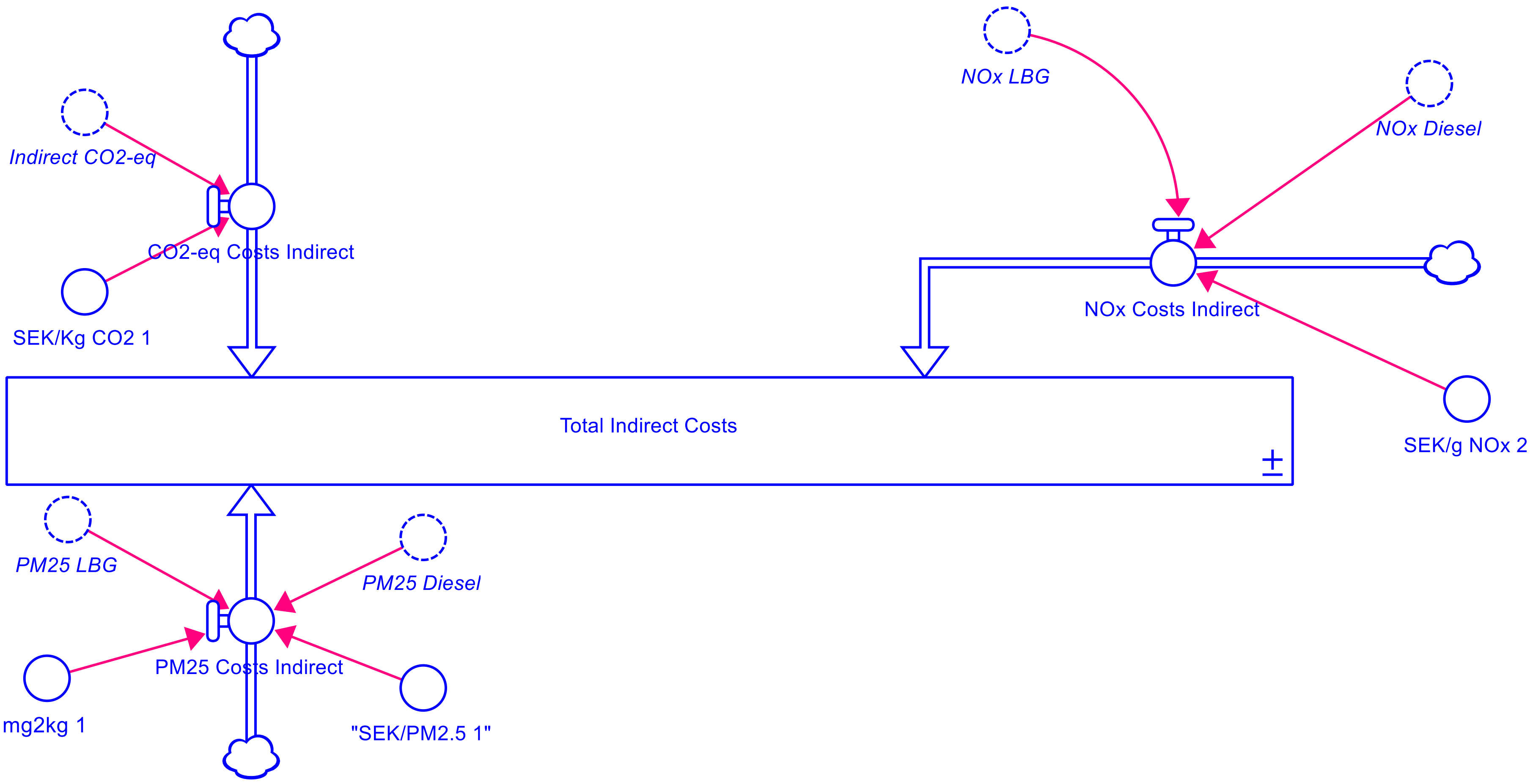

Figure A2-4. Indirect Costs Module.

APPENDIX 3. POLICY BRIEF

WORKSHOP LEADERS

Åsa Romson and Sara Andersson

WORKSHOP PARTICIPANTS

National Policy Actors: Kalle Svensson, Energimyndigheten; Andreas Kannesten, Infrastrukturdepartementet; Ellinor Grundfeldt och Fredrik Svensson, Energigas Sverige and Eva Jernbäcker, Trafikverket/utredning.

