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Final report

SECURITY OF SUPPLY AND CIRCULARITY OF TRANSPORT BIOFUELS

- Method development

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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. 50396-1. 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.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels. The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. Chalmers Industriteknik functions as the host of the f3 organization (https://f3centre.se/en/about-f3/)

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SUMMARY

In socio-economic analyzes, different effects are weighed against each other by quantifying the economic value of the effects and the advantages and disadvantages of different systems can thus be evaluated. If methods are lacking to quantify a certain benefit, its effects cannot be valued either and thus there is a risk that the benefit is not included or considered.

This study reports the findings from the project: Security of supply and circularity of transport biofuels – method development. The main aim of the project has been to develop methods to enable quantification of the benefits of security of supply and circularity for transportation fuels, something that has previously been lacking. Furthermore, the results have been combined with current methodology to assess climate benefit, in terms of GHG-emission reductions, to arrive at a combined value for the evaluated fuels, including all three indicators of: security of supply, circularity and climate benefit.

The main results from this study are the first real attempt to develop methodology to quantify societal benefits stemming from circularity and security of supply, and the development and implementation of these new methods is described in this report.

The results on security of supply shows that domestic Swedish production of renewable fuels can, to some extent, help dampen the impact of global fuel supply disruptions on the Swedish economy.

Applying the method of quantifying circularity to four production systems shows that the studied biofuels perform well (generally above 65 % circularity). This could indicate that other types of biofuels based on secondary resources could perform well in the Swedish context, even if these have not been studied specifically in this project. The proposed method on circularity is currently only able to assess the circularity of production systems and is thus not able to allocate the circularity across co-products. To understand other types of fuel systems and to refine the method, it would be fruitful to apply the method to more cases, both in Sweden and in an international context. Furthermore, exploring other ways of combining the renewability and recyclability parts would be beneficial. Capturing the socio-economic value of circularity was proven difficult due to the vague, broad, and complex nature of the concept. Indeed, circular economy can provide many potential welfare benefits, but it is unclear how these benefits should be realised and whether they should be grouped under a circularity subsidy or not. The approach used herein represents a first step towards thinking about how the socio-economic value of circularity may be captured and further studies are needed.

The methods developed in this project were combined with climate mitigation potential, which herein is expressed as the avoided socio-economic cost related to the GHG emission saving for each fuel. The results show that all studied fuels result in high emission reduction potentials (above 75%). The quantitative results from this assessment are both study and context dependent as they originate from specific LCA studies and process data. Therefore, the results cannot be considered an average value for the respective fuel.

When tested on several different fuels, the methodology developed in this work showed that the effects of the security of supply indicators is considerably smaller than what is being assessed from

reduced climate effects for the same fuels. Regarding the value of circularity, it is about the same magnitude as the lower estimates of the value of reduced climate effects.

Further development of the methods may include: the use of up-to-date data in relation to the LCA models, including a greater variety of fuels that are relevant from the Swedish context, investigation of alternative ways of expressing the socio-economic cost, and the inclusion of more indicators that are of importance for the transport sector (apart from climate change mitigation). Such indicators could be human health and local pollution aspects due to particle emissions. In addition, the methods of estimating the value of security of supply and circularity need further development in order to estimate an accurate value of the important societal benefits that renewable transportation fuels may promote. The current uncertainty regarding their values may have the effect that they are overshadowed by climate related benefits in public debate and policy. Future research may attempt to estimate these parameters and other non-climate related benefits (and costs) accruing from renewable transportation fuels, more accurately, in order to provide a better support for policy decisions.

In summary, these results add perspective to the current policy and debate which is leaned to put a strong emphasis solely on climate-related effects and hence, tend to miss values related to other indicators, such as security of supply and circularity. As a result, the societal benefits related to these indicators may be shadowed by reduced climate emissions.

SAMMANFATTNING

I socioekonomiska analyser vägs olika effekter mot varandra genom att kvantifiera den ekonomiska nyttan av dessa effekter och de för- respektive nackdelar olika system har kan därmed utvärderas. Om metoder saknas för att kvantifiera en viss nytta så kan heller inte dess effekter värderas och då finns en risk att nyttan för den åtgärden inte värderas korrekt.

Denna studie rapporterar resultaten från projektet: Cirkularitets- och försörjningsnytta - metodutveckling. Huvudsyftet med projektet har varit att utveckla metoder för att möjliggöra kvantifiering av fördelarna med försörjningstrygghet och cirkularitet för drivmedel, något som tidigare saknats. Dessutom har resultaten kombinerats med befintlig metodik för att bedöma klimatnyttan, avseende utsläppsminskningar av växthusgaser, för att uppnå ett kombinerat värde för de utvärderade bränslena, inklusive alla tre indikatorerna på: försörjningstrygghet, cirkularitet och klimatnytta.

Huvudresultaten från denna studie är det första riktiga försöket att utveckla metodik för att kunna kvantifiera samhällsnyttor som härrör från cirkularitet och försörjningstrygghet, och utvecklingen och genomförandet av dessa nya metoder är väl beskrivet i denna rapport.

Resultaten för försörjningstrygghet visar att inhemsk svensk produktion av förnybara bränslen till viss del kan bidra till att dämpa effekterna av globala bränsleförsörjningsstörningar på svensk ekonomi.

Resultaten av att tillämpa metoden för att kvantifiera cirkularitet till fyra produktionssystem visar att de studerade biobränslen fungerar bra (i allmänhet över 65 procent cirkularitet), vilket ger starka indikationer på att andra typer av biobränslen baserade på sekundära resurser också förväntas fungera bra i det svenska sammanhanget, även om dessa inte har studerats specifikt. Den föreslagna metoden för cirkularitet kan för närvarande endast bedöma cirkularitet i ett produktionssystem och kan inte skilja mellan dess samprodukter. Detta betyder att det endast är hela produktionssystemet bedöms och det inte går att separera hur mycket cirkularitet som kan allokeras till de olika samprodukterna. Det kan också vara fruktbart att tillämpa metoden på fler fall, både nationellt inom Sverige och internationellt, för att förstå andra typer av bränslesystem och förfina metoden. Dessutom skulle det vara en värdefull strävan att utforska andra sätt att aggregera insatsernas förnybarhet och återvinningsbarhet. Att fånga det socioekonomiska värdet av cirkularitet visade sig vara svårt på grund av begreppet cirkulär ekonomis vaga, breda och komplexa karaktär. Faktum är att den cirkulära ekonomin kan ge många potentiella välfärdsförmåner, men det är oklart hur dessa välfärdsförmåner ska realiseras och om de ska grupperas under ett cirkulationsstöd eller inte. Det tillvägagångssätt som används här representerar ett första steg mot ökad förståelse kring hur det socioekonomiska värdet av cirkularitet kan fångas och det behövs ytterligare analyser och studier.

Metoderna som utvecklats i detta projekt kombinerades vidare med klimatfördelar eller klimatbegränsande potential vilken här uttryckts som den undvikna samhällsekonomiska kostnaden baserad på GHG-utsläppsbesparing för respektive drivmedelsalternativ. Slutsatserna från denna bedömning följde slutsatserna från cirkularitetsindex där alla studerade alternativ resulterar i höga utsläppsminskningspotentialer (över 75%). De kvantitativa resultaten från denna bedömning kan vara studie- och kontextberoende eftersom de hänvisar till specifika LCA -studier och processdata. Således kan de inte betraktas som ett medelvärde för respektive bränsle.

Vid verifiering på flera olika bränslen visade den metodik som utvecklats i detta arbete för kvantifiering av fördelarna med ökad försörjningstrygghet och cirkularitet att effekterna av försörjningstrygghet är betydligt mindre än de samhällsekonomiska värde som bedöms för minskade klimateffekter för samma bränslen. Gällande cirkularitet så är det estimerade värdet i samma storleksordning som de lägre estimaten för värdet på minskade klimateffekter.

Vidareutveckling av metoden kan innefatta: användning av uppdaterade data i förhållande till LCA-modellerna inklusive en större palett av bränslen som är relevanta från det svenska sammanhanget, undersökning av alternativa sätt att visa upp socioekonomiska kostnader och införandet av fler indikatorer, förutom klimatförändringar, som är av betydelse för transportsektorn. Dessa kan till exempel vara människors hälsa och lokala föroreningsaspekter på grund av partikelutsläpp. Båda metoderna behöver också vidareutvecklas för att mer korrekt uppskatta de viktiga samhällsnyttor som förnybara transportbränslen kan främja. Den nuvarande osäkerheten om deras värdering kan innebära att de överskuggas av de klimatrelaterade fördelarna inom offentlig debatt och politik. Framtida forskning kan försöka uppskatta dessa värden och andra icke-klimatrelaterade fördelar (och kostnader) från förnybara drivmedel för att ge ett bättre politiskt beslutsunderlag.

Sammanfattningsvis tillför studiens resultat perspektiv på nuvarande policydebatt som lägger en stark tonvikt enbart på klimatrelaterade effekter och därför tenderar att missa värden relaterade till andra indikatorer, såsom försörjningstrygghet och cirkularitet. Som ett resultat kan de samhälleliga fördelarna med dessa indikatorer överskuggas av minskade klimatutsläpp, en effekt som detta projekt avser dämpa med de nyutvecklade metoderna.

CONTENTS

1 INTRODUCTION

Valuation of socio-economic benefits is used as a basis for decisions where more perspectives than the strictly commercial ones are considered, such as in public procurement or long-term strategic investments, with other goals than profit. In socio-economic analyzes, different effects are weighed against each other by quantifying the economic value of the effects and the advantages and disadvantages of different systems can thus be evaluated. If methods are lacking to quantify a certain benefit, its effects cannot be valued either and thus there is a risk that the benefit of the measure will not be valued correctly.

This project aims to develop methods to enable quantification of the benefits of security of supply and circularity. The project then evaluates the methods for several value chains for renewable fuels[1] and energy carriers.

i) HVO produced from tall oil

ii) Ethanol from forest residues

iii) Swedish-produced electricity[2]

iv) Biogas from residues such as food waste,

Since the aim the project is to develop methods, the focus is not on the individual fuels and value chains.

The method for quantifying the benefits of security of supply are based on estimates of the sensitivity of the Swedish economy to fuel supply shocks, which are obtained following Kilian (2009). The estimated parameters are then used to calculate a damage function that links the size of fuel supply disruptions to the aggregate cost to the Swedish economy. We then discuss how this fuel security premium can help design renewable fuel policy, and the degree of which domestic production of renewable fuels could help protect the Swedish economy against the effects of global fuel market shocks.

The method for quantifying the benefits of circularity required first developing a method to measure the circularity of fuels. This was done by mapping material and energy flows throughout the life cycle of the fuels. These material and energy flows were then evaluated based on how renewable and how secondary they were. This circularity score was then used in assessing the socio-economic value of circularity in transportation fuels. Here, a revealed preferences approach was used to understand the willingness-to-pay for circularity, which was then used to estimate the socio-economic value.

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[1] We refer to these three biofuels and electricity simply as "the studied fuels", or "the studied fuel systems" or "the selected biofuels and electricity". Thus referring to electricity as a fuel for simplicity.

[2] The average Swedish electricity mix considered in this work can be seen in Appendix, Table A1.

1.1 AIM AND OBJECTIVE

The aim of this work is to

i. Develop a new method to quantify security of supply for transportation fuels.

ii. Develop a new method to quantify circularity for transportation fuels.

iii. Integrate the new methods with existing ones (i.e. climate change mitigation) that quantify the value for society of transportation fuels and create a methodology package that may serve as decision support. The methodology package is in turn applied on selected transportation fuels demonstrating that it can be used to estimated different societal benefits associated with renewable transportation fuels.

1.2 METHODOLOGY

Security of supply

The fuel security premium for Sweden was estimated using a quantitative method following Kilian (2009). As a first step, we estimate the sensitivity of the Swedish economy to fuel supply shocks and then use the estimated parameters to calculate a damage function that links the size of fuel supply disruptions to the aggregate cost to the Swedish economy. We then discuss how this fuel security premium can help design renewable fuel policy, and the degree domestic production of renewable fuels could help protect the Swedish economy against the effects of global fuel market shocks.

Circularity

In order to define a working method for quantifying the circularity of transportation fuels the study drew inspiration from definitions and conceptualizations of circular economy. However circular economy is a rather vague and broad term, with many previously proposed definitions (Kirchherr et al., 2017). Therefore, notable institutions that use and have developed the circular economy concept have been used as a basis for the development of the method. This has been supplemented by prominent definitions of the circular economy concept in scientific literature to formulate the theoretical base for the method.

The Ellen Macarthur Foundation (2021a) describes circular economy as “an economy that is restorative and regenerative by design” based on three key principles, namely, to design out waste and pollution, to keep products and materials in use, and to regenerate natural systems. To further clarify their conceptualization of the circular economy, the Ellen Macarthur Foundations has designed a system conceptualization (Ellen Macarthur Foundation, 2021b), whereby it is clear that the circular economy relies on both circular flows of materials in the anthroposphere (reuse, remanufacturing, and recycling) and on circular flows in the natural sphere by replacing non-renewable materials and energy with renewables. Another prominent user of the circular economy concept is the European union in their Circular economy action plan (European Commission, 2020). While the plan does not provide a clear definition of the concept, it introduces several objectives that can help with understanding their use of the concept[3]. The focus is set on sustainable and circular products and reducing waste; however, it also emphasizes empowering consumers and public buyers with the knowledge to choose circular products over linear. This highlights the need for assessment tools and indicators (otherwise, it would be impossible to choose one product over another based on their circularity). Preliminary indicators used by the EU include self-sufficiency, use of green public procurement, waste generation and recycling, use of secondary raw materials, and investments and patents related to recycling and secondary raw material use (Eurostat, 2021).

In scientific literature, efforts to define circular economy have been made. For example, Geissdoerfer et al. (2017) defines circular economy as "a regenerative system in which resource input and waste, emissions and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". The idea is that in the circular economy resource throughput is slowed and material loops are closed (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Stahel, 2016). Korhonen et al. (2018) provides another definition, aimed at bringing circular economy closer to sustainable development. They define circular economy as "an economy constructed from societal production-consumption systems that maximizes the service produced from linear nature-society-nature material and energy throughput flow. This is done by using cyclical material flows, renewable energy sources and cascading-type energy flows". In this study, what is known as the micro-level circularity is in focus, that is, the product level. Common strategies of circular economy at the micro level are to utilize more secondary materials as inputs, to extend the lifetime of products, and to reuse, recycle, or remanufacture products (Bocken et al., 2016; Kalmykova et al., 2018). The idea is often to increase value by either lengthening the use phase of the product (its lifetime) or to upcycle low-value materials (e.g., residues or wastes) to higher value products. Focusing specifically on energy carriers (transportation fuels in this case) shifts the focus from end-of-life measures, such as reuse or remanufacturing, to the input side as the transportation fuel is consumed in the engine. That is not to say that the end-of-life measures are excluded, since there may be by-products in the transportation fuel production system that can be reused, recycled, or remanufactured. Still our focus shifts from the output side of the system (i.e., what happens with materials and energy after it is used in the system) to the input side of the system (i.e., what has happened to materials and energy before it is used in the system). Furthermore, the consumption of the transportation fuel also means that the slowing of resource throughput is not included in the method as the micro-level strategy that relates to this is to increase product lifetimes. However, in the case of transportation fuels, this is not much relevant, although it can be relevant for certain production and storage facilities as well as for the higher-level perspectives (e.g., reducing fuel use on a societal level). Consequently, our focus is rather on the other micro-level strategies, specifically, utilizing secondary materials and energy as input.

While the above-mentioned approach fits well with the studied energy carriers (biofuels and electricity), it faces some tensions with regards to batteries that are used in the electric vehicles. While

[3] The full list of objectives include: Making sustainable products the norm in the EU; empowering consumers and public buyers; focusing on the most resource intensive sectors where potential for circularity is high such as: electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and building, food, water, and nutrients; ensuring less waste; making circularity work for people, regions and cities; and leading global efforts on circular economy.

our analysis is on fuel and electricity, we have included batteries due to their significance for electric mobility. But unlike the energy carriers that are entirely consumed upon use, batteries can be reused and recycled. Indeed, the used batteries may find another application before they reach their end of life (second life cycle). We appreciate this tension in our approach with regards to batteries but for the sake of being able to provide a unified approach that work for the studied energy carriers we adopt a similar approach for batteries. Similar to the by-products from production system, the recycling of the batteries is included in the analysis, even if the slowing strategy remains out of the focus.

With this in mind, the method that we propose for assessing the circularity of transportation fuels is based on the idea that the use of secondary and renewable materials and energy is of primary concern, due to the characteristics of transportation fuels being consumed upon use. Aspects, such as, reuse, recycling, remanufacturing, and cascading energy on the output side further contributes to the circularity of transportation fuels as they are important micro-level strategies of circular economy thinking (Kalmykova et al., 2018), and many materials and energy carriers used in the production can have multiple life cycles (e.g., batteries). Finally, from the EU's perspective on circular economy, the generation of waste and the criticality (or scarcity) of the materials used are of importance and therefore are reflected in the proposed method. This represents the theoretical basis for the method for assessing the circularity of transportation fuels presented in this report, which is further described in Section 4.1.

Climate change benefits

One of the objectives of this project as listed above, concerns the integration of the new methods (indicating security of supply and circularity) with existing ones towards the development of a holistic approach for illustrating the socioeconomic benefits of alternative transportation fuels. Although various additional parameters would have been of interest to consider, covering different societal aspects, the focus of this section is on climate benefits as a result of reduction in life cycle greenhouse gas emissions which is the main motivation behind the introduction of biofuels and low carbon fuels in the transport sector.

With almost 80% of the energy needs in the transport sector in Sweden today, covered by fossil fuels (SEA 2021a), meeting the climate mitigation goals and achieve substantial emission reductions require changes in the existing fleet. Alternative fuels (including renewable fuels or energy carriers) slowly increase their share in the market. Sweden is among the few countries setting an ambition goal to for net zero GHG emissions by 2045 (UNFCCC 2020). The environmental benefits and more specifically the climate benefits resulting from reductions in greenhouse gas emissions are among the most applied and considered parameters when alternative fuels are evaluated (Fagerström, Lönnqvist & Anderson 2019). Hence, different methods and approaches can be adopted to measure and express those benefits (ibid).

In this work, climate benefits are measured in terms of reduction potential of greenhouse gas (GHG) emissions compared to the fossil alternative and will be expressed as the avoided cost from the equivalent reduction in fossil CO_2.

For estimating GHG emissions reductions potentials, established and standardized methods are available often linked to regulatory and emissions monitoring schemes (European Parliament

2018). Here, the GHG emissions of alternative fuels have been quantified from a life cycle perspective and compared to their fossil counterpart to derive the emission reduction levels. By adopting a life cycle perspective all relevant processes along the fuels value chain are considered. However, a detailed inventory and impact assessment of the studied fuels, was out of the scope of this work. For this reason, GHG emissions were determined based on literature data. The two main criteria applied was i) ensuring coherence and comparability with the production pathways followed in the circularity method and ii) to be representative for the Swedish context. The method for assessing the climate change benefits from the transportation fuels presented in this report is further described in Section 5.

The methods discussed above for evaluating security of supply, circularity and GHG mitigation, were tested by applying them on four alternative fuel value chains: HVO of Swedish origin (and specifically HVO produced from tall oil); ethanol from forest residues; biogas from food waste, and electricity generated in Sweden.

1.2.1 Structure of report

This report is structured as follows:

Section 1 states the aim of the study and provides a brief methodology. The second section provides a background. Sections 3, 4 and 5 explain the three themes security of supply, circularity, and greenhouse gas mitigation and presents the methodology of each theme more in detail. Section 6 combines and sums up the results of the three themes. Finally section 7 provides conclusions and a policy discussion.

2 BACKGROUND AND PRODUCTION POTENTIALS

2.1 BACKGROUND TO THE CONCEPT AND PROJECT FORMULATION

This project is based on the intention to address several of the knowledge gaps identified in previous studies. In the study "Knowledge synthesis: Socio-economic analysis of renewable fuels and drivelines" by Fagerström et al. (2019), analyzes from about twenty studies on the socio-economic effect of different vehicles and drivelines were summarized and discussed. The analysis clearly showed that certain aspects of a socio-economic analysis have more standardized and/or established methods than others and identified several knowledge gaps that this project wants to study in more detail Furthermore, the study "Strategic innovation agenda: The Swedish biogas system - the key to circular economy" by Biodriv Öst from 2017 highlights the importance of developing methods for socio-economic analysis for complex problems and complex societal solutions. It highlights the need for research and development efforts for a number of benefits. Two benefits have been identified as being of particular interest due to their potentially large effect on the combined valuation of the benefits of renewable fuels and the general interest in society for these two benefits. At present, the benefit of security of supply for domestically produced fuels and the benefit of circularity in the fuel production chain cannot be satisfactorily assessed.

Increased security of supply is often highlighted as an important socio-economic benefit for most fuels. Among other things, the state public inquiry into the biogas market from December 2019 highlighted security of supply as one of the main benefits for this fuel but pointed out that this benefit is currently not quantifiable. The same benefit can also be attributed to other domestically produced fuels, such as ethanol and HVO. In the strategic innovation agenda of, among others, Biodriv Öst from 2017, access to domestic fuel production is described as something that provides increased robustness and sustainability in the energy system and thus creates value.

The issue of security of supply is partly also a matter of preparedness. The energy system, and specifically the fuel supply, needs to be prepared for any special events, but this is not the same as Sweden becoming completely self-sufficient in fuel under normal circumstances. It should also be pointed out that increased self-sufficiency does not automatically mean genuine security of supply as there are different risks of interruptions along the entire fuel chain, from production to end users. These risks may look different depending on where and how the fuel is produced but are not eliminated because they are produced nationally. On the other hand, risks specifically linked to import dependence can be considered eliminated with domestic production. Sweden lacks oil sources/extraction of oil but produces biofuels. As biofuels are renewable, this provides a certain security of supply over time. The value of this security depends on how large the production capacity is and how large a part of the fossil import dependence it can correspond to.

Circularity is considered both in Sweden and internationally to be an important aspect for sustainable development. The European Commission states that 'the transition to a more circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible and waste generation is minimized, […] is a necessary part of the EU's work to develop a sustainable, low-carbon, resource-efficient and competitive economy. " Unlike a linear economy that produces waste from new raw materials, the circular economy is resource efficient and creates interconnected cycles. The report from the inquiry into the circular economy states that the basic problem with the linear economy is that natural resources are spread out, mixed and diluted until their economic value disappears. The production of renewable fuels can be circular to varying degrees, but at present there is no quantitative methodology for valuing the socio-economic benefit of the circularity of fuels.

There is thus a knowledge gap to the extent that there is a lack of acceptable methods for quantifying the societal benefits for both security of supply and circularity as a renewable fuel can entail. This gap is in sharp contrast to, for example, reduced climate emissions. There are several methods for quantifying and evaluating emission reductions. The fuels included for the method verification process in this project were selected in dialogue with partner representatives in the reference group for the project. The aim was here to get different types of renewable fuels into the verification and to select those with the perceived highest current volumes in the market to maximize the usability of the results.

HVO

HVO is a drop-in fuel[4]; its chemical properties are equivalent to fossil diesel and HVO may be used in existing infrastructure and vehicles (f3 2016). In Sweden HVO is produced by the company Preem mainly from tall oil. HVO from other companies may be produced from other feedstocks. As shown in Table 1 the use of domestically produced HVO is complemented with imported HVO (Drivkraft Sverige 2021). For more information about this fuel see f3 factsheet on HEFA/HVO.[5]

Biogas from anaerobic digestion

Biogas can be produced through anaerobic digestion of sewage sludge, food waste, industrial residues, and agricultural residues such as manure and crop residues, as well as dedicated energy crops. The raw gas from the process is upgraded from approx. 65 % methane to 97 % methane and can then be used as vehicle gas, a transport fuel. This fuel requires dedicated distribution infrastructure and vehicles.[6] Biogas can also be produced from other raw materials and through other conversion processes, e.g. gasification of forest biomass. For more information about this fuel see f3 factsheet on biogas/biomethane/SNG.[7]

Ethanol from cellulose

Ethanol may be produced from woody biomass through hydrolysis and fermentation. This is called second-generation ethanol to distinguish it from so called first-generation ethanol that is normally

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[4] A drop-in fuel may be blended into e.g. conventional diesel or, in some cases, replace it completely.

[5] f3 (2016). *HEFA/HVO, Hydroprocessed Esters and Fatty Acids*. Factsheet. Available: https://f3centre.se/sv/faktablad/hefa-hvo-hydroprocessed-esters-and-fatty-acids/

[6] This distribution infrastructure is semi-established in Sweden. There is a natural gas pipeline in south-western Sweden and other distribution solutions in Mälardalen and other regions but not in the whole country. The gas vehicle fleet is limited to ap. 50 000 vehicles, mostly passenger cars, equivalent to 1% of the total fleet (Energigas Sverige 2021).

[7] f3 (2016). *Biogas/Biomethane/SNG*. Factsheet. Available: https://f3centre.se/en/fact-sheets/biogas-biomethane-sng/

produced from food or energy crops. There are two types of hydrolysis: enzymatic and weak acid. In Sweden the largest ethanol production facilities are based on crops as feedstock, Agroetanol. Domsjö Fabriker has a facility based on woody biomass (Bioenergitidningen 2021). The company SEKAB buys ethanol from Domsjö fabriker and blends it to E85 (15 % gasoline, mainly used in cars) and ED95 (5 % diesel, mainly used in trucks and busses). For more information about this fuel see footnote.[8]

Electric vehicles

Electricity as fuel requires dedicated distribution infrastructure and vehicles. The number of electric vehicles is increasing rapidly in Sweden, by 81 %, from March 2020 to March 2021 according to Powercircle (2021). Albeit from low levels, as over 200 000 vehicles, are chargeable, i.e. either electric (29 %) or hybrid (71 %) (ibid). This is equivalent to 4 % of the total vehicle fleet. For more information about electric vehicles development in Sweden see statistics by e.g. Power circle [9].

2.2 PRODUCTION POTENTIAL

In Table 1 estimations of the domestic production potential for various biofuels are presented. The purpose is to give an *indication* of what role the fuel and technology could play in terms of security of supply, but also in terms of how significant the contribution to circular economy it could make. The table also presents the current production capacity as well as the current use of biofuels in Sweden.

[8] f3 (2020). *Biochemical conversion of lignocellulosic biomass*. Factsheet. Available: https://f3centre.se/sv/faktablad/biokemisk-omvandling-av-lignocellulosa/; Lönnqvist, T., Grönkvist, S., Sandberg, T. (2015) *How can forest-derived methane complement biogas from anaerobic digestion in the Swedish transport sector?* Report No 2015:11, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available: https://f3centre.se/app/uploads/f3_report_2015-11_methane_from_forest_biomass_20160218.pdf

[9] Powercircle (2022). Milstolpen 300 000 laddbara fordon passerades vid årsskiftet. Press release 13 January, 2022. Available: https://press.powercircle.org/posts/pressreleases/milstolpen-300-000-laddbara-fordon-passerades

Table 1: Production potential for 2030 for the transportation biofuels included in the study

Fuel	Type of feedstock	Domestic production potential 2030	Current production capacity in Sweden	Current use in Sweden
HVO	Tall oil (a residue from pulp industry)	4 TWh_{pa} by 2030 (Martin et al. 2017) 10 TWh_{pa} by 2050 (Karlsson et al. 2020)	1,9 TWh (Bioenergitidningen 2021)	11 TWh (Drivkraft Sverige 2021)
Biogas (anaerobic digestion)	Sewage sludge, food waste, industrial residues, agricultural residues, crops grown on fallow land	7 TWh_{pa} by 2030 (Lönnqvist 2017) (SOU 2019)	2.1 TWh (1.3 TWh upgraded) (SEA 2020a)	4 TWh (SEA 2020a) Where of 1,6 TWh as transport fuel
Ethanol (2nd generation)	Forest residues	3 – 4 TWh_{pa} by 2030 (Martin et al. 2017)	0.13 - 0.15 TWh (Bioenergitidningen 2021; SEKAB 2021)	0.85 TWh (Drivkraft Sverige 2021)
Electric vehicles (EV)	N.a. Other limitations e.g. transmission & distribution capacity of the electricity system, materials for batteries in EVs, etc. apply.			

3 SECURITY OF SUPPLY

The role of fuel as a critical input to the economy gained traction decades ago in part because of the oil crises of the 1970s. In this context, economists and analysts recognized that dependence on oil is likely to yield social costs more than the market price paid for oil. The basic idea is that shortages in fuel supply (negative supply shocks) propagate through the economy and have economic impacts that go beyond the direct impact of the fuel shock on the market price of fuels. For example, one channel for this mechanism is that an increase in the price of fuel increases transportation costs, which in turn affects the costs of goods and services, reduce consumer budgets and slow investment and in aggregate dampen Sweden's GDP growth. These GDP losses are external to the price of fuel. From a social point of view, Sweden would be willing to pay a premium to secure its supply of fuel and avoid these losses. This premium is referred to as a fuel security premium.

In this part of the project, we estimate the fuel security premium for Sweden. To do this we first estimate the sensitivity of the Swedish economy to fuel supply shocks following Kilian (2009). We discuss these estimates and use them to derive a damage function that links the size of fuel supply disruptions to the aggregate cost to the Swedish economy. We then discuss how this fuel security premium can help design renewable fuel policy, and the degree domestic production of biofuels could help insure the Swedish economy against the effects of global fuel market shocks.

The method used to estimate the fuel security premium is based on the idea of a marginal benefit of an additional unit of fuel consumption. The security premium is based on the reduction in Swedish economic output arising from sudden, unexpected, disruptions in the supply of fuel. The basic measure that we use is based on the idea of the marginal impact of fuel supply disruptions to economic output. Leiby (2007) discusses other components (such as the monopsony premium, international transfers) that can also be included in the calculation of the fuel security premium, although the impact on economic output is probably the most important, Brown and Huntington (2015).

3.1 ESTIMATING THE DEPENDENCY OF THE SWEDISH ECONOMY ON FUEL

Researchers have developed numerous approaches to assess the macroeconomic impacts of fuel supply shocks to derive fuel security premiums, see Brown and Huntington (2015) for a review of this literature and a discussion of the evolution of these approaches. For this project, we follow the methodology of Kilian (2009) to estimate the impact of fuel supply shocks on the Swedish economy. We follow Kilian's methodology (ibid) because of its relative simplicity, which makes it easier to interpret the results. A challenge that Kilian's methodology seeks to address is that the price and quantity of fuel and GDP growth are intertwined. A decrease in fuel supply can raise fuel prices and dampen GDP growth, but GDP growth can also drive changes in fuel prices. Kilian's methodology seeks to disentangle supply and demand shocks in the global oil market using a Structural Vector Autoregression (SVAR).

We replicate SVAR methodology used by Kilian to decompose the changes in Swedish GDP into orthogonal components, which are the global quantity and price of fuel supplied. The point of the exercise is to illustrate the type of methodology that can be deployed to disentangle the impact of fuel supply shocks on the economy. We will use the estimate in the context of the estimates obtained by other researchers using other methods. The model uses monthly data for the percent change in global fuel production, to disentangle the supply and demand shocks to the fuel market.