Regional Authorities: Maria Dahleman, Region Stockholm; Johan Böhlin, SL; Iris Rehnström, Skånetrafiken; Sabine Tauber, Biogas syd; Hannele Johansson, Energikontoret sydost and Ola Solér, Region Skåne

Biogas Producers/Users: Mikael Antonsson, Gasum; Björn Möller, E.ON; Mikael Olausson, Scandinavian Biogas and Christer Bruzelius, Destination Gotland.

Researchers: Michael Martin, Anders Hjort, Tomas Lönnqvist, and Karl Jivén, IVL Swedish Environmental Research Institute; and Philip Peck, IIIEE.

GE BIOGASEN NYA FÖRUTSÄTTNINGAR ATT UTVECKLAS NÄR BUSSFLOTTAN I FLERA STÄDER ELEKTRIFIERAS: ÅTTA REKOMMENDATIONER TILL BESLUTSFATTARE

Detta är en sammanfattning för beslutsfattare kring hinder och möjligheter för ökad användning av biogas i Sverige. Den är sammanställd inom forskningsprojektet Implikationer vid elektrifierande av kommunala transportsystem: Regionala konsekvenser för produktion av biogas genom rötning, finansierat av Energimyndigheten och f3 – Svenskt kunskapscentrum för förnybara drivmedel. Forskarna i projektet svarar för innehållet som är en utkomst av aktiviteter inom projektet.

Först och främst bör biogasmarknadsutredningens förslag genomföras, liksom förslag i andra utredningar som stärker produktion och användning av biogas. Det finns dock anledning att utöver detta även ge breda incitament för utveckling av fler biogasmarknader:

1. **Utforma EU:s regelverk med biogas i åtanke så att klimatnytta premieras och biogasens breda nyttor kan tillgodoräknas**. T.ex. bör klimatregelverk för tunga fordon inte enbart beakta vad som kommer ur avgasröret (s.k. tail pipe emissions) utan även ta hänsyn till klimatnyttan ur ett livscykelperspektiv för bränslet. Vidare är det även viktigt att kommande regler kring den s.k. taxonomin styr mot att biogasens breda nyttor ska kunna tillgodoräknas.

2. **Skapa incitament för andra nyttor än klimat**. Det behövs incitament för ett effektivt omhändertagande av resurser från avfall och för återföring av näring genom användning av biogödsel. Incitament kan skapas genom utveckling av mål eller krav för användning av biogödsel i kombination av skatter och stöd som gynnar omhändertagande och kretslopp eller gör det svårare och dyrare med icke-resurseffektiva flöden, exempelvis genom ersättning för återvunnen växtnäring som återförs till produktiv mark och skatt på konstgödsel.

3. **Ta med biogas när incitament utvecklas för negativa klimatutsläpp**. Om det sker uppsamling av ’grön’ koldioxid vid uppgraderingsanläggningar för biogas skulle denna kunna vara intressant för lagring eller annan användning som ger negativa klimatutsläpp. Biogasproduktion är också ett viktigt verktyg för omhändertagande av metan som annars skulle läcka ut till luft från exempelvis lagring och hantering av gödsel.

4. **Kompletterande incitament behövs för att fler marknader ska utvecklas för biogas**. Genom förvätskning av biogas utökas marknaden för biogas inom tunga vägtransporter och sjöfart, men också emot industrin. Utvecklingen med elektrifiering och vätgas pågår samtidigt. För att möjliggöra fler marknader för biogas bör både vägtransporter och sjöfart ses som områden där biogas kan ha en betydande roll i framtiden. Även för industrin är biogas intressant som alternativ till fossilbaserad gas. Det behövs dock kompletterande incitament för att betalningsviljan inom internationell sjöfart och industri ska matcha biogasens produktionskostnader.

5. **Privata och offentliga kunders efterfrågan på godstransporter som använder biogas bör stimuleras** som en del av de stöd som idag ges för bland annat produktion och distribution av flytande biogas (LBG). Detta kan stödjas genom riktat upphandlingsstöd och hjälp att sprida kunskap bland privata och offentliga transportköpare, exempelvis

genom information om definitionen av ”miljölastbil” i förordningen om klimatpremien för vissa fordon[13].

6. **Koordinera reformer så de stödjer en övergång till nya marknader utan stora nedgångar i efterfrågan**. Nya biogasmarknader behöver byggas upp innan kollektivtrafikmarknaden minskar för att undvika en stagnation och utebliven klimatnytta för elektrifieringen. Biogasaktörerna behöver få signaler om förändringar i god tid för att själva kunna ställa om och anpassa den infrastruktur som byggs upp.