Following Killian (2009) notation, with monthly data $z_t = (\Delta prod_t, rea_t, rpo_t)'$ where $\Delta prod_t$ is the percentage change in global fuel production, rea_t is an index capturing monthly Swedish GDP growth and rpo_t is the real price of oil in Swedish Crowns. The SVAR is represented by

$$A_o z_t = \alpha + \sum_{i=1}^{T} A_i z_{t-i} + \varepsilon_t, \qquad (1)$$

where ε_t is a vector of serially and mutually uncorrelated structural shocks, and reduced form errors can be represented by $e_t = A_0^{-1}\varepsilon_t$.

$$e_t \equiv \begin{pmatrix} e_t^{\Delta prod} \\ e_t^{rea} \\ e_t^{rpo} \end{pmatrix} = \begin{bmatrix} a_{11} & 0 & 0 \\ a_{21} & a_{22} & 0 \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{pmatrix} \varepsilon_t^{oil\ supply\ shock} \\ \varepsilon_t^{aggregate\ demand\ shock} \\ \varepsilon_t^{oil-specific\ demand\ shock} \end{pmatrix}$$

The matrix A_o^{-1} has a recursive structure that assumes a vertical short-run supply curve of fuel, which is a key assumption of the model. This means that changes in e_t depend on the timing of the oil supply shocks and demand shocks. For example, e_t^{rpo} can be driven by simultaneous changes in $\varepsilon_t^{aggregate\ demand\ shock}$ or $\varepsilon_t^{oil-specific\ demand\ shock}$ but $e_t^{\Delta prod}$ depends only on simultaneous changes in $\varepsilon_t^{oil\ supply\ shock}$.

This restriction is motivated by assuming that quantity of global fuel supply cannot respond to fuel demand within the same month because of it takes time to adjust oil production and because of the difficulty in obtaining information about the state of the fuel market within the same month.

The methodology uses price and quantity shock data for the global oil market, however as Kilian (2009) points out, the estimates obtained from this method are valid for fuels that are close substitutes to oil-based fuels, which to some degree is the case for some of the renewable fuels being studied in this project such as diesels and less so for other renewable fuels such as biogas and electricity. As far as we know, there is yet no methodology in this literature that differentiates between different fuel types.

3.2 DATA

We use monthly data on Swedish GDP from the OECD (Woloszko (2020)), which uses a novel methodology to track monthly Swedish GDP based on data from Google Trends. We gather global oil prices and quantities from Federal Reserve System (US) (2021). Our data spans 119 months over the period from February 2010 through to December 2020. Figure 1, Figure 2, Figure 3 plot the variation in the three variables used in model (1), and are the basis for the computation of the vector $z_t = (\Delta prod_t, rea_t, rpo_t)'$.

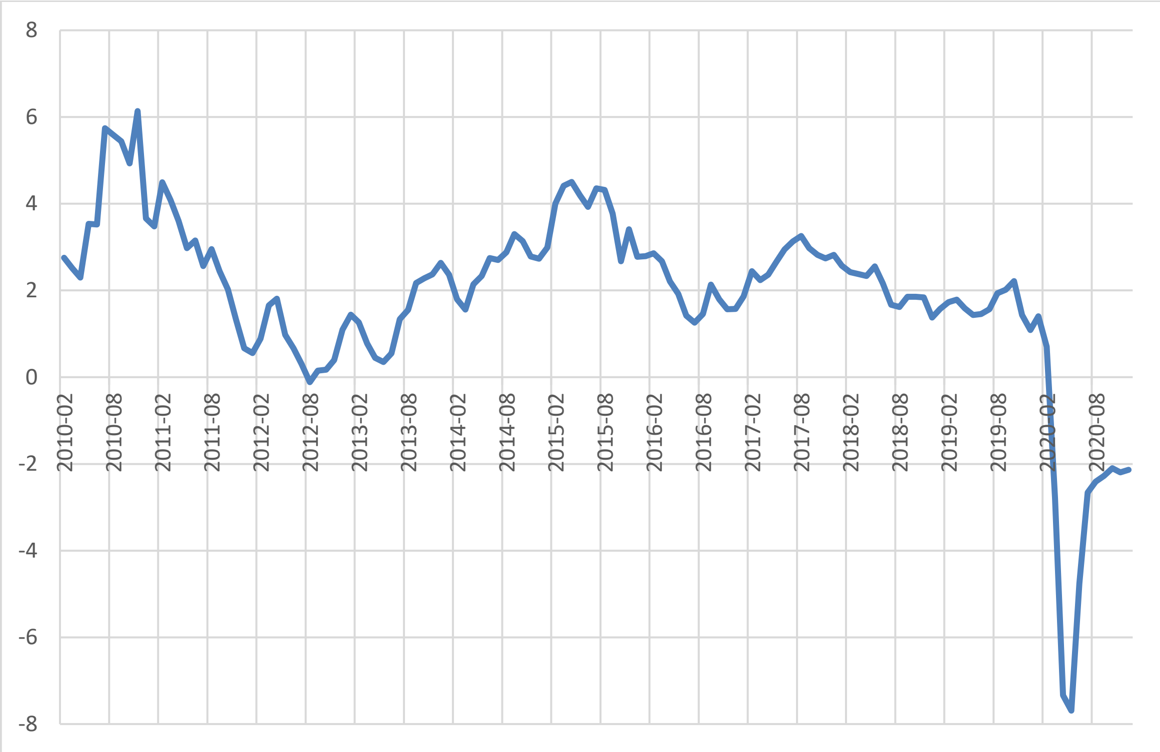

Figure 1. Index of monthly Swedish GDP growth in percent (source Woloszko (2020)).

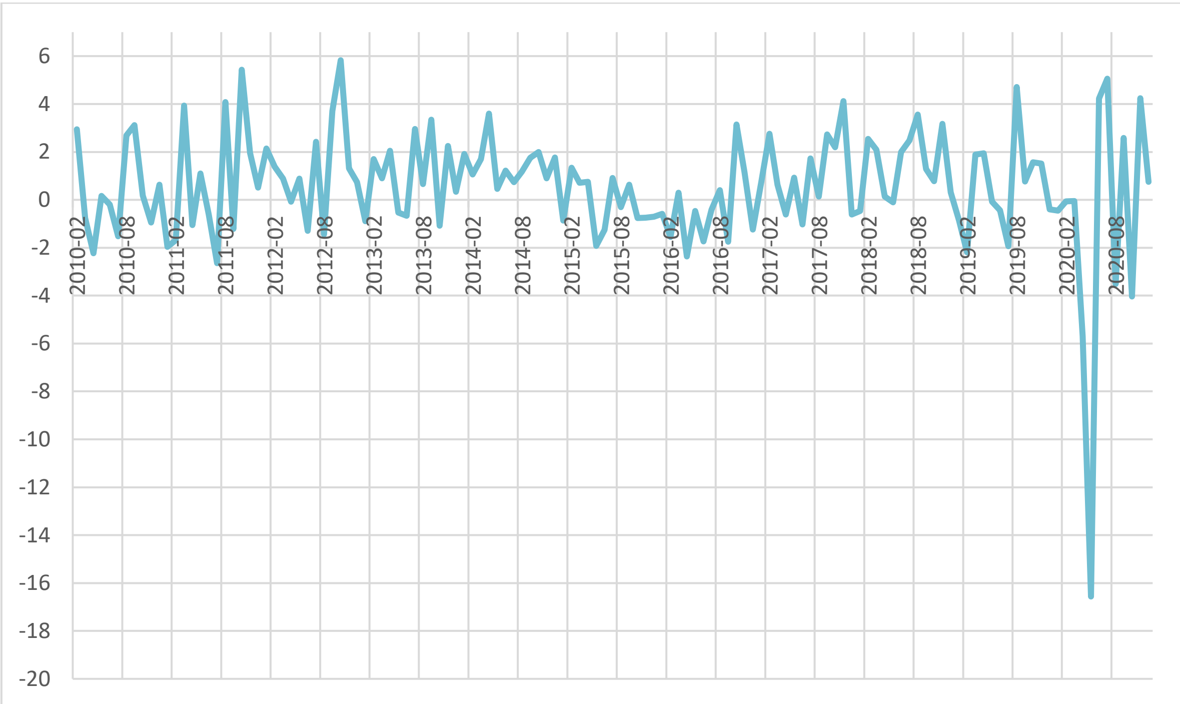

Figure 2. Monthly global oil production growth in percent (source Federal Reserve System (US) (2021)).

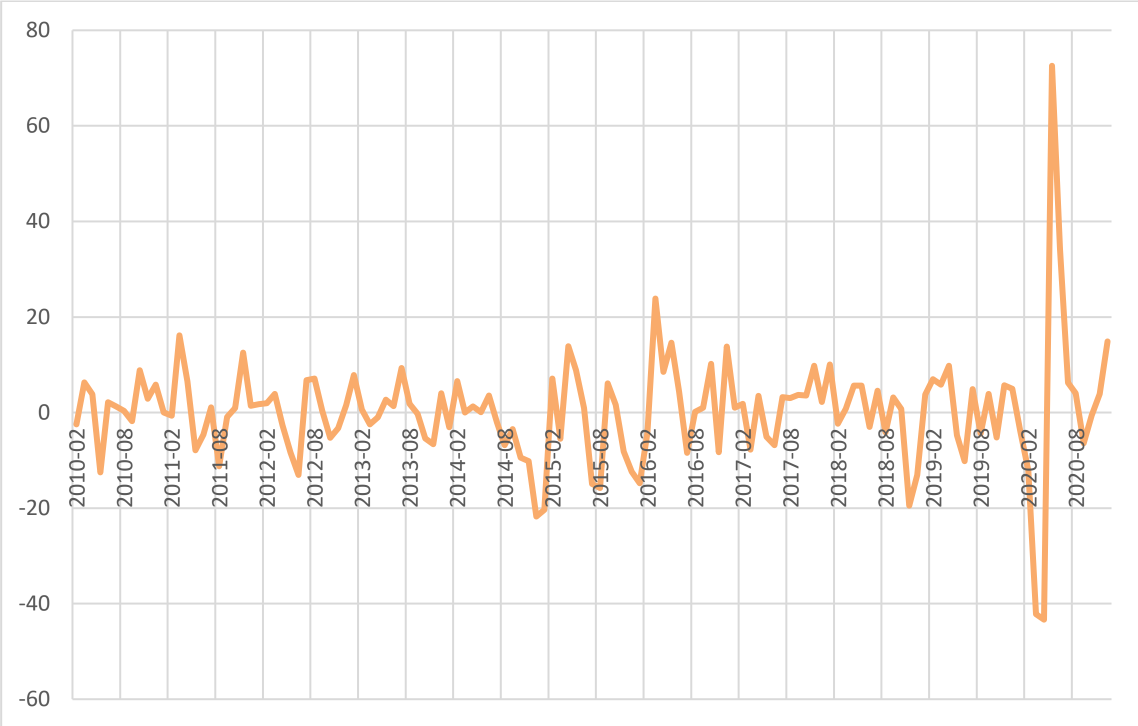

Figure 3. Monthly global oil price growth in percent (source Federal Reserve System (US) (2021)).

Note that the effect of COVID-19 figures prominently in all three time series variables. These shocks were first driven by the collapse in demand for fuel as responses to the pandemic took hold, restricting mobility and thereby demand for fuel. Fuel prices dropped and oil producers responded by cutting oil production, which resulted in fuel prices rebounding. Table 2 summarizes the shape of the key variables.

Table 2. Descriptive statistics of the variables use in the SVAR analysis.

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
$\Delta prod$	119	.007412	.0176107	-.0265139	.0582688
rea_t	119	.0236807	.0122435	-.0011428	.0613667
rpo_t	119	.000787	.077372	-.2177068	.2384565
Date	119	NA	NA	2010-02	2020-12

3.3 SVAR RESULTS

The estimates from the SVAR model yield an impulse-response function. The impulse response function captures the dynamic effect of an oil-price shock to GDP and is a graphical representation of the estimates derived from the SVAR model, where the impulse is the oil supply shock and the response is GDP. This is a standard way of communicating results of time-series analyses. Figure 4 is an illustration of the change in Swedish GDP from a one standard deviation fuel price shock (which is 7.7% increase in the price of oil, see Table 2). The result is derived using the full period through to the end of 2020, which includes the COVID crisis. The results change only slightly if we exclude 2020 observations.

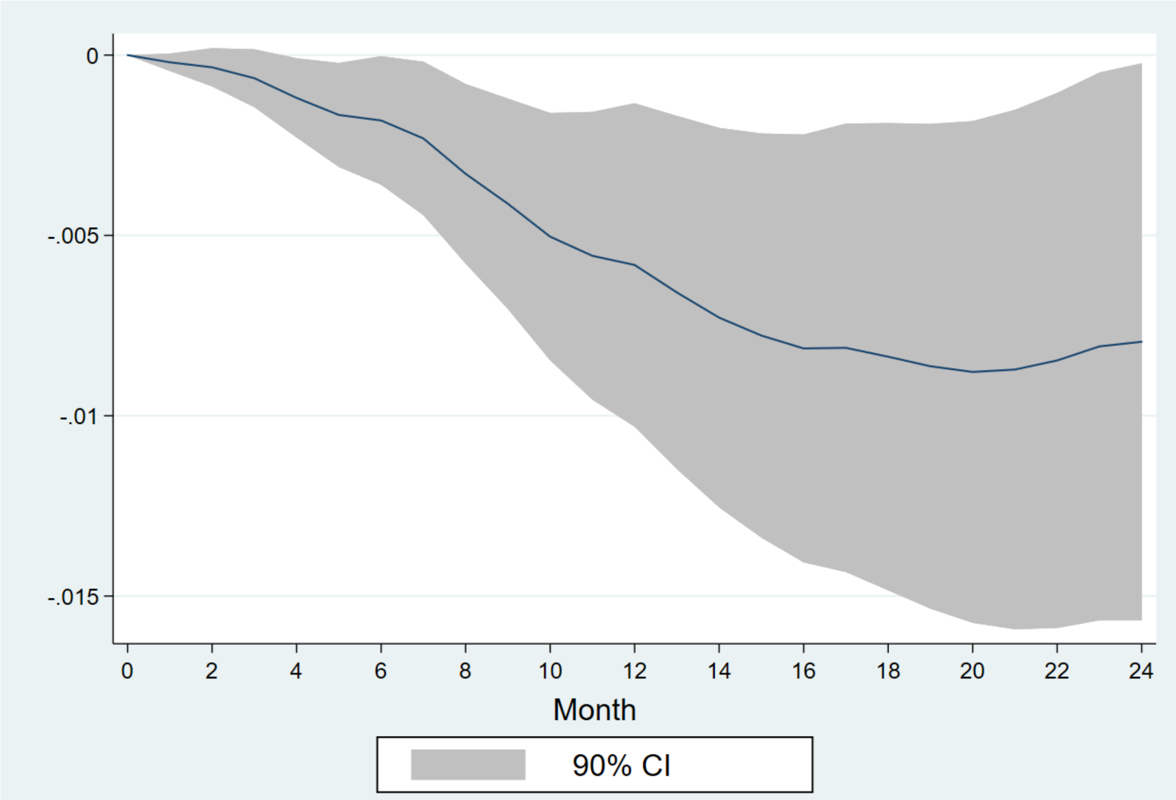

Figure 4: The impulse-response plot for a one standard deviation supply-driven fuel price shock on the Swedish GDP (cumulative), the shaded area is the 90% confidence interval.

Taken at face value, a one standard deviation increase in fuel price (the impulse) would yield around a 0.7% decline in Swedish GDP. From this we can derive the elasticity of Swedish GDP with respect to the price of oil, which is

$$\eta_{GSE} = \frac{0.7\%}{-7.7\%} = -0.10$$

This is within the bounds of the econometric estimates found in the literature for the USA, albeit at the higher end. Reviews of earlier econometric estimates in the literature and finds elasticities that are in the range of -0.012 to -0.12, and the US department of Energy uses values between -0.025 and -0.055 for the USA, see Jones et al. (2004). More recent estimates of this elasticity are at the lower end of these ranges, Brown and Huntington (2017). Many of these estimates are based on decades of observations, going back 20 or so more years. The estimate captures the sensitivity of the Swedish economy to oil supply shocks. A more negative elasticity suggests that a given oil price shock has a larger impact on GDP, and there would be no impact on GDP if the elasticity were zero.

It is interesting to compare the Swedish estimate to the US estimates and note that they are similar. Official GDP statistics are often available only quarterly, which is infrequent enough to miss out on some of the important dynamics between the fuel market and the aggregate economy. This is one of the reasons Kilian (2009) devotes the first part of the research to developing an index that captures higher frequency variations in global output, based on shipping costs. In contrast, the Swedish

GDP data is imputed using a different methodology based on Google Trends data, which captures shorter run variations in GDP that may be missed with the more readily available quarterly GDP.

Of course, another reason for the higher estimate for Sweden versus the US is that Sweden's economy is very different from the US economy in ways that affect the estimate of η_{GSE}. A rigorous analysis of the reasons for these differences is beyond the scope of this project but it is still useful to outline some hypotheses behind the difference.

For one, Sweden is a much smaller and more open, trade intensive, economy than the US. This means that fuel price shocks could affect the Swedish economy via trade flows more than it could affect the US. For example, a global fuel price shock would reduce demand for Swedish exports to Germany, and make Swedish imports from Germany more expensive, augmenting Sweden's exposure to fuel price shocks.

At the same time, Sweden's transportation fleet is both more fuel efficient than the US and distance driven in Sweden are generally shorter than in the US ,IEA (2020), which would suggest a lower η_{GSE} for Sweden. The structure of the Swedish economy, its overall energy mix, tax policies and other factors also probably play a role in determining the estimate of η_{GSE}. The interaction and strengths of these different mechanisms are probably to some degree driving the higher estimate.

The SVAR methodology does not allow us to delve into the contributing factors to the estimates of the interaction between GDP and the global fuel market, which is a drawback of the method. Structural analysis of these issues can help shed light on the specific channels that determine how exposed Sweden is to disruptions in the global fuel market but require many assumptions about structure of the economy. Krupnick at al. (2017) review an example of a structural (Dynamic Stochastic General Equilibrium - DSGE) approach to modelling similar issues.

3.4 EXPECTED SWEDISH GDP LOSSES FROM FUEL SUPPLY DISRUPTIONS

We follow the methodology outlined by Brown (2018) to calculate the expected Swedish GDP losses from fuel supply disruptions. Their methodology was derived to capture the GDP losses to the US economy, which considers domestic US production and consumption of fuel, which can be ignored for Sweden as it is much smaller relative to global production. This simplifies the calculations and reduces the number of parameters required for the calculation.

The objective is to link each size of a disruption to a resulting loss in Swedish GDP – a so called damage function that maps disruptions to economic output. The theory links a disruption in the quantity of fuel supplied to Swedish GDP, through the price of fuel. For a given disruption in fuel supply D_i, the resulting loss in GDP in given year is

$$\Delta Y_i = Y_{SE}\big(1 + \Delta P_i(D_i)\big)^{\eta_{GSE}} \qquad (2)$$

Y_{SE} is Swedish GDP in 2020, and η_{GSE} is elasticity of Swedish GDP with respect to oil prices estimated above. A global quantity of fuel consumed Q_w and a disruption D_i are associated with a change in the price, which follows the function

$$\Delta P_i(D_i) = \left[\left(\frac{Q_w - D_i}{Q_w} \right)^{\frac{1}{\eta}} - 1 \right]$$

Where $\eta \equiv \eta_{DROW} + \eta_{YROW}\eta_{GROW} - \eta_{SROW}$ captures global fuel market dynamics and includes η_{DROW} is the elasticity of fuel demand in the rest of the world, η_{YROW} is the rest of the world's income elasticity of fuel demand, η_{GROW} is the elasticity of global GDP with respect to fuel prices, and η_{SROW} is the short-run price elasticity of Rest of World (ROW) oil supply.

These four elasticities that capture global fuel market characteristics can be obtained from the literature (see Brown and Huntington (2015) for a discussion). With these equations, and the parameter estimates in Table 3 we can link disruptions in fuel supply to Swedish GDP losses. This is the estimated damage function from global fuel supply disruptions to which the Swedish economy is exposed to, which are summarized in Table 2 column 3.

Table 3: Parameter values used in the calculation of Swedish GDP losses resulting from global disruptions in fuel supply.

Parameter	Value	Source
η_{GSE}	-0.10	Author's SVAR estimate
η_{DROW}	-0.05	Brown and Huntington (2017)
η_{YROW}	0.07	Brown and Huntington (2017)
η_{GROW}	-0.05	Brown and Huntington (2017)
η_{SROW}	0.05	Brown and Huntington (2017)
Q_w	100 million barrels	US Energy Information Admin., Eia.gov , 2019
Y_{SE}	5 049 619 Mkr.	Statistics Sweden, www.scb.se

Integrating the damage function over the probability distribution of global fuel supply disruptions yields the expected Swedish GDP losses for any given supply shock event characterized by its size in millions of Barrels of oil per day (BPD) and an annual probability, see Table 4 columns 1 and 2, respectively. Brown (2018) provide the annual probability distribution, which we use to calculate the expected gross domestic product (GDP) losses for any given year, which is summarized in Table 4 column 4. The results of the calculation are summarized in Table 4.

Table 4: provides an overview of the gross domestic product losses associated with each supply disruption D_i, the expected GDP losses, over the probability distribution of the disruptions.

D_i	Annual	GDP loss	E(GDP loss)
Million BPD	probability	MSEK.	MSEK.
0	89,960%	0	0
1	0,369%	-39 835	-147
2	1,215%	-79 772	-969
3	1,500%	-119 812	-1 797
4	1,650%	-159 958	-2 639
5	0,978%	-200 210	-1 958
6	0,876%	-240 570	-2 107
7	1,050%	-281 040	-2 951
8	0,800%	-321 620	-2 573
9	0,499%	-362 313	-1 808
10	0,259%	-403 120	-1 044
11	0,312%	-444 043	-1 384
12	0,213%	-485 083	-1 033
13	0,087%	-526 243	-456
14	0,088%	-567 523	-499
15	0,005%	-608 927	-28
16	0,053%	-650 455	-343
17	0,013%	-692 110	-93
18	0,011%	-733 893	-78
19	0,012%	-775 807	-95
20	0,002%	-817 854	-20
21	0,011%	-860 037	-91
			-22 114

The estimated damages increase with the size of the fuel supply disruption, but the probability falls with the size of the disruption, see figure 5. The expected annual GDP loss resulting from fuel disruptions is about 22 billion SEK[10]. The security premium per liter of fuel follows directly from these calculations and is around 0,7 SEK per liter of fuel and increases slightly with the size of the supply disruption following equation (2).

[10] Expected losses are calculated as the product of the losses associated with a supply shock and the probability of the supply shock occurring in a given year. For example, if a supply shock of 7 milllion barrels a day has a 1% probability of occurring in a given year and would result in a loss of 281 billion SEK. then the expected loss from that shock is 1% of 281 billion SEK., or 2.81 billion SEK. In a given year, the expected economic loss is the sum of all expected losses across all probable oil shock events, i.e. annual probabilities in Table 4 sum to 1,0 and the expected losses sum to 22 billion SEK.

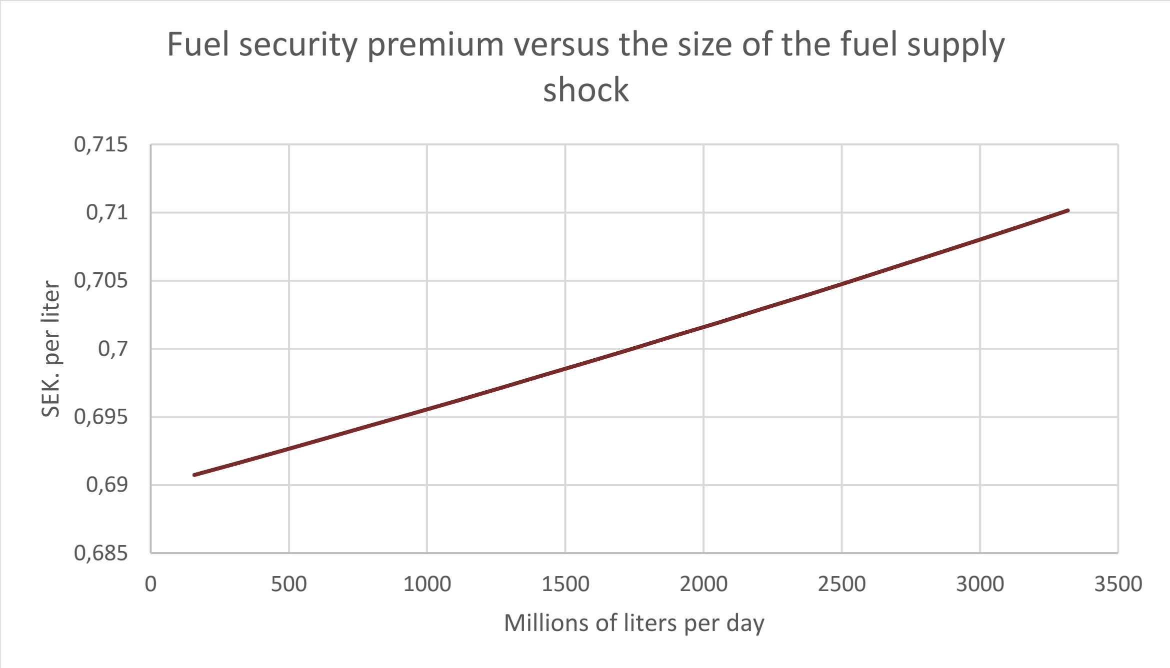

Figure 5: Fuel security premium in SEK. per liter as a function of the size of the fuel supply shock.

3.4.1 Damages not captured by SVAR method

These GDP losses based on the assumption that global fuel supply and demand follow market forces, i.e. prices adjust and markets are cleared and the GDP losses arise through the higher price of fuel paid and the resulting impact on the economy. The elasticities used to calculate this damage, including but not limited to the elasticity of GDP to fuel price shocks, is estimated around the market "equilibrium" and damages are a function of these elasticities that capture the interaction between the global fuel market and the aggregate economy.

What is not captured are the GDP losses arising from fuel disruptions that are severe enough to limit the capacity of essential services or to fuel the military. Discussions of fuel security often revolve around these uncertain but potentially very damaging events, which may arise from conflict/war or other catastrophes. Diving into this discussion is outside the scope of this project, but these damages are probably increasing at an increasing rate, i.e. Massive fuel supply disruptions have a disproportionately large economic impact. The intuition for these increasing damages is straightforward: essential functions which are very valuable to society (by definition) cease to operate in cases of extreme fuel shortages. With smaller fuel supply disruptions, essential services can continue to operate. Moreover, damages from a stop in essential services are hard to quantify in monetary terms and their probability of occurring is also difficult to quantify (uncertain). These types of severe damage events under structural uncertainty are a particularly thorny problem that researchers have had to wrestle with, e.g. Weitzman (2009).

The Swedish Energy Agency is responsible for managing Sweden's exposure to these extreme events, and managing this risk is one of the motivating factors for holding strategic fuel reserves, which can be used to dampen the effects of the worst fuel shortages[11].

3.4.2 How can we reduce the damage?

The damages from fuel supply disruptions arise from our heavy dependence on a single commodity, oil, which continues to play a critical role in much of the transportation and mobility services that we rely on. For a given level of Swedish fuel demand, shifting to renewable fuel sources would clearly reduce Sweden's exposure to disruptions to the oil market, but may increase Sweden's exposure to other disruptions in the supply of other transportation fuels/energy carriers (e.g. electricity supply disruptions)[12].

However, Sweden's domestic capacity to produce renewable fuel would to some extent help insure Sweden against oil supply disruptions. Moreover, there would be a social benefit from reduced emissions of greenhouse gases and other pollutants. The dual benefit of reduced dependence on oil imports, a more diverse fuel mix, and the benefit to the climate would work in favor of policies designed to boost domestic biofuel production.

The potential climate benefits notwithstanding (see section 5), the case for domestically produced renewable fuel's ability to reduce the impact of oil supply disruptions depends in part on the ability to substitute between fuel types, as well as how domestically produced fuel use can be controlled and/or constrained.

Some renewable fuels are perfect substitutes with petroleum-based fuels, e.g. biodiesel is blended with diesel and bioethanol is blended with petrol.[13] Domestically produced renewable fuels that are perfect substitutes with their petroleum-based counterparts have a limited scope to reduce the impact of oil price shocks on the Swedish economy unless they can be produced in sufficient quantities to affect global fuel market outcomes (which it is probably safe to say is not the case) or if exporting domestically produced fuels is prohibited, Nordhaus (2009). Higher fuel prices abroad would lead Swedish producers to export their fuel, which in turn would mean little impact on local Swedish fuel prices.

On the other hand, fuels that are poor substitutes with petroleum-based fuels, such as electricity, reduce Sweden's dependence on oil imports. Electricity could also help ensure Sweden's economy

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[11] See Regeringens proposition 2020/21:30. Available: https://www.regeringen.se/4a965d/globalassets/regeringen/dokument/forsvarsdepartementet/forsvarspropositi on-2021-2025/totalforsvaret-2021-2025-prop.-20202130.pdf

[12] Reducing overall demand for fuel through efficiency improvements would translate into a lower η_GSE elasticity of GDP with respect to oil price shocks.

[13] Some biodiesel types such as FAME are restricted to 7 % blend-in or as pure biodiesel if approved by vehicle manufacturer. Other biodiesel types such as HVO that is studied in this report can be interchanged perfectly with fossil diesel. Ethanol may be blended-in 10 % in gasoline in Sweden which is approved for most vehicles or used as E85 (85 % ethanol and 15 % gasoline) for specially adapted vehicles.

against unforeseen short-run oil supply shocks to the degree that Swedish fleets could substitute to a degree between electricity and fossil fuels, e.g. plug in hybrids.

In the same light, we can argue that biogas (as transport fuel) has a special status. From the perspective of the engines, it is a perfect substitute for fossil alternatives such as natural gas or diesel fuel. But at the same time, it is not as easy to be transported over long distances (e.g. exported) at a cost-efficient manner; especially in Sweden where the coverage of gas grid is limited to certain areas. Long distance transportation of biogas in LBG form is easier and more affordable, but lot of upgraded biogas is transported in compressed form or in local gas networks. So, biogas is different from HVO/ethanol (liquid fuels) in the sense that its production and use is more spatially bounded. From the perspective of security of supplies this is a strength as in case of international shock in oil prices, a large fraction of the produced biogas will most likely remain in the country.

Both electric and gas vehicle fleets are relatively small in Sweden compared to the total vehicle fleets (Lönnqvist 2017; Power Circle 2021).