7. **Staten behöver ha beredskap att agera utifrån utvecklingen av import och export av biogas**. Det är viktigt att staten noggrant följer hur stödsystem som används för produktion och användning av biogas i grannländerna samt agerar för att ta omhand biogasens samhällsnyttor i Sverige samtidigt som en sund konkurrens bibehålls.

8. **Staten bör uppmärksamma regionernas arbete med biogasutvecklingen**. Staten skulle därför kunna efterfråga att det i alla regionala utvecklingsplaner finns analyser kring utvecklingen för biogas i regionen samt en plan för utveckling av konkurrenskraftiga regionala biogassystem i syfte att ta vara på produktionspotentialen. Detta skulle vara viktigt underlag för Energimyndighetens arbete i uppföljning av ett eventuellt nationellt produktionsmål för biogas, vilket föreslogs av biogasmarknadsutredningen.

Varför behövs dessa reformer?

Ökad biogasanvändning men bara svagt ökad biogasproduktion i Sverige idag

I Sverige produceras årligen omkring 2 TWh biogas från främst avloppsslam, matavfall och gödsel. Den största andelen av biogasen som produceras uppgraderas och används som fordonsbränsle (64 procent), resen används som värme (19 procent), för elproduktion (2 procent), till industriella processer (2 procent) eller facklas bort (11 procent)[14]. En majoritet av biogasen som går till transportsektorn används idag som bränsle för bussar i kollektivtrafiken i städer.

Sedan 2015 har biogasanvändningen i Sverige mer än fördubblats, medan svensk produktion bara ökat med 9 procent under samma period. År 2019 uppgick användningen av biogas till knappt 4 TWh i Sverige. Den ökade efterfrågan har täckts med en ökad import av biogas, främst från Danmark. Merparten av den biogas som importeras används i industrin och till uppvärmning[15]. Den svenska produktionspotentialen för biogas från rötning har bedömts vara mellan 14 och 15 TWh år 2030[16]. Produktionspotentialen baseras framför allt på ökat nyttjande av rester och åkerbaserade grödor utan annan avsättning (s.k. ILUC-fria grödor[17]) men även bättre nyttjande från matavfall, avloppsslam, gårdsgödsel och avfallsdeponier.

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[13] Förordningen om statligt stöd till vissa miljöfordon. SFS 2020:750
[14] Energimyndigheten. Produktion och användning av biogas och rötrest år 2019. ER 2020:25
[15] ibid
[16] SOU 2019:63 Mer biogas! För ett hållbar Sverige. Betänkande av biogasmarknadsutredningen (2019)
[17] Ahlgren, S., Björnsson, L., Prade, T., & Lantz, M. (2017). Biodrivmedel och markanvändning i Sverige. Miljö- och energisystem, LTH, Lunds universitet

Vem efterfrågar biogas i framtiden?

Den stora andelen av biogasproduktionen som idag används för bussar i kollektivtrafik i städerna väntas minska kraftigt de kommande åren[18]. Biogas kan dock användas i många olika sektorer. Hälften av de branscher som formulerat en Färdplan för fossilfri konkurrenskraft pekar ut biogas som del av omställningen, däribland gasbranschen, lantbruksbranschen, flygbranschen, sjöfartsbranschen, stålindustrin, fordonsbranschen för både lätta och tunga fordon samt åkerinäringen.[19] Många spår en ökad biogasanvändning främst inom tunga vägtransporter. Biogas i flytande form (LBG) ses som viktig för långa godstransporter medan biogas i komprimerad form (CBG) ses som strategisk för främst bussar i regionaltrafik[20]. Samtidigt pågår även elektrifieringen brett inom vägtransporterna. Både aktörer och biogasmarknadsutredningen pekar på att det finns stor potential för ökad användning i industri och kraftvärme, särskilt den som är kopplad till gasnätet, och för sjöfarten där många fartyg redan är anpassade att drivas med gas[21].