3.5 KEY INSIGHTS AND REMARKS

Fuel security is often discussed in terms of avoiding the worst effects of a catastrophic fuel shortage. We estimate a function that links economic damages to fuel supply shocks. The analysis is based on high frequency (monthly data) over the 119 months from 2010 through to 2020 inclusive, and provides some insights on the role that renewable fuels can play in reducing Sweden's exposure to disruptions in global fuel markets:

- There are potentially significant losses in economic output arising from smaller fuel supply shocks with a higher annual probability of occurring.
- We find that the annual expected GDP losses from fuel supply shocks is around 22 billion SEK, an estimate that does not consider the value of essential functions such as the military.
- Domestic Swedish production of renewable fuels can help to some extent dampen the impact of global fuel supply disruptions on the Swedish economy.
- Fuels that are a poor substitute to petroleum fuels such as electricity or biogas (due to it being more spatially bounded compared to other biofuels), can dampen the impact to the extent Swedish fleets can switch between fuel types.
- Fuels that are good substitutes to petroleum fuels (bioethanol and biodiesels) can also dampen the impact provided they are supplied with use restrictions like those governing the distribution of strategic fuel reserves.
- Decreasing Sweden's dependence on oil-based fuels will reduce Sweden's exposure to the economic impact of oil supply disruptions but will increase Sweden's exposure to supply disruptions affecting other fuel types.
- Domestic fuel production can only support fuel supply security to the degree that production/supply shocks are uncorrelated across domestic and foreign fuel types. Having an economy that depends on different fuel types that are produced from distinct supply chains

will help protect the economy against shocks to the supply of one fuel - the benefit of a diversified fuel portfolio.

- Sweden's strategic fuel reserves help protect Sweden from the effects of a catastrophic fuel shortage. The effectiveness of the strategic reserve in dampening the impact of fuel disruptions relies in part on the ability of the government to restrict how the reserves are used (e.g. exclude export).

4 CIRCULARITY

In this section, the method and results for assessing and evaluating the circularity of the studied fuel production systems are presented. The method builds on the methodology presented in Section 1.2 and is divided into two distinct parts. The first part (Section 4.1 and 4.2) details the method to assess the circularity of the studied production systems and how circular each production system can be. In the second part (Section 4.3 and 4.4), the method and results are shown for the evaluation of the socio-economic value of the circularity of each respective production system.

4.1 METHOD TO ASSESS CIRCULARITY

The first part of the assessment is to identify the key material and energy inputs and outputs of the studied transportation fuel production system. This should include material and energy used in the entire life cycle of the fuel excluding its combustion or use (a so-called well-to-tank boundary). This system boundary was chosen as the primary concern of the assessment method is the fuel production and not the consumption and use of the fuel (see section 1.2 for why the production and input side is in focus). This typically includes collection, extraction, or cultivation of raw materials, various production and refinement processes, and distribution of the fuel. Infrastructure changes and the vehicle itself are excluded since their contribution to the circularity of transportation fuels is negligible compared to the material and energy used to produce the fuel. An exception is made for the batteries in the electric mobility pathway, which are included since they represent a large part of the potential circularity or linearity of that particular fuel system. After this is done a functional unit that represents the primary output of the system is chosen drawing inspiration from life cycle assessment literature (Bjørn et al., 2018). In the case of transportation fuels, this is usually a specific amount of fuel produced, for example, 1 MJ of fuel. The chosen functional unit is not of the same importance as in life cycle assessment since the result of our method (i.e, the circularity score) is a unitless ratio. Subsequently, the functional unit is simply used as a steppingstone to the final results. Therefore, if the system boundaries are not changed, changes to the functional unit does not impact the results (assuming it is a unit used to represent an amount of vehicle fuel). After the functional unit is defined, the amount of each key material and energy input to produce the defined functional unit is calculated. Similarly, the amount of co-products or by-products that are produced within the system are calculated based on the functional unit. For simplicity in this project, the life cycle of each studied fuel is divided into three phases: collection, production, and distribution. Collection represents the collection, extraction or cultivation of raw materials used in the production of the transportation fuel. Production includes energy and material inputs needed at the production facility to refine the raw materials. Finally, distribution includes energy and materials needed to distribute the transportation fuel (and possible co-products) to the end-user.

Next, two indicators are assessed for each energy and material input, namely, *recyclability* and *renewability*. Recyclability refers to whether the material or energy input is of secondary nature, that is, if it isa reused or recycled material or previously cascaded energy flow. Renewability, on the other hand, refers to whether the material or energy is renewable or not, reflecting the emphasis on renewable material and energy sources as well as the importance of utilizing natural cycles in the circular economy. Each key material and energy input identified is assessed based on how recyclable and renewable it is.

Table 5 shows some examples of ideal-typical materials and energy carriers as well as how they would score regarding recyclability and renewability. This is shown to aid in understanding how various types of materials and energy inputs would score when applying the method. In reality, very few materials and energy carriers are, from a life cycle perspective, fully renewable or fully secondary, however, the idealized view is helpful to understand how similar materials and energy carriers may perform. We argue that since the primary purpose of this study is method development, using these ideal-typical values is justified. However, in case-specific and more empirically based analysis it is important to provide a realistic estimate of renewability and recyclability of all key input flows.

Table 5. Ideal-typical input flows and how these would score regarding recyclability and renewability. In reality, some of the example flows would possibly score differently, for example, due to the use of non-renewable material or energy use in their respective life cycles. The double tilde sign (≈) indicates approximately equal as the renewability and recyclability as many of the input flows are simplified to their ideal values.

Type of flow	Examples	Renewability	Recyclability
Material, secondary, biological	Wastewater from pulp and paper mill, municipal wastewater	≈100 %	≈100 %
Material, secondary, mineral	Scrap aluminum, shredded metals	0 %	≈100 %
Energy, secondary, renewable	Residual heat from ethanol plant	≈100 %	≈100 %
Energy, secondary, fossil	Residual heat from oil refinery	0 %	≈100 %
Material, primary, biological	Timber	≈100 %	0 %
Material, primary, mineral	Virgin lithium, virgin cobalt	0 %	0 %
Energy, primary, renewable	Solar energy, wind energy	≈100 %	0 %
Energy, primary, fossil	Oil	0 %	0 %

After the input scoring is done, any potential reuse, recycling, remanufacturing, or cascading of the inputs after they are used in the system are added as additional recyclability. For example, if timber is used as input to the system, it has an assumed recyclability of 0 %, but if half of it is reused in another system the recyclability of that timber would be 50 %.

To assess the recyclability and renewability of the output of the system, all inputs need to be aggregated, that is, we need to estimate the recyclability and renewability of process outputs that are based on more than one input flow. This is related to life cycle assessment ideas about allocation, namely that environmental impact of the main output of a process (a process that has more than one outputs) can be estimated through allocation of its total environmental impact to its different outputs based on some common characteristics such as energy content (energy allocation) or cost (economic allocation) (ISO, 2006). In our method, we use this logic to aggregate (weighted aggregation of the inputs) rather than allocate (proportional distribution of impacts between different outputs). So the same logic is applied but in reverse.

To do this, weighted average should be used based on a property that can be commonly expressed for all types of flows (either energy or material). For examples different flows can be aggregated based on their energy content, life cycle primary energy, or estimated price/value, but mass would not be suitable because flows such as heat or electricity do not have mass. In this study, we utilized the cost of each input. This is done for two main reasons, first, costs represents an approximation of the criticality and scarcity of the input and has been identified in previous literature as being able to form a basis for circularity indicators (Kambanou and Sakao, 2020; Linder et al., 2017). Second, from a practical standpoint, costs represent one of the few common measurements between energy and material flows. Physical measurements such as energy content, mass, and volume are only representative for either material or energy flows and are not suitable for aggregation between the two flow types. For each key input, the costs are estimated based on the newest available yearly average of the energy or material needed. These costs are added throughout the life cycle so that the output of each phase of the system is represented by the sum of all input costs, this is known as the cumulative input cost.

This aggregation is done for each phase of the system and is done by multiplying the recyclability and renewability of each input flow with that input flow's percentage of the cost, see Equation 1 and 2. For example, imagine a fuel A is produced by input X and Y. Input X represent 40 % of the total material and energy cost of A and Y represents 60 %. Input X is 95 % renewable and 100 % recyclable while input Y is 0 % renewable and 0 % recyclable. In this case, fuel A would receive a score of 38 % renewable and 40 % recyclable (renewability = $0.95 \cdot 0.4 + 0 \cdot 0.6$; recyclability = $1 \cdot 0.4 + 0 \cdot 0.6$).

$$Ren_{tot} = \sum_{i=1}^{n} Ren_i \cdot Cost\%_i \qquad \text{(Equation 1)}$$

Where Ren is the Renewability;
Cost% is the inputs share of the total material and energy cost in percentages;
i represents each material and energy input from 1 to n;
n is the number of material and energy inputs.

$$Rec_{tot} = \sum_{i=1}^{n} Rec_i \cdot Cost\%_i \qquad \text{(Equation 2)}$$

Where Rec is the Recyclability;
Cost% is the inputs share of the total material and energy cost in percentages;
i represents each material and energy input from 1 to n;
and n is the number of material and energy inputs.

A special case is made for losses within the system, that is, if there are resources within the system that could have been used (either in the system itself or in other potential systems) but that goes to waste. Losses are dealt with when aggregating the recyclability of the output of each life cycle stage. Here losses are accounted for in terms of percentage of input material that is lost. This percentage is then used to adjust the recyclability fraction of the input material that is lost (see Equation 3).

$$Rec_{input} = Ren_{base} \cdot (1 - loss_{\%}) \qquad \text{(Equation 3)}$$

Where Rec is the recyclability;
input refers to the recyclability used for the input material in further calculations;
base is the original recyclability score of the input material prior to losses;
$loss_{\%}$ is the percentage of input material lost in the processing.

For many production systems there will be by-products or co-products produced alongside the fuel. However, the circularity assessments are done by assessing the entire production system circularity, which means that the system is expanded to include the life cycles of all co-products. Thus, renewability and recyclability of all co-products are calculated for their full life cycle (including potential inputs of energy or materials for distribution and use of the by-products), which provides the basis for the circularity of the production system. Therefore, the cumulative input cost, renewability, and recyclability of the co-products are based on the data from all input material into the system, regardless of if they are specific to one co-product or not. If a co-product cannot be used (sold, traded, given away for another party to use, or used internally) this is treated as a loss in the system and should be calculated as such (see Equation 3).

Finally, in order to generate a single "circularity score" we need to aggregate the recyclability and the renewability scores. This can be done in different ways including using the higher value (e.g., low renewability and high recyclability yields high circularity), the lower value (e.g., low renewability and high recyclability yields low circularity), or the average. In this study we have used the latter approach and the circularity score is based on the average of the two indicators. In this approach, the recyclability and renewability are seen as of equal importance to the circularity of the studied fuel. In the definitions and conceptualizations there are no indications that one of the two aspects should be seen as more important than the other, which is why the study assumes equal importance between the two aspects. However, as mentioned above other aggregations methods can be used and generally speaking it is possible to introduce an importance coefficient here should the relative importance between renewability and recyclability be further defined in the future (see Equation 4).

$$Circ_{tot} = a \cdot Ren_{tot} + b \cdot Rec_{tot} \qquad \text{(Equation 4)}$$

Where Circ is the circularity;
a is the importance coefficient for renewability;
b is the importance coefficient for recyclability;
and a + b must equal 1 and are both set to 0.5 in this study.

4.2 RESULTS AND ANALYSIS, CIRCULARITY

The results are presented for each studied production fuel system, that is, HVO from tall oil, ethanol from forest residues, electric mobility, and biogas from organic waste. For each fuel production system, the renewability and recyclability fractions of all outputs and the entire system are shown. In addition, the total system circularity is presented. The data and data sources used can be seen in the Appendix.

4.2.1 HVO—tall oil

In Figure 6, the system for the HVO production studied is presented. The system produces one output, namely, HVO. Two co-products are produced in the hydrogen production; however, the hydrogen production is not included in the studied system. The hydrogen that is needed in the processing stage of the HVO to hydrate the raw tall diesel is instead seen as an input material into the process with its own circularity score.

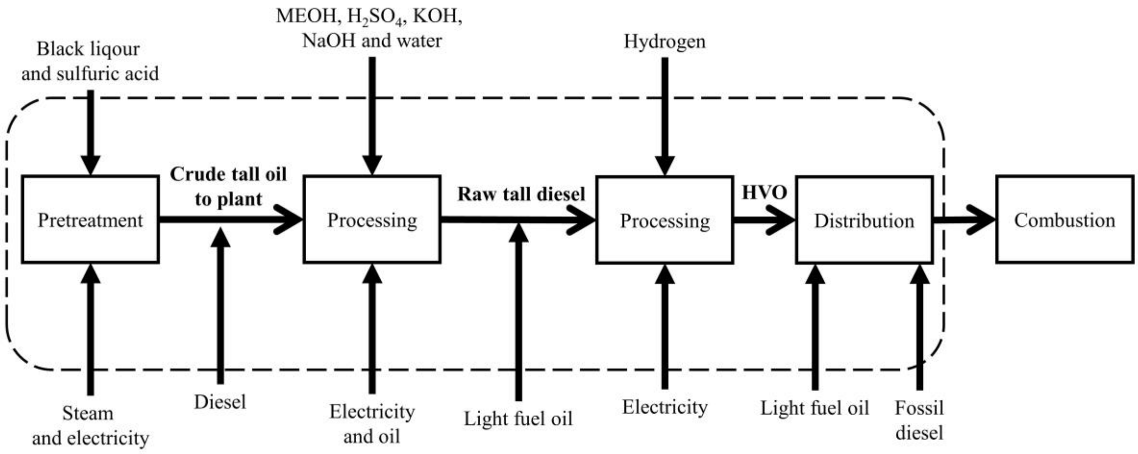

Figure 6. The system diagram of the HVO production system and inputs.

Table 6 shows the renewability, recyclability, and circularity of the HVO production system. The renewability and recyclability are quite high for the system and very close in proximity to each other. The reason for this is that the black liquor holds a large portion of the cumulative costs of the system and while the input energy and material is mostly fossil and primary in nature, their costs are small in relation to the black liquor and therefore, does not impact the system circularity much. The negative impact on circularity comes mainly from the use of oil in the processing stage to convert the crude tall oil to raw tall diesel and the hydrogen used to hydrogenate the raw tall diesel.

Table 6. The renewability, recyclability, and circularity of the HVO production system. Percentages have been rounded to the closest integer.

Output	Renewability	Recyclability	Circularity
HVO production system	*76 %*	*73 %*	**75 %**

For each fuel production system, one probable positive change was assessed to analyze how the circularity of the production systems may change with future opportunities and technological advances. For the HVO system, a possible way to improve the circularity would be to replace the fossil hydrogen with hydrogen from wind and solar powered electrolysis. This hydrogen would have a renewability score close to 100 % (and a recyclability of 0 %). The change (see Table 7) does benefit the circularity of the HVO production system but the hydrogen is still a minor part of the cumulative cost of the system, which is why the change is not larger.

Table 7. The renewability, recyclability, and circularity of the HVO production system when considering hydrogen produced by wind and solar powered electrolysis. Percentages have been rounded to the closest integer.

Output	Renewability	Recyclability	Circularity
HVO production system (green hydrogen)	*83 %*	*73 %*	**78 %**

4.2.2 Ethanol—forest residues

The system diagram for the studied ethanol production system is shown in Figure 7. The outputs are—other than ethanol—lignin and biogas. In this scenario they are both used to generate electricity and heat, which means that no further additives or processes are needed to further refine these co-products. The ethanol is mixed with 15 % gasoline to produce E85, which is the most common way to use ethanol as a vehicle fuel in Sweden. While the amount of gasoline mixed into the E85 can shift during the year, it is common that this equals out to about 15 %.

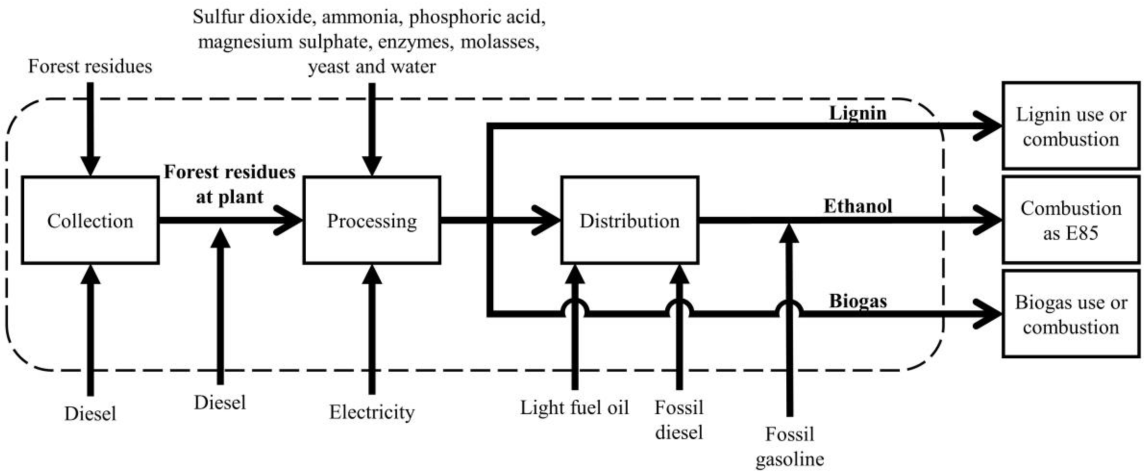

Figure 7. The system diagram of the ethanol production system and inputs.

The circularity of the ethanol production system, which is shown in Table 8, is lowered by the large amount of fossil fuels that are needed for the collection, transportation, and distribution of the ethanol. Furthermore, many of the additives used in the processing stage have low circularity scores that negatively impact the system's circularity. However, the largest negative impact on the circularity of the ethanol production system is the mixing of the ethanol with gasoline to produce E85.

Table 8. The renewability, recyclability, and circularity of the ethanol production system. Percentages have been rounded to the closest integer.

Output	Renewability	Recyclability	Circularity
Ethanol system (at production facility)	*71 %*	*56 %*	**64 %**
E85 system	*50 %*	*40 %*	**45 %**

The ethanol system was also assessed considering a possible change to improve its circularity. The change investigated was to increase the share of renewable fuels in collection and distribution of the ethanol (as this represents a major source of non-circular energy use in the system). Instead of using fossil diesel for collection of forest residues and road transports in the system, HVO from tall oil was used (see Table 6 for this fuels circularity score). This provides a significant improvement to the system, both considering the renewability and recyclability scores (see Table 9).

Table 9. The renewability, recyclability, and circularity of the ethanol production system when assuming HVO is used for collection and road transports in the system. Percentages have been rounded to the closest integer.

Output	Renewability	Recyclability	Circularity
E85 system (HVO for road transport)	*59 %*	*48 %*	**53 %**

4.2.3 Electric mobility

The electric mobility system included both the generation of electricity and the batteries that are required to store the electricity due to the significant contribution that batteries have on the circularity of electric mobility systems, which is not the case for liquid or gaseous fuels where the circularity or linearity of the storage (i.e., the fuel tank) is negligible.

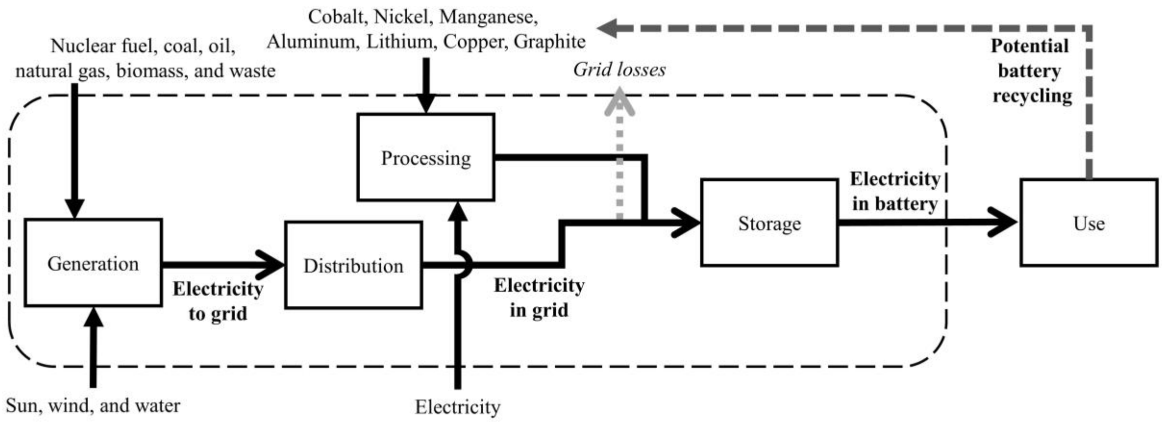

Figure 8. The system diagram of the electric mobility production system and inputs.

The electric mobility system performs the worst of the four tested system when it comes to its circularity (see Table 10). This is, in part, due to the low portion of recycled fuels that are used to produce electricity in the Swedish electricity grid. In addition, the high amount of nuclear fuel also reduces the renewability of the electricity by a large part. The circularity of electric mobility is further lowered by the fact that the battery has only about 2 % circularity due to them being almost entirely made out of primary materials. Since the battery accounts for almost as much of the cumulative input costs as the electricity, the low circularity of the battery has a large input on the circularity of the production system.

Table 10. The renewability, recyclability, and circularity of the electric mobility system. Percentages have been rounded to the closest integer.

Output	Renewability	Recyclability	Circularity
Electricity in the grid	*57 %*	*7 %*	**32 %**
Electricity in battery	*30 %*	*4 %*	**17 %**

To understand how future developments in the battery production systems may impact the circularity of the electric mobility system, the circularity of this system was assessed considering a fully reused or recycled battery (i.e., a battery with a 100 % recyclability score). This provides a large benefit to the electric mobility systems circularity; however, it still remains the least circular system of the four investigated systems (see Table 11).

Table 11. The renewability, recyclability, and circularity of the electric mobility system when considering a fully reused or recycled battery. Percentages have been rounded to the closest integer.

Output	Renewability	Recyclability	Circularity
Electricity in battery (re-used or recycled battery)	*30 %*	*53 %*	**42 %**

4.2.4 Biogas—organic wastes

The biogas system studied can be seen in Figure 9 and generates two outputs, biogas and biofertilizer. The biogas system is based on household food waste that is processed in a continuous stirred tank reactor.

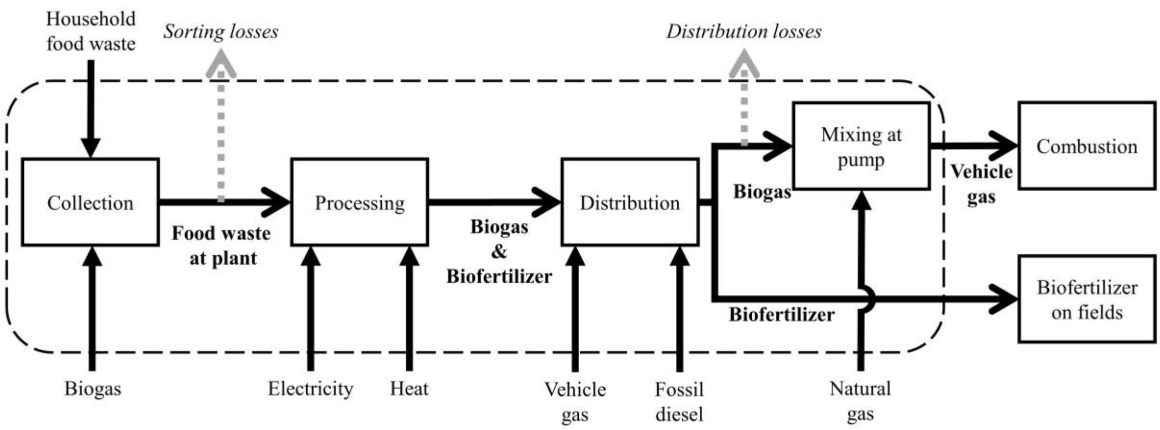

Figure 9. The system diagram of the biogas production system and inputs.

The renewability, recyclability, and circularity of the biogas production system can be seen in Table 12. Notable is the high portion of renewability and the somewhat lower, but still high, portion of recyclability. This is mainly due to two aspects of the system, the sorting losses and the high amount of electricity introduced in the processing to stir the reactor and pretreat the food waste before the reactor. These two aspects lower recyclability more than it lowers renewability (the first aspect only impacts recyclability). Another part worth highlighting is that the upgraded biogas has a renewable fraction of 92 % and recyclable fraction of 76 % before distribution. This is then lowered by the fact that the system is modeled after the average vehicle gas sold at pump in Sweden which has a 4 % natural gas content; the introduction of which, lowers the renewability and recyclability fraction somewhat.

The high circularity score of the biogas production system is due to its use of very little fossil material and energy in the process combined with the use of energy carriers with high or average circularity scores (such as district heating, vehicle gas, and electricity).

Table 12. The renewability, recyclability, and circularity of the biogas production system. Percentages have been rounded to the closest integer.

Output	Renewability	Recyclability	Circularity
Biogas system	*92 %*	*76 %*	**84 %**
Vehicle gas system	*88 %*	*73 %*	**81 %**

To understand how the biogas system may improve its circularity, a model where it was assumed the plant only uses green electricity (wind, solar, or hydro power) and waste heat for their pre-treatment, reactor, and post-treatment processes. This provides a small increase to both renewability and recyclability of the system as the relative cost of electricity and heat in the system is small (see

Table 13).

Table 13. The renewability, recyclability, and circularity of the biogas production system when considering green electricity and waste heat in the production processes. Percentages have been rounded to the closest integer.

Output	Renewability	Recyclability	Circularity
Biogas system (green electricity and waste heat)	*97 %*	*78 %*	**88 %**
Vehicle gas system (green electricity and waste heat)	*93 %*	*75 %*	**84 %**

4.2.5 Summary

A summary of all investigated fuel systems and their circularity scores are shown in

Table 14. Notable is that the biofuel systems all perform relatively well, although the biogas system stands out a bit from the ethanol and HVO system. This is because they are all based on renewable secondary materials; however, the biogas system received less non-renewable and primary input material and energy, hence, the higher circularity score.

Table 14. Overview of all investigated fuel systems and their respective circularity scores.

Production system	Renewability	Recyclability	Circularity
HVO	*76 %*	*73 %*	**75 %**
Ethanol E85	*50 %*	*40 %*	**45 %**
Electricity in the grid	*57 %*	*7 %*	**32 %**
Electricity in battery	*30 %*	*4 %*	**17 %**
Biogas	*92 %*	*76 %*	**84 %**
Vehicle gas	*88 %*	*73 %*	**81 %**

4.3 METHOD TO EVALUATE THE MONETARY VALUE OF CIRCULARITY

Monetary evaluation is most commonly done through what is known as a cost-benefit analysis (CBA), which aims to estimate how large the socio-economic cost or benefit of a certain good is

(Boardman et al., 2018). This can then be used to rectify market failures[14] when it is used as basis for a tax or subsidy. To estimate the cost or benefit of environmental and resource related impact categories several methods are available, which can be divided into four categories (Pizzol et al., 2015): Observed preference methods, revealed preference methods, stated preference methods, and abatement cost methods. Observed preference methods rely on existing markets where willingness to pay can be observed, that is, the studied good must be traded on a market. Revealed preference methods, instead, try to elucidate the willingness to pay of consumers through indirect valuation. This may, for example, be through a surrogate good (i.e., a market good whose price is affected by the availability of the non-market good under study), a preventative good (i.e., a market good that can prevent the studied non-market cost from occurring), travel costs (i.e., what is the cost that people are willing to pay to travel to experience the non-market good), or hedonic pricing (i.e., evaluating a non-market good that is a part of the total price of the market good). Stated preference methods, as the name implies, base their estimation of the monetary value of a good on the stated willingness to pay for said non-market goods by consumers, for examples, through a survey or interviews with potential consumers. Abatement cost methods try to estimate the monetary value of a non-market good by estimating the potential costs for reverting or preventing a potential change induced by the non-market good (for example, using the potential cost for society to deal with consequences of climate change to evaluate the monetary value of fossil carbon dioxide emissions).

Understanding the monetary value of circularity is not a trivial matter; in fact, it is even difficult to state clearly what the externalities of circularity are. Circularity builds on the idea of the circular economy, a concept that aim to bring several positive welfare benefits through increased resource productivity, reduced waste, reduced environmental impact, availability of resources for future generations, and more circular resource flows (Ellen Macarthur Foundation, 2021a). Obviously, many of these traits could be seen external to the price of a circular good and may befall society at large rather than the individual consumer of said circular good. As such, they may all be valuable from a welfare perspective; however, some may already be properly valued through market mechanisms (for example, resource productivity) or already existing taxes or subsidies (for example, taxes on polluting emissions). While it is possible to evaluate circularity on the basis of itself, that is, including all these traits and not dividing them, this approach risks double counting individual benefits as some positive traits of circular goods are already taxed or subsidized (for example, reduced climate gas emissions).

Here in this study, special attention is given to the availability of resources for future generations and reduced waste generation as these are aspects that do not seem to be dealt with elsewhere in the economy. This is mainly because resource productivity is (at least theoretically) dealt with through market mechanisms (as higher productivity should result in more goods per resource, which befalls each individual consumer and not society at large), reduced environmental impact are typically dealt with separately from circularity in policy, and because circular flows in themselves are not an end goal, that is to say, that the circular flows are means to achieve positive societal benefits

[14] Market failures are aspects of the market that lead to lower socio-economic efficiency on the market. Common examples are externalities, collective goods, monopolies or oligopolies, and non-pareto efficient taxes and subsidies.

(which are the end goal). This leaves the aspects of reduced waste generation and increased availability of resources for future generation. Regarding the second aspect, it was not possible within the frame of this project. This is mostly because the potential benefactors of this (i.e., future generations) are not available to use to infer preferences from, which means that only abatement cost approaches are left. This type of approach would require an in-depth study on how future resources may be used and how fuel production systems could impact availability of resources for future generations. As for the reduction of waste generation a revealed preference method was chosen, specifically, a preventative cost approach, whereby the monetary value of reduction of waste generation is estimated by seeing what individuals are willing to pay to get rid of waste once it is generated.

The proposed method for evaluating the monetary value of circularity thus equates to approximating the societal value of circularity by using the willingness to pay for getting rid of waste and the circularity score developed in section 4.1. The circularity score provides a measurement for how circular a fuel production system is and the willingness to pay for getting rid of waste is used to approximate the societal value of this circularity. How the monetary value is calculated can be seen in Equation 5.

$$V_m = WtP_{waste} \cdot weight \cdot Circ \tag{5}$$

Where V_m is the monetary value of circularity of transportation fuels;
WtP_{waste} is the revealed preference value of reduced generation of waste;
weight is the input weight of all materials used in the fuel production system;
and Circ is the circularity score.

To estimate the willingness to pay for getting rid of waste two values are used. The first is an incineration gate fee of 750 SEK per ton waste (Sysav, 2020). The second is the landfill tax, which is seen as the societal willingness to pay for avoiding waste generation, this amounts to 540 SEK per ton of waste (Skatteverket, 2021). These two are chosen to portray two perspectives on the willingness to pay of avoiding waste. The first, the willingness to pay to avoid waste from individual waste-generating actors and the second the willingness to accept landfilling by society (as per their elected representatives). In both cases these are generic values and should preferably be further developed to specific values for each feedstock, for example, the gate-fee for forest residues would be lower (incineration plants may even pay for that feedstock) than the gate-fee for food waste.