Biogas har fler nyttor än klimat

Biogas är ett bränsle med flera miljönyttor, både vid produktion och användning. Vid användning av biogas som fordonsbränsle i bilar, lastbilar och fartyg kan fossila bränslen ersättas, vilket leder till att utsläppen av växthusgaser och en del andra luftföroreningar minskar i jämförelse med konventionella drivmedel. Vid produktion av biogas tas avfall och restprodukter omhand för energiutvinning och produktionen ger utöver biogas även s.k. biogödsel, där de näringsämnen som finns kvar efter rötning tas om hand och används som biogödsel i lantbruket med förbättrad markkvalité och kolinlagring i marken som följd. I de fall där gårdsgödsel används för produktion av biogas kan även metanutsläppet från gödselhanteringen minska, vilket leder till minskad klimatpåverkan (sk gödselkredit i RED2). På detta sätt bidrar biogas till både effektiv resursanvändning och till klimat- och miljönytta. Produktionen sker spritt över hela landet och kan därför även bidra till det regionala näringslivet, landsbygdsutveckling samt en försörjningstrygghet av förnybar energi.

Produktion och användning av biogas är ofta starkt regionalt förankrat men saknar nationell strategi

I många regioner i Sverige finns en utvecklad strategi kring produktion och användning av biogas. Regionerna är engagerade i biogasens utveckling utifrån att de värnar om god resurseffektivitet från offentliga avfallsanläggningar, styr mot minskad klimatpåverkan genom utbyte av fossila energikällor och ökad miljönytta i lantbruket. Biogasens många nyttor har till stor del synts lokalt och regionalt när kommunala reningsverk kunnat bidra med drivmedel till kollektivtrafiken samt att lokala lantbruksföretag kunnat minska metanutsläppen, återföra näring till jorden och samtidigt bidra till drivmedel för exempelvis livsmedelstransporter.

[18] SOU 2019:63

[19] Genomgång av 22 färdplaner publicerade av regeringsinitiativet Fossilfritt Sverige.

[20] Debattartikel Fossilfritt Sverige och transportaktörer om vilken nisch de ser för olika fossilfria lösningar, DN 2017

[21] SOU 2019:63 och workshop med 15-tal biogasaktörer inom ramen för detta forskningsprojekt hos IVL Svenska Miljöinstitutet 2021-01-21

I flera regioner har det formats ’biogas-kluster’, antagits biogasstrategier eller tillsatts biogassamordnare för att underlätta informationsspridning och planering hos både offentliga och privata aktörer. Regionalt finns nyttan av närhet mellan produktion och marknad. Regioner har bland annat initierat och drivit samverkan med (i) industrikluster som har gasbehov och hjälpt dessa med systemtänk där biogas kan vara en del, (ii) stöttat lantbruket och avfallsbolagen så att fler restprodukter kan tas omhand till biogas, samt (iii) stärkt efterfrågan på biogas genom att jobba med upphandlingsfrågor[22]. En ändring i synsätt märks nu då kollektivtrafikmyndigheternas upphandlingar visar att biogas inom kort konkurrerar med flytande biobränslen och att det främst är klimatvillkor som ställs.

På nationell nivå saknas motsvarande starka politiska förankring och engagemang för svensk biogasproduktion och biogasanvändning. Biogas stöds främst utifrån klimataspekten. Många av de stöd och styrmedel som har kommit biogasen till del har inte utgått specifikt ifrån biogasens förutsättningar och många samhällsnyttor. Stöd i form av skattenedsättningar för drivmedel har införts för begränsad tid och varit svåra att förutse, och reformerna av reglerna kring s.k. miljöbilar har ibland varit oklara i relation till biogas som drivmedel. Någon specifik plan eller strategi för biogasproduktion och biogasanvändning i Sverige har inte funnits på nationellt plan. Nu förbereds ett förslag om ett nationellt produktionsmål[23] vilket till viss del skulle kunna ha en sådan strategisk effekt, särskilt om det kopplas till ett regionalt ansvar för utveckling av planer för regionala biogassystem.

Nya marknader för biogas kräver incitament nu för att övergången ska funka

Biogasmarknadsutredningen bedömde att det inom kort kommer saknas tillräckliga incitament för att växla upp inhemsk produktion av biogas till större volymer samt till ett konkurrenskraftigt pris som industrin kan efterfråga. Utredningen bedömer därför att åtgärder bör vidtas för att främja en ökad konsumtion av inhemskt producerade förnybara gaser. Utredningen la fram konkreta förslag för flera produktionsstöd för biogas[24].