4.4 RESULTS AND ANALYSIS OF MONETARY VALUE OF CIRCULARITY

Estimations for the monetary value of circularity was performed for the four studied fuel systems according to Equation 5. The result can be seen in Table 15 where comparison can be made between the fuels (using the SEK/kWh values) and with current sale prices of the fuels (using SEK/l, MWh, and kg values). As is shown in the results, the biogas system is given the highest amount of societal value for its contribution to circular economy. This is based on both the fact that there is a large amount of bulk material used in the biogas production process (i.e., a large amount of material that does not become waste) and that the production system has a very high circularity score. The ethanol production system is given the second highest societal value due to it being the system that upcycles the largest amount of bulk material, although its circularity score is lower than both the biogas and HVO systems. Despite having a high circularity score, the HVO production systems do not upcycle the same amount of bulk material and is thus given a lower monetary value score. A note should be given to the fact that this does not promote inefficient systems because while inefficient systems would mean a larger bulk material of inputs it would also mean more losses in the system, which would equate to a lower circularity score as per Equation 3. The value of the electric mobility system's contribution to circularity is close to zero since the bulk material input into the system is very low and the circularity score of the system is also the lowest of the studied systems (i.e., it does not upcycle any material).

Table 15. The estimate socio-economic value of the circularity of the four tested fuel production systems. First shown in Swedish SEK per MJ for comparison and SEK per l, kWh, and kg, which are commonly sold units for each fuel system.

Fuel	**HVO [SEK/kWh]**	**Ethanol [SEK/kWh]**	**Electric mob. [SEK/kWh]**	**Biogas [SEK/kWh]**
Incineration gate fee	0.179	0.404	≈0	0.553
Landfill tax	0.129	0.291	≈0	0.398
Fuel	**HVO [SEK/l]**	**Ethanol [SEK/l]**	**Electric mob. [SEK/MWh]**	**Biogas [SEK/kg]**
Incineration gate fee	1.69	2.35	0.58	7.45
Landfill tax	1.22	1.70	0.41	5.37

There are some limitations to this method worth mentioning. The first is the inability to disentangle co-products, that is, it is not possible to say how much of the monetary value should befall each product in multi-product production systems. This means that any subsidies based on this must befall the producer (since it is the same producer that produces all co-products while it is most commonly not the same consumer that consumes all co-products).

In addition, there are limitations that how far the method was able to be developed during this project. Here many improvements can be made but the authors would highlight two primary ones. First, the method should be improved to include the value of increased availability of resources for future generations. This is preferably done through an *abatement cost approach* but could potentially be done through other means. Such an abatement cost approach would aim to estimate the cost of not going circular, for example, by estimating future price increases and volatility due to increased resource scarcity. Second, the estimation of the value of avoiding waste generation should be improved to take into account that the revealed values is different for different material types and geographical contexts (i.e., it is more or less costly to get rid of waste depending on what type of material this waste is). Using a singular value, such as is done in this report, is not recommended as some type of secondary materials (such as the forest residues used in the ethanol production system) would likely only pay a small gate fee (or even negative gate fees implying getting paid) for incineration, while others may need to be pre-treated and destroyed in a sanitary way, which could mean much higher gate fees.

5 GREENHOUSE GAS MITIGATION

5.1 DEFINING GHG EMISSIONS REDUCTION

As discussed before, estimating the climate benefits is based on existing methods with the aim to combine the GHG emissions reduction potential of alternative transport fuels with the associated avoided cost for fossil GHG emissions.

To estimate the GHG emissions reduction potential, the life cycle environmental impact of transport fuels is determined and then compared to the fossil counterpart. The approach and values suggested in the Renewable energy directive (the so-called RED II) are adopted in this work (European Parliament 2018). As defined in RED:

$$GHG\ emissions\ saving = \frac{Ef - Eb}{Ef} \qquad (6)$$

Where Ef is defined as the total, life cycle, GHG emissions of the fossil baseline alternative, and Eb is defined as the total, life cycle, GHG emissions from the biofuel considered.

The fossil baseline alternative in this case results in 94g CO2 /MJ for diesel and petrol fuels (SEA 2021b).

Numerous studies are available looking on the environmental performance of the fuels included in this work. The selected studies and respective GHG emission intensity are shown inTable 16. The specific studies were selected aiming to represent the production pathways described and considered when measuring the circularity of the fuel and also to represent a Swedish context (when it comes to data selection and scope).

Table 16. GHG emissions intensity and emission reduction potential considered for the studied fuels. HVO=hydrotreated vegetable oil, CBG=compressed biogas, MSW=municipal solid waste.

	Emission factor g/MJ	Emission reduction potential %	Reference
HVO (tall oil)	5.35	94	Källmén et al 2019
Ethanol (forest residues)	22	77	Poulikidou et al 2019
Electricity (Swedish mix)	13	86	SEA 2021c
Biogas CBG (MSW)	15.8	83	Hallberg et al 2013

The type of transport fuel, its feedstock and production route can influence its environmental performance to a great extent. This is especially true for renewable fuels as well as electromobility where the majority of fossil GHG emissions occur upstream i.e. when feedstocks are extracted and converted to fuels. It is therefore of great importance that the emission reduction potential is considered in the suggested approach.

5.2 MONETARY ESTIMATION OF CLIMATE BENEFITS

Various approaches can be implemented for linking the GHG emission reduction potential or climate impact mitigation to socioeconomic benefits (Isacs et al. 2016). One example is by estimating the avoided socioeconomic cost or avoided damage which can in turn be expressed in various terms. Here we investigate two options:

- A monetary value based on policy instruments such as energy or carbon taxes applied to fossil transport fuels[15]
- A monetary value based on the estimated socioeconomic cost (ASEK) for climate change as suggested by Swedish Transport Administration (Trafikverket).

Transport fuels[16] in Sweden and specifically fossil fuels (petrol and diesel), are taxed by three different taxes, the energy tax, the carbon dioxide tax, and a value added tax. The carbon tax, introduced in Sweden in 1991, targets fossil fuels—such as petrol, oil, etc. used as motor fuels but also for heating purposes. The tax is calculated based on the carbon content of fossil fuels i.e. based on the estimated amount of CO_2 emissions the covered fuels emit upon combustion. The current rate of the carbon tax in Sweden is at 1190 SEK/ton CO_2. Renewable fuels of high blends[17] are exempted from the carbon tax and have no or a very low energy tax. Low-blend biofuels are covered by the reduction obligation system. Taxes on these biofuels are applied based on the emission reduction potential from their fossil equivalent.

An alternative approach for expressing the climate benefits or avoided socioeconomic cost that can be obtained via alternative fuels, is by using the latest ASEK values suggested by the Swedish Transport Administration (2020). ASEK (Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn), provides the principles and values that are recommended to be used in social cost-benefit analyses (CBA) and decision making in the Swedish transport sector. The method covers different socioeconomic parameters where the cost of global warming is only one of them. In the most current version ASEK 7, a cost estimate of 7 SEK per kg of CO_2, or CO_2 eq. is suggested expressed in the 2017 price level that is closely linked to the GHG emissions reduction obligation system. ASEK also considers other aspects such as reduced particles which are not included here.

The emission reduction obligation on petrol and diesel was introduced in 2018 to enhance and promote the use of biofuels in the transport sector.[18] The scheme suggests that fuel suppliers shall reduce greenhouse gas emissions from petrol and diesel by a certain percentage each year which can be done by increasing the share of biofuels in petrol or diesel blends over time. The reduction obligation for the year 2021 for instance 6% for petrol and 26% for diesel (on energy basis). This share is expected to increase to 28% and 66% respectively in year 2030 (Swedish Government 2021; UNFCCC 2020). A fee is applied to the part that remains until fulfillment. The fee is 5 SEK per kg of CO2 eq. for petrol and 4 SEK per CO2eq for diesel fuel (SEA 2021d). For fossil fuels sold without any biocomponents the fee is 0.39 SEK per liter petrol and 2.69 SEK per liter diesel. This value

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[15] Additional taxes and instruments are available e.g. at vehicle level but these are not considered in this estimate.

[16] Fuels used for road vehicles, non-road mobile machinery and private vessels and aircrafts.

[17] Containing more than 98% biocomponents, or blends such as E85 (85 % biocomponents) or ED95 (95 % biocomponents).

[18] Energimyndigheten (2021). *Reduktionsplikt*. Available: http://www.energimyndigheten.se/fornybart/hallbarhetskriterier/reduktionsplikt/ Last modified: 2021-12-06.

is in between the carbon tax and ASEK values explained above although they both represent the similar principles. As explained previously, the purpose is to show how the method can be combined with the new methods described this report, not to find an exact value of the socioeconomic cost of climate change.

5.3 RESULT

Based on the information presented above, the climate benefit could be estimated for the four alternative fuels and energy carriers considered in this project. The results indicating the climate benefit for each fuel is presented in Table 17.

The general formula applied to each fuel option is:

$$\begin{aligned} Climate\ benefit\ \ or\ Avoided\ cost\ \left(\frac{SEK}{MJ}\right) \\ = GHG\ emissions\ reduction\ potential\ (\%) \\ *\ GHGemissions\ from\ fossil\ alternative\ \left(\frac{kgCOeq}{MJfuel}\right) \\ *\ \ Emissions\ Cost\ (\frac{SEK}{kgCO2\ eq.}) \end{aligned}$$

Table 17 Result illustrating the climate benefit as calculated for the four alternative fuels in the study. HVO=hydrotreated vegetable oil, CBG=compressed biogas, MSW=municipal solid waste

Fuel option	Climate benefit when the carbon tax is applied		Climate benefit when the ASEK value is applied	
	SEK /GJ	SEK/MWh	SEK /GJ	SEK/MWh
HVO (tall oil)	106.4	382.6	620.5	2232.2
Ethanol (forest residues)	86.4	310.7	504.0	1812.9
Electricity (Swedish el)	97.2	349.6	567.0	2039.5
Biogas CBG (MSW)	93.8	337.5	547.4	1969.0

6 COMBINED METHODOLOGY AND VERIFICATION

6.1 SECURITY OF SUPPLY

The security premium estimated in Section 3 provides a rationale for policy that can support the domestic fuel production. The idea is that Sweden would be willing to pay up to the security supply premium to avoid the economic damages arising from a negative global fuel supply shock. Securing each unit of fuel would avoid economic losses and applying the assumptions outlined in this report, we estimate that the premium is around 0.7 SEK/liter of fuel. The security of supply is one component of the “social” benefit of supporting domestic renewable fuel production.

However, domestic renewable fuel production could probably not perfectly compensate for global shocks to the fossil fuel market. One reason for this is related to the economics of international fuel markets. One, albeit extreme view, is that domestic production can only dampen the damages to the domestic economy via its stabilizing effect on the global fuel market. In this view, domestic production increases the global quantities of fuel supplied, which in turn stabilizes global fuel markets, and helps reduce the economic damages suffered by Sweden, as well as the rest of the world. Of course, Sweden’s capacity to produce fuel is **relatively** small and as a consequence the impact of any Swedish fuel production on global fuel market quantities and prices is quite close to zero. From this it would follow that an appropriate security premium for domestic fuel would also be close to zero.

This theoretical reasoning is appealing but evidence suggests that fuel markets are not necessarily quick at equalizing prices across regions. Several studies (e.g. see Hastings 2004 and Beatty et al. 2021) examine the effects of local fuel supply shocks and persistent price differences between regions that could be considered to have well integrated fuel markets (e.g. neighbouring US states). This would suggest that there is some potential for domestic fuel production used to reduce the economic losses arising from global fuel shocks although to what degree is an open question. It is not surprising that governments have discretion on how and by whom strategic reserves of fuel can be used so that essential fuel resources are not exported. From this it would follow that there is a role for policy to support/subsidize domestic fuel production.

A second constraint to the role of renewable fuels in protecting the Swedish economy is about technology diversity and flexibility and the degree to which fleets can substitute across different fuel types. Some fuels are close substitutes for each other such as HVO and fossil diesel. Fleets that can adapt to different fuel mixes provide some level of security. In the extreme, car fleets that can operate on a variety of fuel types would of course be able to run on domestic renewable fuels, and that there is a role for policy to support/subsidize domestic fuel production.

Finally, protecting the Swedish economy requires that supply shocks that affect global fuel supply are uncorrelated with shocks that affect domestic fuel supply. It is probably the case that events in oil producing countries do not affect the production of HVO in Sweden: fossil fuel supply and HVO based fuels are therefore uncorrelated. But as the world moves away from fossil fuels and becomes increasingly dependent on renewable fuels, then shocks between domestic and foreign fuel supply will probably become increasingly correlated. For example, a large portion of the production of Swedish biofuels relies on imported feedstocks (SEA 2020b), which are traded on global markets and a shock would affect both domestic and foreign fuel producers. The risk mitigation benefits of diversifying fuel supply decrease with increased correlation across foreign and domestic fuel types. However fuels like biogas mostly depend on production of waste and residues which are locally generated (ibid).

Fuel security is one component to the "social" benefit of domestic renewable fuel supply. We also investigate the climate benefits as well as the value of circularity.

6.2 CIRCULARITY

The method used to assess the circularity of transportation fuel production systems relies on analyzing and aggregating the renewability and recyclability of input material and energy. As such, systems that have a high use of renewable and secondary material and energy receive a high circularity score. This approach takes the "circularity" aspect of circular economy seriously: things have to be circular to be counted as circular; that is, it has to be based on renewable inputs or secondary resources (recycled or reused). There are other conceptions of circular economy that focus on other aspects (such as zero waste that focuses on the outputs) and are not directly linked to renewability and recyclability. Based on those conceptions a production system that delivers high value products or has high resource productivity may still be considered as "circular" regardless of the type of resources that were used as input. While we do not deny the value of such approaches, we have tried to clarify our particular view on circularity especially in relation to fuel production systems (as fuels are consumed and their further recycling or reuse is often not relevant). In short, the method was based on theories of circular economy where a circular transportation fuel was defined as a fuel based on renewable and secondary input material and energy where non-fuel outputs (for example, co-products or spent batteries) are recycled or reused. A high circularity score represents a production system that efficiently upcycles low value materials to high value products.

Translating the circularity of transportation fuel production systems into how much this circularity might be worth from a socio-economic perspective has been proven a difficult and complex task. This is partly due the broad nature of the concept of circular economy and that it promises to bring several different societal benefits. In this study, a first step is taken towards evaluating the value of circularity by using the revealed willingness-to-pay for waste removal as an approximation of the societal value of circularity. However, aspects such as availability of resources for future generations and innovation related benefits still remain unexplored and unevaluated, which is why the results of societal evaluation should be used carefully and are primarily for learning and demonstration of the method.

This is important to consider when attempting to combine this value with other estimations for socio-economic values. In reality, the value of circularity is likely much higher than what is estimated here. This is partly due to the fact that the value of resource availability for future generation has been left out of these results, and partly because as knowledge about the benefits of circularity increases, it is likely that consumers and stakeholder's perception of the value of these benefits also will increase. Another potential challenge with combining the value of circularity estimated in this report with other values is the fact that this value represents the benefit of the entire production system while the other two values in this study (greenhouse gas mitigation and security of supply) represent values tied to only the fuel. This is because it was not possible to differentiate co-products of the transportation systems in relation to their circularity as this is a characteristic of the production system, not the products.

6.3 GREENHOUSE GAS MITIGATION

Life cycle thinking and inventory of material and energy flows has been used to define the GHG emission reduction potentials. According to the applied methodology and typology for different raw materials, systems that use waste or residues as feedstock for fuel production tend to perform better than systems based on primary feedstocks. This is mainly because no environmental impact is allocated to residues streams apart from the collection and transport of the material which favors of course the overall environmental performance of those pathways. However, process materials and energy sources needed in during production or fuel distribution (chemicals, process energy etc.) are also shown to affect the system, especially if fossil resources are used.

One important point to note however, is that the demand of a specific biofuel is seldom supplied by a single feedstock thus the rates and saving potentials obtained in this part shall be considered with care to avoid misleading conclusions. The main constraint with raw materials that are based on residues or recycled streams is availability. Increasing demand of those feedstocks to achieve higher emission benefits maybe negatively affect security of supply as more resources would need to be imported.

For the estimation of the socioeconomic benefit from GHG emission reduction different approaches can be applied. Here two alternatives are presented, both focusing on values presented for Sweden and have a strong connection to the transportation sector.