Drivkrafter för en ökad elektrifiering är starka och den pågående övergången till elektrifiering av bussarna i innerstäderna försvagar den hittills största marknaden för den svenska biogasproduktionen. Samtidigt är en positiv klimateffekt av elektrifieringen av innerstadsbussarna avhängigt av att biogasen ersätter andra fossila utsläpp, vinsten uteblir om biogasen i stället slås ut. Då omläggningen riskerar förskjuta den nuvarande biogasen till nya och hittills mindre utvecklade marknader krävs koordinerade insatser för att lyckas.

Utmaningar att etablera biogas på nya marknader kan handla om pris, volym, teknik, eller distribution och leveranssäkerhet. Utmaningar ligger i att stora investeringar har gjorts i infrastruktur för biogasbussar inom kollektivtrafiken som inte är avskrivna och svåra att flytta på

[22] Anderson S, Lind L (2018). Framtidens kollektivtrafik i Stockholms Län - En framtidsstudie över olika drivmedelsval och möjligheter att använda el och biogas i kollektivtrafiken. 2050 Consulting, på uppdrag av Scandinavian Biogas; Lönnqvist, T. et. al., (2020) Verktyg för biogasutveckling. En skrift för dig som jobbar för med hållbara transporter. Rapport nr FDOS 01:2020.
[23] SOU 2019:63
[24] ibid

och att svårigheter finns för aktörerna att förstå och följa med i de politiska beslut som fattas[25]. Biogasen har utvecklats mot en nischmarknad (kollektivtrafiken) där förutsättningarna försvinner innan teknologin och marknaden hunnit mogna kommersiellt. Nya aktörer efterfrågar en delvis långsammare förändring i villkoren för biogas för att kunna göra anpassningar till framtida efterfrågan på flytande biogas. Vid en förskjutning av biogasen från kollektivtrafiken till tung trafik och sjöfart är det troligt att betalningsviljan för biogasens samhällsnyttor minskar på grund av en övergång från offentliga till privata kunder[26]. Detta givet att den sjöfart som upphandlas offentligt såsom Gotlandstrafiken står för en mindre del av efterfrågan.

Styrmedel och regelsystem missar ofta biogas

De senaste åren har industrin visat ett ökat intresse för användning av biogas, exempelvis som ersättning för gasol. Flera industrier utmed gasnätet har också valt att gå över från naturgas till biogas när priset på biogas varit tillräckligt konkurrenskraftigt. Ett hinder för ökad biogasanvändning inom industrin har dock varit att biogasanvändningen inte kunnat tillgodoräknas inom ramen för EU:s utsläppshandelssystem, EU-ETS. Beslut om förordningsändringar i EU:s regelverk möjliggör nu att biogasens klimatnytta kan tillgodoräknas genom att från 2022 använda utsläppsfaktor 0 för biogas i gasnät, baserat på köpekontrakt. Det är viktigt att dessa EU-regler nu implementeras i Sverige med ett enkelt administrativt förfarande för aktörerna på marknaden.

Skattemässigt gör Sverige en skillnad på biogas och fossil naturgas vilket appliceras då gaserna blandas i samma ledning eller distributionsnät, s.k. grön-gas-principen. Men EU:s regelverk som sätter krav för koldioxidutsläpp för bilar och lastbilar gör ingen skillnad. Idag görs ofta ingen rättvis utvärdering av klimatnytta gentemot elfordon då man inte mäter påverkan i ett livscykelperspektiv. Regelverk avseende koldioxidnormer för tunga fordon inom EU tar inte hänsyn till biogasens klimatnytta utan styr enbart utifrån koldioxidutsläpp från avgasröret, så kallade *tail pipe* emissions. Ska biogasen ges rättvisa förutsättningar bör dessa EU- regelverk utvecklas till att mäta klimatnytta i livscykelperspektiv.

När nya styrmedel övervägs, exempelvis för negativa utsläpp i Sverige[27] och EU:s regler för vad som anses vara hållbara investeringar, den s.k. taxonomin, är det viktigt att regelverk utformas så att biogasens klimatnytta i ett livscykelperspektiv och breda samhällsnytta kan tillgodoräknas. Detta möjliggör en rättvis värdering och jämförelse mellan olika alternativ.

[25] Workshop med 15-tal biogasaktörer inom ramen för detta forskningsprojekt hos IVL Svenska Miljöinstitutet 2021-01-21

[26] Hagstroem A. Masteruppsats KTH 2019.' Prospects for continued use and production of Swedish biogas in relation to current market transformations in public transport'

[27] SOU 2020:4 Vägen till en klimatpositiv framtid. Betänkande från klimatpolitiska vägvalsutredningen (2020)

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