6.4 SUMMARY

Table 18 below shows the sum of the estimated values, security of supply, circularity and climate change benefit. A lower and an upper value are reported for each fuel. The values are expressed per kWh to make them comparable. The combined value of the three benefits is expressed both per energy content (kWh) and per volume (liter for liquid fuels and Nm^3 for biogas). These are presented for learning and should not be used directly in decision-making or policy development as the value of circularity does not represent the entire socio-economic value of circularity and represents the value of the production system, rather than only the fuel (which the other two values represent).

It can be of interest to investigate the magnitude of the values to understand how valuable these may be in relation to each other. In this study, the estimated values for security of supply are quite a lot smaller in magnitude than the values for circularity and climate change reduction. On the other hand, the value for circularity is close to the lower bound of the climate change reduction values although quite a lot smaller than the upper bound of the same. The differences between each dimension of benefit arises in part from the different methodologies applied. The climate benefits are global in nature, in that it is based on the socially optimal price of carbon and incorporates not only intergenerational aspects but also the benefits across the whole global economy. On the other hand, the security of supply benefits are national in nature, and are based on the social benefits to Sweden alone over the period of months (rather than generations). Circularity benefits are a mix of direct, shorter/longer run, and global/local benefits.

Table 18: Summary table of estimated values

Fuel	Security of supply (SEK/kWh)		Circularity (SEK/kWh)		Climate benefit (SEK/kWh)		Combined societal value (SEK/kWh)		Combined societal value (SEK/liter)		Combined societal value (SEK/Nm^3)	
	Lower	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**
HVO	**0**	**0.071**	**0.13**	**0.18**	**0.38**	**2.23**	**0.51**	**2.48**	**3.72**	**23.42**	**n.a**	**n.a**
Ethanol	**0**	**0.071**	**0.29**	**0.40**	**0.31**	**1.81**	**0.60**	**2.29**	**3.50**	**13.33**	**n.a**	**n.a**
Electric vehicles	**n.a.**	**n.a.**	**≈ 0**	**≈ 0**	**0.35**	**2.04**	**0.35**	**2.04**	**n.a**	**n.a**	**n.a**	**n.a**
Biogas	**0**	**0.071**	**0.40**	**0.55**	**0.34**	**1.97**	**0.74**	**2.59**	**n.a**	**n.a**	**7.24**	**25.44**

7 CONCLUDING DISCUSSION

Current policy and debate seem to focus almost exclusively on the climate benefits of renewable transportation fuels. Our analysis has highlighted other benefits associated with renewable transportation fuels, i.e. security of supply and circularity. There are large societal values deriving from these fuels. However, these values are small compared to the higher estimations of the value of the climate benefits expressed in different policies, such as the ASEK model. As a result, these societal benefits risk to be shadowed by the GHG reduction benefits. However, the value of (non-climate) benefits may be much larger than what has been estimated in this study. For example, security of fuel supply for critical functions in society such as an ambulance has a much higher value, although it is not estimated in this study. In addition, the debate and the policies supporting circular economy are younger than the climate debate and policies, which may result in and reflect a more uncertain value for circularity (Johansson and Henriksson 2020). In some case policies to support circularity may not even exist.

There are thus big differences between policies promoting GHG mitigation, circularity and security of fuel supply. In addition, there are methodological differences in our estimations of these values. However, we have made a first attempt to add these together to see what an aggregated value may look like. An aggregated value could be used to motivate a subsidy to support the renewable fuel in question. Further research could investigate how the different values may be weighted. Such weight should be given together with policy makers.

Security of supply

Domestic Swedish production of renewable fuels can help to some extent dampen the impact of global fuel supply disruptions on the Swedish economy. The possibility to dampen the impact depends on the substitutability. For example, HVO is interchangeable with fossil diesel. Ethanol may be blended in fossil gasoline to a certain degree [19] but may not substitute gasoline completely in gasoline vehicles. Sweden's strategic fuel reserves help protect Sweden from the effects of a catastrophic fuel shortage. The effectiveness of the strategic reserve in dampening the impact of fuel disruptions relies in part on the ability of the government to restrict how the reserves are used (e.g. exclude export). Other fuels, such as biogas and electricity are not substitutes to liquid petroleum fuels such as gasoline and diesel. They may however dampen the impact of a supply shock to the extent that vehicles can switch between fuel types. Electric hybrid cars and most gas vehicles can do that, but both electric vehicle and gas vehicle fleets are currently small in Sweden (Lönnqvist 2017; Power Circle 2021). However, biogas and electric vehicles decrease the initial dependence on imported fossil fuels.

There are potentially significant losses in economic output arising from smaller fuel supply shocks that occur relatively frequently (circa 10-year return period). We find that the annual expected GDP losses from fuel supply shocks is around 22 billion SEK. These losses capture the impact of increases in fuel prices arising from fuel supply shortages. The resulting high fuel prices reduce Swedish GDP as the effects of the fuel price shock propagate through the economy. The estimate that

[19] Most vehicles tolerate 10 % ethanol blended into gasoline

does not consider the potential losses associated with a catastrophic fuel shortage where even essential functions are disrupted such as the military, critical services such as policing and health care. Losses associated with essential functions are probably even higher and are also difficult to quantify.

Decreasing Sweden's dependence on oil-based fuels will reduce Sweden's exposure to the economic impact of oil supply disruptions but will increase Sweden's exposure to foreign and domestic supply disruptions affecting other fuel types.

In much the same way investors manage risk by diversifying a portfolio by investing in uncorrelated assets, domestic fuel production can only support fuel supply security to the degree that production/supply shocks are uncorrelated across domestic and foreign fuel types. The benefits of diversifying Sweden's fuel supply depend in part on the degree to which shortages in one fuel type can be compensated by the supply of other fuel types and in part on the degree to which transport fleets can switch between fuel types.

Circularity

A method was developed that assesses the contribution of transportation fuels to the circular economy based on the principles of circular economy. It builds on the idea that in a circular economy it is desirable to use material and energy with a high degree of renewability and a high degree of recycling and reuse (circular material flows and energy cascading), where priority is given to scarce and valuable materials. These aspects are all represented in the method and together lead to an estimation of the studied fuel's contribution to circular economy, which is called a circularity score.

The results of applying the method to four production systems show that the studied biofuels perform well (generally above 65 % circularity without including mixing with fossil fuels), which give strong indications to that other types of biofuels based on secondary resources would be expected to also perform well in the Swedish context, even if these have not been studied specifically. The biogas system scores slightly higher than the other biofuels studied (ethanol and HVO) due to the production process requiring less input of primary energy and materials compared to the other fuel production systems. The high score of biofuels from secondary resources is to be expected as these production systems are good at taking low value material and upcycling them into high value products, something that is key for the circular economy. Regarding electric mobility, it scores lower than the studied biofuels concerning circularity, although this can be substantially improved through a higher degree of renewable energy in the electricity system (specifically by reducing nuclear energy in the Swedish case) and through increased reuse and recycling of batteries.

Although this study gives interesting insights into the circularity of a few different fuel production systems, it is just a first step towards further understanding and enabling decision-making based on the circularity of transportation fuels and further methodological development will be needed. For example, development is needed to find ways of disentangling co-products. Currently the proposed method can only assess the circularity of a production system and is not able to distinguish between its co-products. It may also be fruitful to apply the method to more cases, both nationally within Sweden and in international settings, to understand other types of fuel systems and refine the method. Furthermore, exploring other ways of aggregating the renewability and recyclability of inputs would be a valuable endeavour. In the current method, market price is suggested because it represents a common unit between material and energy inputs and because it is often a realistic representation of an input's criticality; however, other common units may be explored, such as, primary energy use (or embodied energy). Finally, ways of managing uncertainty in the method is needed as much of the data on material and energy flows in transportation fuel systems can be difficult to acquire and economic data is inherently variable and irregular.

Capturing the socio-economic value of circularity was proven difficult due to the vague, broad, and complex nature of the concept of circular economy. Indeed, the circular economy can provide many potential welfare benefits, but it is unclear how these welfare benefits should be realised and whether they should be grouped under a circularity subsidy or not. Again, the approach used here represents a first step towards thinking about how the socio-economic value of circularity may be captured and much further thought and studies are needed. Specifically, other studies should focus on how to capture the value of the availability of resources for future generations and attempt to assess the socio-economic value of circularity through stated preference or abatement cost methods. Refinement to the revealed preference approach chosen in this study is also required, for example, by different types of wastes are accurately evaluated using prices specific to each type of waste (and not using a generic price for all types of waste as was done in this study).

Climate change benefits

The methods developed in this project were further combined with traditional indicators commonly included when alternative fuel options and technologies for the transport sector are assessed. One such indicator is looking at the climate benefits or climate mitigation potential expressed here as the avoided socio-economic cost based on the respective GHG emission savings for each fuel option.

The conclusions drawn from this assessment followed the conclusions obtained from the circularity index where all studied alternatives result in high emission reduction potentials (above 75%). These rates fulfil the targets suggested by the RED II. The highest emissions savings were obtained from HVO produced from tall oil as well as from Swedish electricity. Consequently, the highest socio-economic benefits in terms of climate change mitigation were obtained for HVO and Swedish electricity. It should be noted however, that the raw materials needed for the batteries were not included thus the final savings from electricity as energy carrier can be expected to be lower. However, batteries have a long lifetime, and this would also need to be taken into consideration.

The quantitative results from this assessment can be study and context dependant as they refer to specific LCA studies and process data. As such they cannot be considered an average value for the respective fuel. Moreover, methodological variations when different LCA frameworks are applied can also lead to differing results thus alignment of the background processes, and assumptions is essential. The fossil comparator used in this study reflects the guidelines suggested at EU and Swedish context, but these can also be changed or revised over time. Moreover, and as earlier mentioned it is rather uncommon that one feedstock alternative would cover the entire demand for a specific fuel (i.e. HVO supply includes a variety of feedstocks) and therefore a fuel mix would provide a more representative value assisting in avoiding trade-offs and handling availability constraints.

Further development of the method may include the use of up-to-date data in relation to the LCA models (sector specific or BAT) including a greater variety of fuels that are relevant from the Swedish context[20] or investigation of alternative ways of exhibiting the socio-economic cost by applying more global values and alternative methods (such as the EPS Environmental Priority System or the EU carbon trading scheme). Sweden has a relatively high carbon dioxide tax which can influence the result if compared to other countries. Applying more universal factors would allow for the method to be used in a broader context (other than the Swedish context for example) Finally, inclusion of more indicators apart from climate change that are of importance for the transport sector could be considered. These can for instance be human health and local pollution from particle emissions, job creation opportunities and economic development from avoided imports of fossil fuels.

In addition, the methods of estimating the value of security of supply and circularity need further development in order to estimate an accurate value of these important societal benefits that renewable transportation fuels may promote. The current uncertainty regarding their values may imply that they are overshadowed by the climate related benefits in public debate and policy. Future research may attempt to estimate these values and also of other non-climate related benefits (and costs) accruing from renewable transportation fuels in order to provide a better policy decision support.

[20] Examples of fuels important in the Swedish context that could be included in future research are: first generation ethanol, hydrogen, RME, HVO from other sources than tall oil, and possibly also methanol.

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APPENDIX

DATA AND DATA SOURCES FOR THE STUDIED FUEL PRODUCTION SYSTEMS

Table A 1. Data and data sources for the HVO from tall oil production system used in circularity score calculations. Data is shown per MJ of produced fuel.

Input	Amount	Unit	Renewability	Recyclability	References
Black liquor	0.075	kg	100 %	100 %	(Källmén et. al., 2019)
Sulfuric acid	0.011	kg	0 %	0 %	(ibid)
Steam	0.094	MJ	100 %	0 %	(ibid)
Electricity	0.094	MJ	56.6 %	7.2 %	(ibid)
Diesel	0.005	MJ	7 %	0 %	(ibid)
Methanol	0.421	g	0 %	0 %	(ibid)
Potassium hydroxide	0.145	g	0 %	0 %	(ibid)
Sodium hydroxide	0.215	g	0 %	0 %	(ibid)
Water	0.011	kg	100 %	0 %	(ibid)
Oil	0.050	MJ	0 %	0 %	(ibid)
Light fuel oil	0.010	MJ	0 %	0 %	(ibid)
Hydrogen	1.573	g	0.4 %	0.1 %	(ibid)

Table A 2. Data and data sources for the ethanol from forest residues production system used in circularity score calculations. Data is shown per MJ of produced fuel.

Input	Amount	Unit	Renewability	Recyclability	References
Forest residues	0.287	kg	100 %	100 %	(Poulikidou et al., 2019)
Diesel	0.092	MJ	7 %	0 %	(ibid)
Sulfur Dioxide	3.720	g	0 %	0 %	(ibid)
Ammonia	1.870	g	0 %	0 %	(ibid)
Phosphoric Acid	0.425	g	0 %	0 %	(ibid)
Magnesiumsulphate	0.111	g	0 %	0 %	(ibid)
Enzymes	3.995	g	100 %	0 %	(ibid)
Mollasses	2.295	g	100 %	0 %	(ibid)
Yeast	2.125	g	100 %	0 %	(ibid)
Water	0.033	kg	100 %	0 %	(ibid)
Electricity	0.094	MJ	56.6 %	7.2 %	(ibid)
Light fuel oil	0.005	MJ	0 %	0 %	(ibid)
Gasoline	0,15	MJ	0 %	0 %	(ibid)

Table A 3. Data and data sources for the electric mobility system used in circularity score calculations. Data is shown per MJ of electricity stored in the battery.

Input	Amount	Unit	Renewability	Recyclability	References
Nuclear power	0.401	MJ	0 %	0 %	(IEA, 2021)
Coal power	0.010	MJ	0 %	0 %	(ibid)
Natural gas power	0.005	MJ	0 %	0 %	(ibid)
Oil	0.002	MJ	0 %	0 %	(ibid)
Biomass	0.051	MJ	100 %	0 %	(ibid)
Waste (non-renewable)	0.031	MJ	0 %	100 %	(ibid)
Waste (renewable)	0.015	MJ	100 %	100 %	(ibid)
Household waste	0.030	MJ	59.5 %	100 %	(ibid)
Hydro power	0.392	MJ	100 %	0 %	(ibid)
Wind power	0.119	MJ	100 %	0 %	(ibid)
Solar power	0.004	MJ	100 %	0 %	(ibid)
Cobalt	0.330	kg/kWh capacity	0 %	0 %	(Mayyas et al., 2019)
Nickel	0.330	kg/kWh capacity	0 %	0 %	(ibid)
Manganese	0.310	kg/kWh capacity	0 %	0 %	(ibid)
Aluminum	0.270	kg/kWh capacity	0 %	0 %	(ibid)
Lithium	0.130	kg/kWh capacity	0 %	0 %	(ibid)
Copper	0.620	kg/kWh capacity	0 %	0 %	(ibid)
Graphite	1.650	kg/kWh capacity	0 %	0 %	(ibid)
Electricity (battery production)	0.205	GJ/kWh capacity	56.6 %	7.2 %	(Kurland, 2019)

Table A 4. Data and data sources for the biogas from organic household waste production system used in circularity score calculations. Data is shown per MJ of produced fuel.

Input	Amount	Unit	Renewability	Recyclability	References
Household food waste (dry weight)	0.084	kg	100 %	100 %	(Feiz et al., 2020)
Electricity	0.157	MJ	56.6 %	7.2 %	(ibid)
Heat	0.050	MJ	74 %	33 %	(ibid)
Vehicle gas (collection and distribution)	0.061	MJ	92.3 %	76.2 %	Based on estimated result in this report
Fossil diesel (biofertilizer spreading)	0.011	MJ	0 %	0 %	(Lantz et al., 2009)
Natural gas	0.040	MJ	0 %	0 %	(Energigas Sverige, 2021)

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